NBER WORKING PAPER SERIES

THE GLOBAL ECONOMIC IMPACT OF CLIMATE CHANGE: AN EMPIRICAL PERSPECTIVE

Solomon Hsiang

Working Paper 34357
http://www.nber.org/papers/w34357

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
October 2025

I thank Luke Sherman for excellent research support and feedback, Serena Ng, Marshall Burke, Tamma Carleton, Ishan Nath, Simon Greenhill, Andrew Hultgren, Rachel Young, Thomas Bearpark, Dylan Hogan, and the Global Policy Lab for feedback, and Wolfram Schlenker, Rachel Baker, and the Climate Impact Lab for sharing data. All errors are my own. I have no conflicts to disclose. The views expressed herein are those of the author and do not necessarily reflect the views of the National Bureau of Economic Research.

The Global Economic Impact of Climate Change: An Empirical Perspective
Solomon Hsiang
NBER Working Paper No. 34357
October 2025
JEL No. Q54

ABSTRACT

Empirical research has revolutionized how we understand the global economic impacts of climate change. Recent empirical analyses have tested theoretical ideas, challenged prior estimates, and revealed important and unexpected impacts. Further, the credibility and replicability of empirical results have played a critical role in guiding high-stakes climate policies. Here, I describe the landscape of empirical economic research on global impacts, I explain elements of modern analyses, I summarize recent findings on a range of topics, and I point towards promising new areas of investigation. In particular, I focus on empirical perspectives for six “grand challenges” in the field: understanding climate change’s global impact on economic output, health, conflict, food security, disasters, and migration. Overall, I argue that interwoven empirical findings across outcomes are aligning to paint an increasingly coherent picture of a future global economy impacted by climate change. Taking the literature as a whole, the global consequences of unmitigated climate change are likely to be substantial, unequal, negative in net economic value and potentially destabilizing.

Solomon Hsiang
Stanford University
and NBER
solhsiang@stanford.edu

1 Introduction

Determining whether and how much we should attempt to mitigate climate change is an empirical question that depends on data. Early theoretical and numerical analyses correctly identified that climate change would generate both benefits and costs, and that there would be major expenditures required to achieve meaningful mitigation (1–6). Thus, it is in principle possible that the costs of some mitigation policies outweigh their benefits. However, balanced evaluation of policies was historically challenging because the potential costs of mitigation were easier to establish, based on economic and engineering understanding of technologies (7–9), compared to the benefits of mitigation. Quantifying the benefits of mitigation was difficult because it depends on understanding the causal effect of the climate on society and the economy. When evidence on the nature of this relationship was absent, thinkers applied their intuition and experience to fill the gaps. However, over the last two decades, empirical findings describing the economic and social impacts of climate has ballooned, driven by advances in data availability, computing power, and methodological innovations. These findings, in turn, have reshaped how we understand the social value of climate change policies.

This article aims to describe some of what we have learned from data about the global economic impact of climate change. This line of inquiry is sometimes described as researching "the damage function" (7, 10, 11), a shorthand taken from early theoretical work that summarized all effects of climate change into a single function of global mean temperature for tractability. However, new evidence indicates that the relationship is complex, with many aspects of climate affecting many dimensions of the economy and human well-being in non-linear and state-dependent ways. As data and methods and have improved, many of these findings have been replicated, corroborated, or aligned with other findings. Yet despite this progress, there remain many gaps in our understanding. Thus, it is not yet possible to simply state what the total cost of climate change is to the global economy, but the remarkable and sustained efforts of a broad interdisciplinary research community have brought us closer to this goal than many may have expected.

Scope of this paper This article discusses empirical evidence that helps us understand the global consequences of climate change. *Empirical evidence* results from work that is focused on measurement of causal relationships. These measured relationships can then be "put to work" by analyzing their implications in a model. I focus on *global* impacts by considering analyses that are global in scale or collections of studies that, when combined, provide a patchwork of evidence that is plausibly representative of the global experience. Restricting attention to *consequences of climate change* means that I concentrate on findings directly relevant to climate change, ideally with implications that are drawn out for specific climate projections.

1.1 Major messages

Some general facts can be drawn from this literature.

Unmitigated climate change is likely to have a substantial net negative impact on the global economy. Empirically-based estimates broadly agree that global aggregate impacts are likely to be negative in net economic value, although all estimates have incomplete coverage of impacts. In some cases, the possibility of net benefits emerge in the short-run, for certain sectors or populations, or due to statistical uncertainty; but long-term impacts are generally damaging. Taking the literature as a whole, the global consequence of unmitigated climate are likely to be large, negative, and destabilizing.

Globally, the impacts of climate change are likely to be highly unequal with important distributional consequences. Unequal impacts are prominent in nearly all global-scale analyses. This results from the differing nature and magnitude of projected impacts between locations and industries. Low income regions and individuals tend to be more adversely impacted, suggesting that climate change is likely to widen economic inequality.

Many important economic impacts of climate change will occur outside of the market. Health, happiness, and security are projected to be impacted, presenting a challenge for efforts to monetize total impacts. Market measures associated with some impacts (e.g. food security) are seemingly modest due to currently low commodity prices — but associated welfare effects and non-market impacts (e.g. stunting, wasting) may be larger. Reporting impacts using in-kind units (e.g. conflict risk) partially helps characterize difficult-to-monetize impacts but does not ensure they are included in monetized impact estimates.

Benefits and costs of adaptation are now accounted for in some empirical analyses. Measurable adaptation is uneven across impact categories, but is important to account for in some cases. It remains difficult to determine empirically if rates of adaptation are optimal.

The largest global impacts tend to result from small but sustained pressure on large populations. Public attention often focuses on acute impacts for small populations (e.g. local extreme events), but most known global costs result from smaller but widespread chronic impacts (e.g. persistent warming). Accounting for the gradual distortion of economic patterns that result from chronic climate pressures has been an important methodological advance.

The greatest documented costs worldwide are driven by the effects of temperature. Global costs tend to be dominated by effects on human health (due to its high value) and on GDP (due to compounding of chronic conditions). Tropical cyclones and wildfires also generate substantial measured costs. Sea level rise is likely to have acute costs but for a limited population. Impacts of changing precipitation have been modest and challenging to measure outside of agriculture. Social stability in some regions is likely to be affected by climate change, but economic analyses struggle to quantify the social value of these impacts.

The delayed indirect impacts of extreme weather events (e.g. unearned income) tend to be greater and longer lasting than the direct impacts that occur during the event (e.g. capital losses). Public attention focuses on immediate direct damages because they are salient, but delayed damages tend be at least an order of magnitude larger. Empirical analyses have been essential to quantifying these long-term effects.

1.2 Organization for this article

The remainder of this article first provides a concise orientation and introduction to work in this field, and then describes findings for different major topic areas. To do this, Section 2 describes how readers can approach the literature in this field by providing an overview of the landscape, the role of empirics and a brief description of methods. Section 3 summarizes findings on six topics that I term the "Grand Challenges" of climate change impacts, each examining how climate change will impact a fundamental aspect of human society worldwide: understanding effects on economic output, health, conflict, food security, disaster impacts, and migration. Section 4 briefly describes some key findings in eight other major topic areas: behavior and decision-making, cities, energy, human capital and productivity, insurance, sea level rise, real estate, and trade. Section 5 describes areas that I believe future research should focus on. Section 6 offers a concluding discussion.

Other resources This article synthesizes findings and provides a perspective from examining the literature broadly, but it is not possible to summarize the entire field satisfactorily in a single review. Many excellent articles summarize different branches of the literature. Readers interested in starting empirical research on climate change can find reviews of the global challenge (7, 12), climate models (13), climate data (14), empirical methods (15, 16), and earlier empirical findings across the broad literature (17–19). Policy-oriented perspectives are contained in the report of the United Nations Intergovernmental Panel on Climate Change Working Group 2 (20), the United States National Climate Assessment (21), and articles on connections to integrated assessment models (IAMs) (11, 22–26). Readers interested in specific topic areas can find reviews of empirical findings linking climate change to adaptation (27, 28), inequality (29), health (30, 31), conflict (32, 33), agriculture (34–36) energy use (37), biodiversity (38), migration (39, 40), disasters (41, 42), insurance (43), labor (44, 45) and finance (46–48), among others. This article aims to help readers feel prepared to engage with this extensive literature.

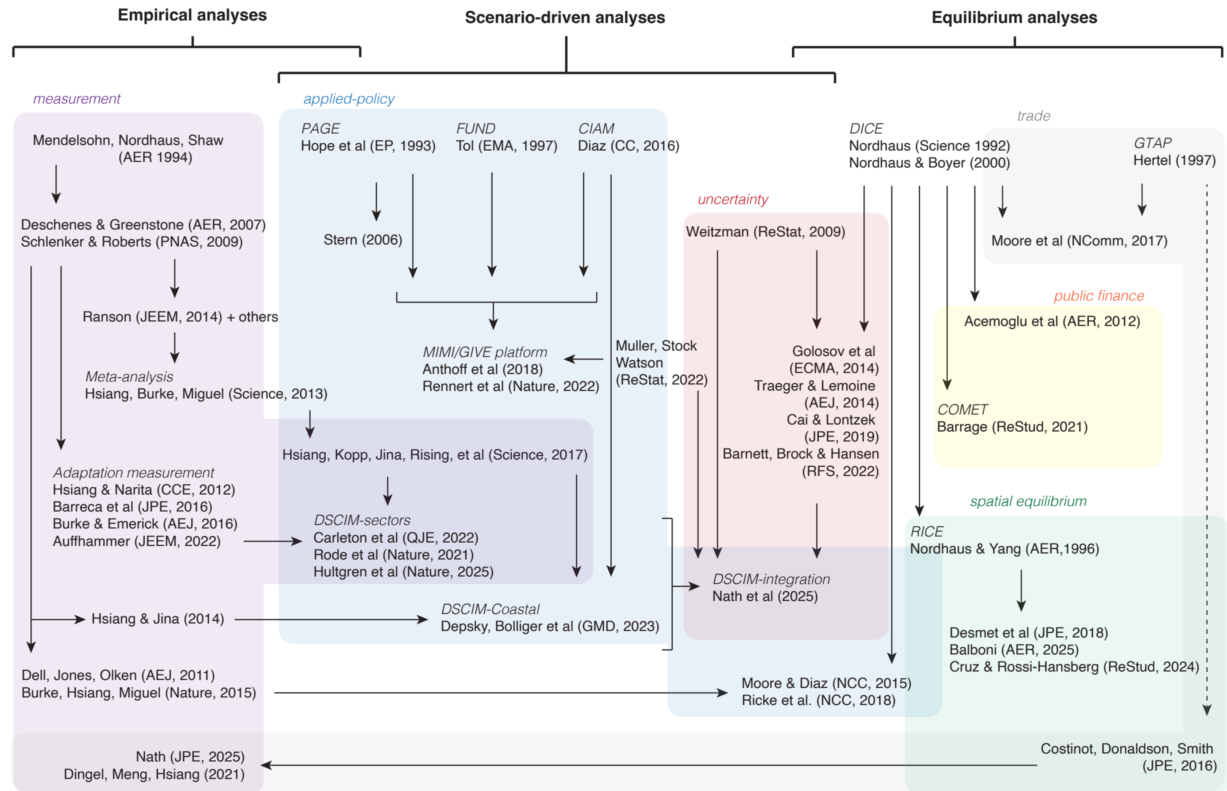

Figure 1: Sketch of the research landscape for studies on the economic consequences of climate change. The oldest studies are at the top, and arrows indicate studies that can be (approximately) thought of as "intellectual descendants" of prior studies. Colored areas indicate groupings of studies that are focused on particular types of questions. Three general branches of the literature that I identify and discuss in the main text are "*Empirical analyses*" (left), "*Scenario-driven analyses*" (center), and "*Equilibrium analyses*" (right). See text for descriptions and references.

Online appendix The Appendix also contains a primer on advances modeling adaptation, a discussion of quantities used to characterize climate change impacts, additional description of methodological considerations, and a discussion of some particular prior empirical findings.

2 Reading the literature

The economics of climate change is a large and rapidly growing literature, with various branches addressing different questions. The range of methods and disciplines applied to this challenge is correspondingly diverse. Here, I provide a brief orientation to the literature on the economic consequences of climate change, and the role and structure of empirical analysis within it.

2.1 The research landscape

At a high level, this literature can be roughly broken into three branches, which I call "*empirical*", "*scenario-driven*", and "*equilibrium*" focused analyses. Each branch focuses on specific types of questions and often uses a core set of methods. Figure 1 depicts a sketch that tries to map the literature landscape and these three branches, identifying linkages between some key or representative studies. The boundaries of the three branches are fuzzy, but generally correspond to the three labeled columns of studies. The oldest studies are at the top with arrows indicating studies that can be loosely thought of as "intellectual descendants" of prior studies. These descendant studies may not explicitly build directly on the indicated prior studies, but they build on ideas or questions raised in the prior work. Colored areas indicate groupings of studies that are focused on particular types of questions: measurement (purple), applied policy questions (blue), uncertainty (red), public finance (yellow), spatial equilibrium (green) and trade (grey). This figure is not designed to be comprehensive, since thousands of studies are omitted; rather, it aims to help researchers organize their sense of the literature and locate the approximate position of work based on its similarities to the limited set of studies that are visualized.

Empirical analyses The empirical branch of research is focused on measuring the causal effects that climate has on society and the economy. The core challenges for research in the empirical branch concern data collection and identification. The results of these studies are increasingly being integrated into the applied policy studies of the scenario-driven branch. I think it is broadly accepted that this branch originated in the seminal analysis by Mendelsohn, Nordhaus, and Shaw (1994) (49) estimating the effect of climate on farm profits in the United States. Subsequent work developed methodological innovations, such as accounting for unobserved confounding heterogeneity (50, 51), accounting for adaptation (52–59), and estimating impacts on growth (60–62) or trade equilibria (63, 64). In some cases, many studies have measured related parameters, motivating efforts to consolidate findings (e.g. meta-analysis) to inform policy applications (32, 65–67). This branch is the focus of the present article.

Scenario-driven analyses The scenario-driven branch of research focuses on answering policy questions, such as estimating the "social cost of carbon" (SCC, discussed below) (24, 25), that require simulation of different climate and policy scenarios. The structure and scope of these analyses are shaped by the limitations of computing resources and usually conform to standardized climate, policy, and socioeconomic scenarios that are taken as exogenous (13). These studies tend to abstract away from many of the rich insights generated elsewhere in the literature due to practical concerns, such as modeling resources, but are increasingly incorporating empirical results. Many models in this branch are deterministic with few or no endogenous variables. Early work in this branch developed the integrated assessment models (IAMS) FUND (2) and PAGE (3) later used in the first estimates of the social cost of carbon by the US Federal government (68). Subsequent efforts have focused on making these models modular and interoperable (69, 70), updating scenarios used for projections (71, 72) or integrating empirical analyses (57–59, 73, 74).

Equilibrium analyses The equilibrium branch of research focuses on understanding conceptually how economic equilibria respond to climate change. These studies use theoretical and numerical models to describe components of an economic system and study how the model's endogenous elements might respond to climate change, often characterizing optimal solutions. These studies usually focus on simplified models that can be solved analytically, facilitating insight and understanding. These studies sometimes integrate empirical findings in a calibration step, develop future projections, or compute policy-motivated metrics (such as an SCC), but their greatest strength is to illuminate how a climate-economic response should be thought about, not to estimate precisely what it will look like. The equilibrium branch spans a range of diverse questions and topics and uses specialized models drawn from economic sub-fields. Nordhaus's DICE model[1] was seminal for this branch because, unlike other early IAMS, it solved for an optimal economic response to climate change (1, 5, 75). Later work explored optimal public spending (76, 77). Nordhaus and Yang (78) developed the first regionally disaggregated IAM "RICE"[2] aiming to understand trade and general equilibrium for major world regions within a framework of optimal climate change responses. This problem has been studied further using computable general equilibrium (CGE) models (79, 80), structural country-to-country trade models (81), and recent work that accounts for optimal trade and investment in continuous space (82–84). I also think of Weitzman (2009) (85) as triggering an explosion of research on how to account for uncertainty in these contexts (86–89), although much of this subsequent work does not build directly on his framework or insights.

[1]DICE = Dynamic Integrated Climate Economy model
[2]RICE = Regional Integrated model of Climate and the Economy

Convergence As indicated by Figure 1, many research lineages are beginning to mix and merge. Multiple lines of inquiry are discovering benefits from drawing on insights or methods developed in other research areas. This is perhaps most visible in the development of applied-policy models that are increasingly drawing on both empirical results from one side and theoretical insights on the other side. For example, several research lines converge at the Mimi-GIVE modeling platform[3] developed by David Anthoff's Lab at UC Berkeley and Resources for the Future (69, 70) and the DSCIM framework[4] developed by the Climate Impact Lab (57, 58), both of which were used to compute the US EPA's most recent estimate of the SCC [5] (25).

2.2 The role of empirical analysis

Within the broader research landscape, empirical research plays a crucial role in our understanding of the economic consequences of climate change, both conceptually and in decision-making. As suggested by Figure 1, alternative approaches are valuable, since empirical research cannot deliver many insights provided by the other research branches. However, empirical research is essential to any exercise in which quantification is important. For example, determining how much public funding should be reallocated from other uses to invest in emissions mitigation, how much emitters should be taxed, or whether the benefits from a specific investment in emissions reduction outweighs its cost, all require credible measurement of the effect of climate change.

In addition, our conceptual understanding of climate change effects may become clouded when theoretical or numerical analyses are not constrained by empirical analysis, since it may be difficult to select between competing hypotheses. Often, multiple analyses all provide excellent reasoning but diverge in their conclusions if none are anchored to data. While this point applies to many sub-fields in economics, two aspects of this context amplify the importance of empirical analyses in the development of theories and models.

First, because analysis of climate change describes future conditions and events, it is easy, and perhaps natural, to drift into speculations that might be difficult to defend under the glare of empirical analysis. (For example, some writers casually argue that climate change will "end civilization" as if the conclusion is self evident.)

Second, many relationships studied in the literature are unintuitive (e.g. the effect of temperature on civil conflict), making it challenging for researchers to imagine many findings without data. Often, robust empirical findings do not match any previously written hypotheses, suggesting that it may simply be too difficult to have natural intuition for many questions in this field. Theoretical and numerical analysis benefit when empirical findings open up new and unexpected lines of inquiry.

Overall, empirical evidence has proven essential to progress in the field. Many hypotheses about the potential impacts of climate change have been falsified based on empirical findings in the last two decades. For example, some early analysis argued that the largest economic cost of climate change were energy expenditures due to air conditioning uptake in poor countries, a theory that has since been rejected by data (58); or that the net amenity value of climate change in the US would be positive (90), when recent analysis suggests it is very likely to be negative (91). By rejecting theories, empirical analyses have enabled scientific progress that moves the research community forward. With greater confidence in surviving theories, researchers are able to build on prior findings, developing an increasingly rich understanding of likely outcomes.

2.3 The empirical problem

Empirical climate change impact estimates assume there exists an underlying primitive relationship between the environment and an economic outcome that can be characterized by a "dose-response function," a concept adopted from epidemiology. In this framework, an observational unit (e.g. an individual) exhibits an outcome (the response y) that results from a "weather hazard" (the dose x) interacting with that unit's "vulnerability" (β):

$$\underbrace{outcome}_{\text{"response"}\, y} = \underbrace{vulnerability}_{\beta} \cdot \underbrace{weather\_hazard}_{\text{"dose"}\, x} + \epsilon \tag{1}$$

[3]Mimi = modular modeling framework; GIVE = Greenhouse gas Impact Value Estimator
[4]DSCIM = Data-driven Spatial Climate Impacts Model

Here, *weather_hazard* is a physical event or condition (hereafter "hazard"), considered an independent variable x, and *vulnerability* describes how that hazard is translated into an economic impact, expressed as a marginal effect β (note that in practice, many impacts are non-linear functions of weather). ϵ is the unmodeled component or "residual." The empirical challenge to estimating Equation 1 are to construct meaningful measures of the weather hazard x and to recover causal estimates of vulnerability β. With such a model, impacts of climate change can be computed by altering the distribution of x, reflecting climate changes, and then computing the resulting change in outcomes (18).

The literature studies many types of economic impacts (e.g. GDP, health, etc), each of which is potentially influenced by multiple dimensions of the climate (e.g. temperature, precipitation, cyclones, etc). Thus, over time, researchers are collectively populating the vulnerability matrix $\mathbf{B}$:

$$\underbrace{\begin{bmatrix} GDP \\ health \\ conflict \\ \vdots \end{bmatrix}}_{\mathbf{y}} = \underbrace{\begin{bmatrix} \beta_{GDP,T} & \beta_{GDP,P} & \beta_{GDP,C} & \cdots \\ \beta_{health,T} & \beta_{health,P} & \beta_{health,C} & \cdots \\ \beta_{conflict,T} & \beta_{conflict,P} & \beta_{conflict,C} & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix}}_{\mathbf{B}} \cdot \underbrace{\begin{bmatrix} temperature \\ precipitation \\ cyclones \\ \vdots \end{bmatrix}}_{\mathbf{x}} + \underbrace{\begin{bmatrix} \varepsilon_{GDP} \\ \varepsilon_{health} \\ \varepsilon_{conflict} \\ \vdots \end{bmatrix}}_{\epsilon} \quad (2)$$

where elements of $\mathbf{B}$ are zero if a particular dimension of the climate does not affect an outcome. $\mathbf{B}$ is large and many gaps remain, but numerous entries in $\mathbf{B}$ have now been recovered. To illustrate some important contributions to our understanding of $\mathbf{B}$, Figure 2 shows several dose-response relationships relevant to the six "grand challenges" discussed later in this article. Note that each figure panel is discussed in a later section.

2.4 Identification strategies

Developing research designs to credibly measure the effect of climate on society, captured by $\mathbf{B}$ in Eq.2, has been a major catalyst for progress in the literature. I summarize key advances very briefly.

Stated simply, the climate is a distribution over possible states of weather. The empirical challenge has been to measure how this distribution affects economic and social outcomes. Early work, such as Mendelsohn, Nordhaus and Shaw (1994) (49) and Nordhaus (2006) (92) conditioned outcomes (e.g. farm profits) on summary statistics for this distribution, (e.g. long-run average temperature) in pooled cross-sectional regressions of county observations (known as a "between design").

Later work by Deschênes and Greenstone (2007) (50) and Schlenker and Roberts (2009) (51) pointed out that unobserved confounding heterogeneity between locations was correlated with these summary climate statistics. Instead, they proposed a solution that conditions outcomes on location-specific fixed effects, exploiting identifying variation from inter-temporal changes to realized weather distributions within a location (known as a "within design"). This research design aimed at identifying how components of a climatological distribution, i.e. finite intervals of time experiencing specific weather events, generate end-of-period outcomes. The key benefit of this strategy is that it allowed the use of panel data methods, such as location and time fixed effects, which nonparametrically account for many forms of unobserved heterogeneity.

A conceptual challenge of the within design was that it was unclear how to interpret. Specifically, to what extent do the estimated effects of a realized weather distribution capture adaptations to climate? This was the sometimes-spirited "weather vs. climate" debate. Three solutions to this problem are used in the literature.

First, if the outcome of interest is a maximized quantity, then the marginal effect changes in the realized weather distribution are the same as the marginal effect of changes in the long-term climatological distribution of weather (15, 93). These two marginal effects do not represent the same mathematical object but they are nonetheless generally (sometimes approximately (94)) equal, a result of the Envelope Theorem.

Second, if the outcome of interest is not a maximized quantity, a general solution is to estimate the effect of realized weather conditional on climate measures (e.g. long-run average temperature). Since adaptations are responsive to expectations about the climate, conditioning on climate serves as an effective proxy for these adaptations. This was described implicitly by many authors for years and initially made explicit by Hsiang and Narita (2012), and recently expanded upon by Carleton et al (2022) (57). This strategy often motivates the use of models that are nonlinear in weather (e.g. $\alpha T + \beta T^2$), since these models are nearly identical to simpler models for weather effects that are interacted with the a corresponding climate analog (e.g. $\alpha T + \beta \bar{T} \cdot T$) (e.g. ref. (61)).

Third, sometimes the within approach can be altered so that the units of observation cover long periods (e.g. decades) that capture a meaningful measure of climate (e.g. decadal average temperature). This "long differences" approach thus conditions outcomes directly on climate, rather than weather, while still benefiting from the advantages of the within design (e.g. using location fixed effects). Dell et al (2012) (60) proposed this strategy, which was developed further and expanded on by Burke and Emerick (2016) (54). Hsiang (2016) (15) demonstrated a generalization of this approach using low-pass filters.

Lastly, a recently developed approach returns to a between design while accounting for unobserved heterogeneity. This allows estimated outcomes to reflect long-term climate distributions directly. The "spatial first differences" (SFD) approach proposed by Druckenmiller and Hsiang (2018) (95) removes the effects of unobserved confounding variables by differencing them out from pairs of spatial neighbors. Thus, causal inferences using SFD are analogous to a regression discontinuity in space, but implemented continuously between all pairs of neighbors. Because SFD conditions on long-term climate, the effects of adaptations are implicitly accounted for, as originally argued in Mendelsohn et al (1994) (49).

For more detailed background and discussion of identification strategies and other methodological considerations, see Hsiang (2016) (15) and Hogan and Schlenker (2024) (16). I also discuss **Additional methodological considerations** in Appendix C.

2.5 Adaptation

As discussed above, a core technical and conceptual challenge to nearly all empirical analyses of climate change impacts has been to understand, model, and project human adaptation. Broadly speaking, adaptations are behaviors or investments that individuals use to protect themselves from the adverse impacts of climate change or take advantage of new opportunities created by climate changes. Adaptations are expressed in data as altering a population's vulnerability ($\mathbf{B}$). Many disagreements between pre-empirical studies ultimately boiled down to untested assumptions about the degree of adaptation populations actually undertake. In current frontier research, many researchers are now measuring the scale and scope of real-world adaptation and using these values to understand how much adaptation will influence climate change impacts, essentially building projections of adaptation that are then used to modify a baseline impact projection (e.g. (57, 59)).

Here I briefly summarize recent advances on two general technical topics that connect to nearly all branches of the broader empirical literature. I provide a more complete introduction on these advances in Appendix section A ("**An Adaptation Primer**") and further discussion are in the reviews by refs. (15, 27). Empirical results regarding adaptation in particular domains are discussed in later sections.

Adaptation costs Some early literature assumed that populations would adapt to climate extensively because the costs of adaptation would "vanish in the long run". This idea implied that all populations should utilize frontier adaptation technologies and exhibit identical vulnerability, which Hsiang and Narita (2012) demonstrated was not true by measuring distinct vulnerabilities to tropical cyclones across countries (52). Such differences in vulnerability are reconciled by non-vanishing adaptation costs. Optimizing populations adapt up to a level where the cost of marginal adaptations equal their expected marginal benefit, which may differ by population. Deryugina and Hsiang (2017) (93) point out that in general equilibrium, adaptations are a reallocation of resources, such that impacts of climate on total revenues (i.e. GDP) implicitly include all adaptation costs for actions that are priced in the market. For cases where the outcome of interest is not GDP, Carleton et al. (2022) (57) developed a general approach to account for unobserved adaptation costs explicitly, by integrating unobserved marginal costs that are assumed to be equal to measurable marginal benefits.

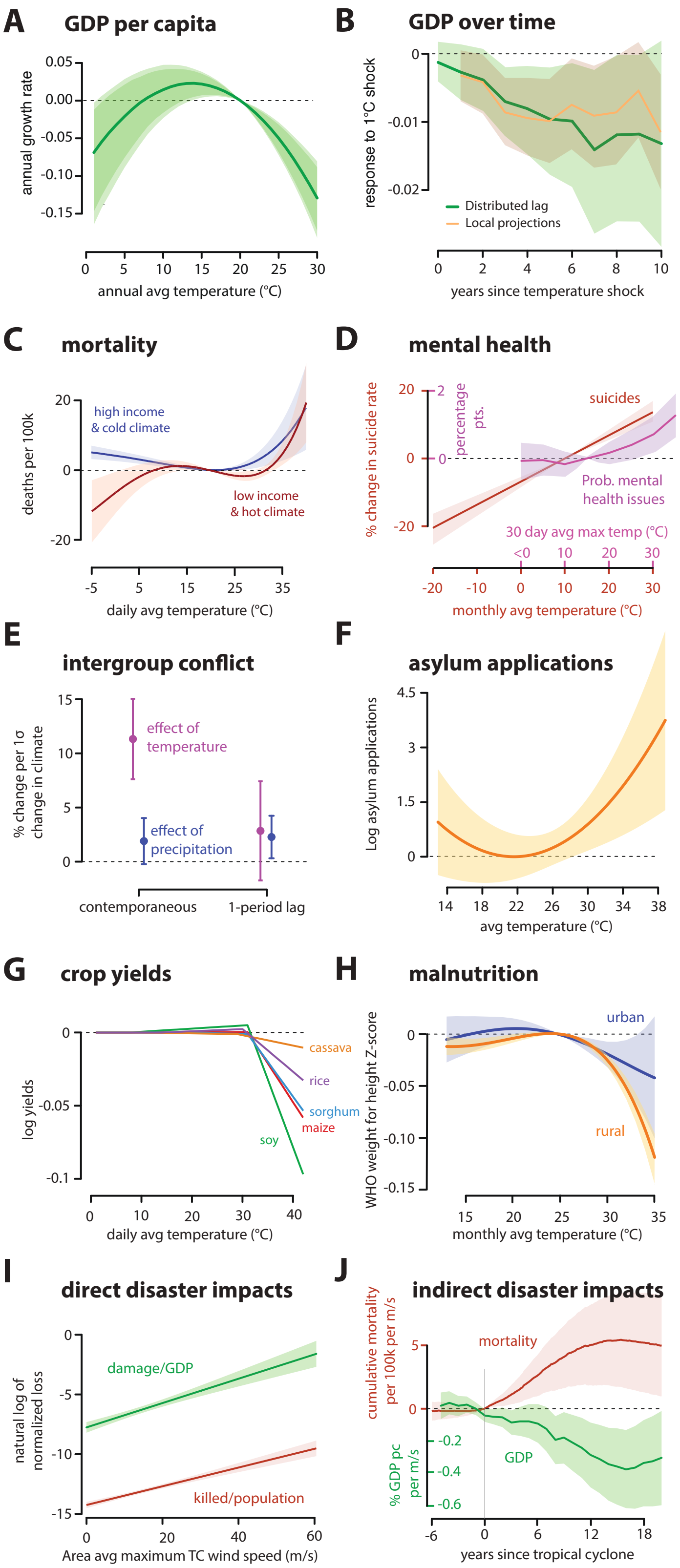

Figure 2: Empirical dose-response relationships for select studies on six "grand challenges" of climate change impact research: (A)-(B) economic output; (C)-(D) health; (E) conflict; (F) migration; (G)-(H) food security; (I)-(J) disasters. Thick lines indicate point estimates, shaded regions indicate confidence intervals. Figures are reproduced from referenced studies, see studies for estimation details. (A) Estimated effect of annual average temperature on the contemporaneous growth rate of GDP per capita (global, 1960-2020) (96). (B) Similar to (A), but the cumulative income-weighted average marginal effect over time of a 1°C temperature change, using a distributed lag (green) or local projection (orange) model (96). (C) Estimated effect of daily temperature on mortality for a large international sample, shown for two subgroups in a model that accounts for adaptation in response to both income and climate (57). (D) Changes in suicide rates in response to monthly average temperature (red) (97) and the probability of mental health issues (purple) in response to 30-day avg maximum temperature (98), both for the United States. (E) Estimated effect of a 1 SD change in temperature (purple) or precipitation (blue) on contemporaneous and lagged intergroup conflict, from a meta-analysis of 14 (temperature) and 19 (precipitation) studies (32). (F) Estimated effect of average growing season temperature on asylum applications from all countries into the European Union (99). (G) Estimated effect of daily temperature on five crop yields for a large international sample, shown for sample average temperatures in a model that account for adaptation in response to income, climate, and irrigation (59). (H) Estimated effect of lifetime exposure to monthly average temperatures and on weight-for-height z-scores among children in DHS surveys of 30 countries in Sub-Saharan Africa for urban (blue) and rural (orange) populations (1993–2012) (100). (I) Direct damages from all tropical cyclones (1950-2008): global average damage/GDP (green) and killed/population (red) (52). (J) Indirect damage from tropical cyclones: GDP loss in a global sample (green) (62) and excess mortality in the USA (red) (101).

Quantifying adaptation There are two general approaches to studying adaptations empirically. First, it may be feasible to study adaptation actions directly, treating them as an outcome. For example, studying the use of irrigation (102, 103). Second, researchers study how protective adaptations are. This can be done by studying a real or natural experiment where only some populations can utilize a certain type of observable adaptation (e.g. (53, 104–106)). Alternatively, many unobservable adaptations can be accounted for by modeling vulnerability as a function of proxy variables, such as income or average climate, that can be used to index a large number of unobserved adaptive actions (see Appendix Figure A.1). The literature generally assumes measures of long-term climate are a sufficient statistic for all adaptations associated with a change in climate (57–59, 67, 93, 94).

2.6 Characterizing impacts

It is can be helpful to clarify some metrics and mathematical objects that are commonly used to characterize empirical estimates of climate impacts but are somewhat unique to this literature. As described in Eq. 1, **dose-response functions** characterize the effect of a *local* hazards, such as exposure to a heat wave, on *local* outcomes, such crop yields (e.g. Figure 2). In contrast, **damage functions** summarize aggregate *global* outcomes based on the level of *global* climate change, usually indexed by a change in global mean surface temperature (ΔGMST). Below, Figure 5 will show six example global damage functions derived from empirical analyses (each is discussed in a following section). When costs are aggregated over time, **historical attribution** is the procedure of estimating the impact that *historical* climate [change] has had on a population. Alternatively, the **Social Cost of Carbon [and other GHGs]** (SCC or SC-GHGs) is the total net present value of *future* social costs (or benefit) that results from emitting a marginal ton of CO_2 (or other GHG) at a specific moment in time (24, 25) (see Appendix Figure A.2). Sometimes a component of the SCC that represents damages (or benefits) in a particular impact category is transformed into a **partial SCC** just for that impact. I more fully discuss these terms and several others in Appendix B.

3 Progress and perspective on six "Grand Challenges"

Empirical research has uncovered many pathways through which climate impacts societies worldwide. Among these, I view six broad classes of impact as the most critical. Each of these six "grand challenges" asks how climate change will impact a fundamental aspect of human society worldwide. How will climate change affect (1) economic economic output, (2) human health, (3) conflict, (4) food security, (5) disaster impacts, and (6) human migration? Here, I provide perspective on some of what we have learned about each grand challenge from empirical research, focusing on a global perspective. For example, Figure 2 depicts several key dose-response functions that address elements of each of these six grand challenges, each panel of which is discussed below. This is not a comprehensive review of these topics, but most grand challenges are the focus of reviews elsewhere (18, 30, 32, 34, 35, 39–42, 65).

3.1 Economic output

Available evidence indicates that climate change will almost certainly impact economic output. This intuition was captured in Nordhaus' early formulations of the DICE model (5) which assumed a productivity loss that was quadratic in contemporaneous temperature. Since then, much empirical work has gone into quantifying and studying how climate affects output.

Perhaps the most important empirical result is that GDP is highly responsive to climatological hazards. Temperature (60, 61, 93, 96, 107–112), tropical cyclones (62, 113), heat waves (114) and the El Niño-Southern Oscillation (ENSO) (115–117) have clear impacts on GDP, with rainfall having small insignificant effects (e.g. Figure 2A-B).

Empirical analysis has highlighted numerous channels through which climate affects GDP. Early literature focused on agriculture and poor regions as the main entry points for climate to influence global output, but there is now evidence that most industries and regions are affected. For example, human labor and/or energy consumption are adversely affected by high temperatures nearly everywhere — partially because in wealthy countries, impacts on energy substitute for some impacts on labor. Extreme climate conditions

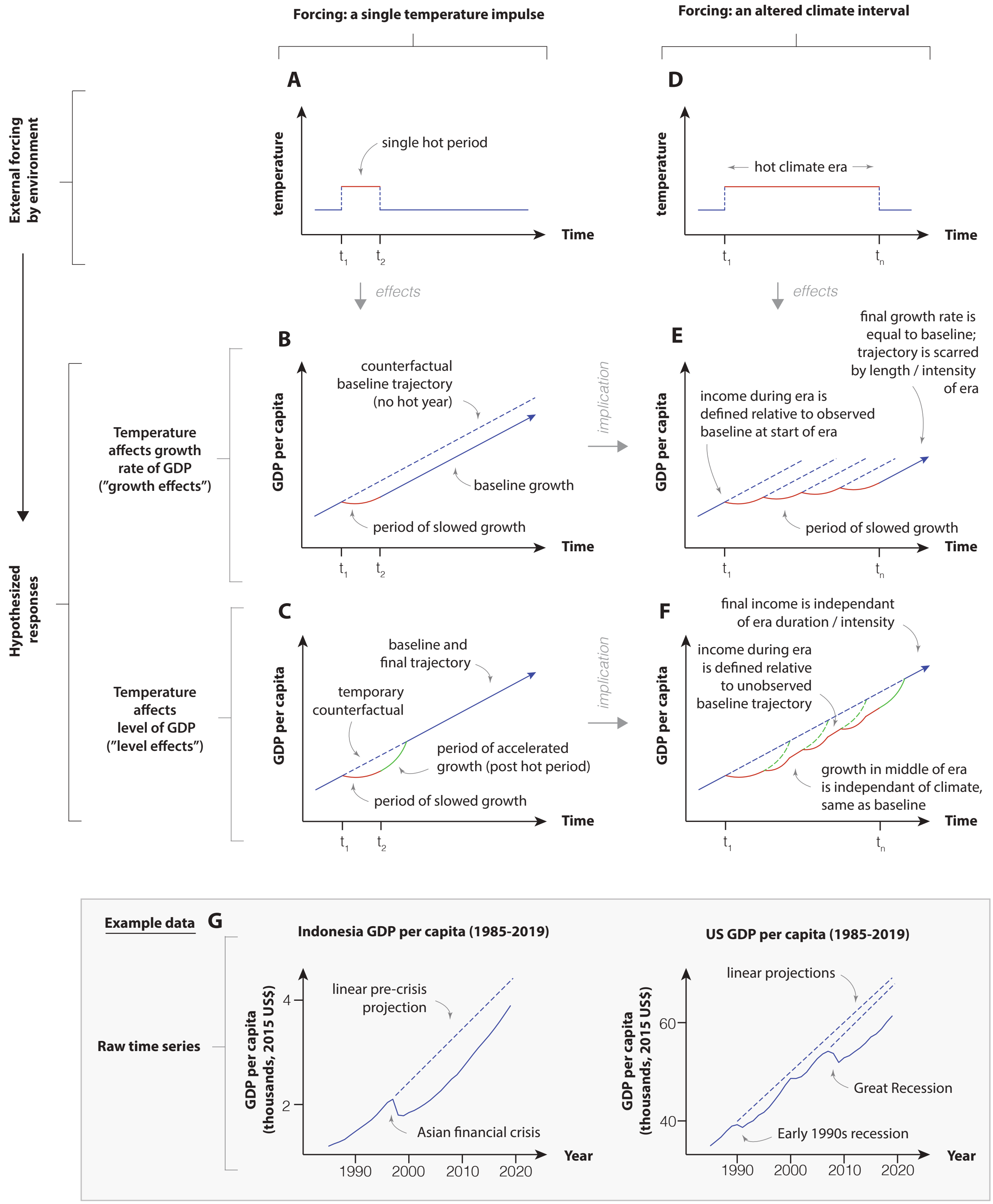

Figure 3: Illustrated difference between hypothesized "growth effects" and "level effects" of temperature on GDP. (A) Exogenous forcing is a single hot period lasting from t_1 to t_2. (B) Impulse-response of GDP to the forcing in A if higher temperature affects GDP growth. Dashed line indicates unobserved counterfactual GDP trajectory. (C) Same as B, but if temperature temporarily affects the level of GDP. (D) Exogenous forcing is a sustained hot climate era from t_1 to t_n. (E) Altered trajectory if temperature affects GDP growth as in (B). (F) same, but if temperature affects level of GDP as in (C). (G) Examples of raw GDP time series from Indonesia and the US (1985-2019), dashed lines are linear fits to years just preceding each crisis.

impact many components of an economy, mainly in a large number of small ways, making it analogous to throwing sand in the gears of a large machine (45). In practice, to simplify modeling, this often results in models of climate affecting factor productivity, similar to Nordhaus's original assumption. Also consistent with prior thinking, evidence indicates that agriculture is generally one of the most sensitive industries (59, 93, 107, 118). In other industries where workers are exposed to environmental conditions that are correlated with outdoor climates (e.g. workers outdoors, in factories, or most industries in low income countries) there is also high sensitivity of output to climate (119, 120). There remains more mixed results on the effects in high value-added industries in wealthy countries (45), but there is general agreement for some non-zero degree of impact.

The most important debate on this topic is the structure and the persistence of these effects. At issue is understanding (i) the *structure* of the mapping from climate conditions to changes in economic output and (ii) whether impacts *persist* for extended periods or dissipate following the return of a historical climate.

Regarding (i) structure, there is an emerging consensus for the general magnitude and shape of impacts that occur contemporaneously with climate shocks, particularly for temperature. In general, studies consistently report a nonlinear relationship between temperature and output (60, 61, 93, 96, 107–110, 112), where cold and hot conditions both reduce output relative to an optimum of roughly 13-15°C (55.4-59°F, see Figure 2A). Hot temperatures generally reduce total output roughly 1-2% per 1°C. This basic nonlinear structure has been reported across many contexts with consistency. (Important early work by Dell et al. (2012) (60) assumed a linear relationship but presented findings consistent with later nonlinear results, discussed in Appendix D.) Overall, the estimated effects of climate shocks on GDP tend to be substantial in comparison to many other less common shocks discussed in the literature (e.g. tax changes (121)), leading to a growing recognition of the climate as an important force in driving patterns of productivity (18, 92, 93, 112, 122–124).

Regarding (ii) persistence, there is less explicit agreement in published writing, but I argue that there is emerging consistency in actual findings. The central debate is whether the effect of a temporary change in climate conditions (Figure 3A), e.g. a hot year or tropical cyclone strike, affects the growth rate of GDP or the level of GDP. If climate has a "growth effect" (Figure 3B), then the growth rate of output declines during the anomalous period and later returns to its baseline once the climate reverts, and GDP never returns to its initial trend. If climate has a "level effect" on GDP (Figure 3C), then the response is similar except there is a period of accelerated growth after an anomalous period ends, causing GDP to recover to its pre-anomaly trend. (Note that Nordhaus' original DICE model was driven by level effects.)

Distinguishing between these two models of persistence is important because they have different implications if the climate is altered for an extended interval of time, which I call a "hot climate era" (Figure 3D). If climate has a growth effect, then growth slows during the hot climate era and the trajectory of GDP is permanently altered, relative to its pre-era trend, when the era ends (Figure 3E). If climate has a level effect, then growth slows when a hot climate era begins, it stabilizes at baseline rates in the middle of the era when income is depressed relative to the baseline trajectory, and then it accelerates after the era ends – allowing GDP to catch up to its pre-era trend (Figure 3F). In contrast to the permanent negative offset caused by growth effects, level effects imply that the level of GDP is not altered in the long-run by a hot climate era of any intensity or any duration, so long as it eventually ends. Because growth effects compound, they produce larger cumulative impacts of warming than level effects of similar magnitude.

The definitive empirical test to distinguish level and growth effects is to examine the lagged effects of anomalous climate conditions on growth (60). If there is a period of accelerated post-anomaly growth large enough that GDP catches up to its pre-anomaly trend (green segment in Figure 3C), then the data exhibits a level effect. For an analogy: imagine national incomes are cyclists in a race. Level effects would imply that if a cyclist falls, they always accelerate their peddling post-fall enough to catch up to the other cyclists and a fall does not affect the later outcome of the race. Growth effects would imply that cyclists pedal similarly before and after a fall, such that the fall-induced gap with other riders does not close. The literature has not yet recovered clear empirical evidence for a post-anomaly period of accelerated growth that would justify rejecting growth effects. Many studies consistently find either no acceleration or a limited acceleration that does not fully offset the initial slowdown in growth (e.g. see Figure 2B) (60–62, 96, 109, 110, 116). This indicates that some portion of the climate's impact on GDP is highly persistent, consistent with macroeconomic dynamics following other non-climate shocks (125), such as financial crises, political crises, wars, and tax changes (121, 126) (e.g. Figure 3G). Thus, as a corollary, if climate induced level effects on

GDP, this would require that the GDP response to climate is fundamentally different from its response to other shocks. Note also that another complication with levels effects, as a theory, is that the GDP impact from a century of climate change would vanish quickly if, hypothetically, the climate were somehow restored to its pre-industrial state in 2100. For these various reasons, below I focus on the economic implications of growth effects.

Accounting for nonlinear effects of temperature on growth tends to generate projections with large economic losses. For example, the empirically-based damage function from Burke et al (2015) (Figure 5A) indicates that 3°C of warming would reduce global GDP per capita by roughly 19.6% in 2100 relative to a counterfactual growth trajectory without warming. Notably, these models also exhibit large uncertainty in aggregate future projections (e.g. -38.2 to +12.2% at 3°C), mainly resulting from uncertainty in the turning point of the dose-response function.

Non-linear growth effects of temperature on GDP have crucial implication for global inequality. Because warming is relatively more harmful for hot countries and hot countries tend to be poorer, the projected impacts of warming are to dramatically reduce incomes in tropical and subtropical regions, while having muted or even positive impacts in higher latitudes (Figure 4A). An open empirical question is whether and how incomes have historically converged despite persistent climate impacts on growth (109, 122).

The projected impact of heat waves and ENSO on GDP is less clear, primarily because physical projections of these phenomena are weaker. Changing tropical cyclone distributions will impact long term GDP growth for chronically cyclone-prone countries, likely generating trillions of dollars in foregone earnings this century (62). This impact is largest in East Asia where storms will intensify the most, while some countries may benefit modestly from experiencing fewer storms.

SCC calculations that incorporate empirical estimates of GDP growth impacts tend to estimate larger impacts than models that were historically calibrated independent of these estimates. For example, Moore and Diaz (2015) (73) modify the DICE model to account for GDP effects estimated by Dell et al. (2012) (60) and obtain an optimal-policy SCC of $291 per ton of CO_2 (inflation adjusted to 2024 USD), larger than the $45 in the baseline parameterization. Ricke et al (2018) (74) use the nonlinear estimates from Burke et al (2015) (61) and recover an SCC of $519 per ton of CO_2. In an update, Burke et al (forthcoming) re-estimate the temperature-GDP relationship based on methodological advances from the literature (Figure 2A-B) and report an SCC of roughly $2,000 per ton of CO_2 (2% discount rate) (96).

Burke et al. also use these updated results to construct estimates for "Loss and Damage" (see Appendix B) using an SCC-consistent approach, finding that one ton of CO_2 emitted in 1990 caused roughly $180 of harm by 2020 and will cause an additional $2000 of damage by 2100.

Overall, the accumulation of effects on economic output from chronic climate changes leads to projections that exhibit large impacts that can be difficult to imagine. These projections describe an economic environment that is fundamentally altered by decades of numerous marginal changes (see Appendix C). It is important to acknowledge both the difficulty of imagining these counterfactuals and that such difficulty is not evidence to reject the underlying empirical findings.

Future work should focus on understanding the underlying mechanisms driving climatological impacts on GDP and how to ameliorate them.

3.2 Health

Estimates suggest that health impacts are a major, if not the greatest, economic consequence of climate change (18, 22, 25, 66, 70)— in large part because health and human lives tend to be highly valued. However, because much of health's value emerges outside of the marketplace (and is not captured in GDP), a recurring challenge is determining how these impacts should be priced. For example, the value of a statistical life (VSL) plays a role in converting mortality impacts into monetary units, introducing uncertainty and potentially contentious choices into these calculations.

Accounting for adaptation is particularly important for health impacts, since the extent of measurable adaptation is so great (52, 55, 57, 104). Across locations, literature repeatedly finds that health tends to be better protected from many hazards in contexts where they are more common (e.g. a hot days are less deadly in hot locations), indicating adaptation. Some patterns of adaptation might result from actions intended to protect health from climate, but many vulnerability reductions probably result from comfort-focused investments (e.g. air conditioning protects health (127), but is usually installed for comfort). In general, adaptations emerge for hazards that result in clear and acute impacts on health (e.g. immediate deaths from disasters) but there is less adaptation for less obvious health impacts (e.g. indirect deaths from disasters) (67, 101).

The health impacts of climate change have meaningful distributional implications, creating "winners" and "losers" (e.g. Figure 4B). Many wealthy populations live in temperate environments where health benefits from warming can offset some costs and/or they may have more resources to protect themselves (29, 52, 57, 127, 128). Poorer populations tend to be more exposed to harmful conditions based on their geography, they may have difficulty identifying or financing defensive investments, and protecting their health may have fewer pecuniary benefits (e.g. due to low wages).

The thermal impact of climate change on mortality, i.e. the direct effects of hot and cold temperatures, is well-studied empirically, due to its importance and the availability of data. Research has focused on excess all-cause mortality, which captures all pathways that generate mortality (53, 55, 57, 127, 129). Studies consistently recover a dose-response function that is U-shaped (Figure 2C), with hot days causing deaths quickly and cold days causing deaths over a longer period (130). Adaptation mediates the shape of this curve, shifting the "mortality minimizing temperature" towards common local temperatures and enabling hotter and richer locations to reduce their vulnerability somewhat (55, 57, 129). In the US, mortality from heat declined rapidly at mid-century, probably due to expanded access to air conditioning (53) and community health clinics (104), but rates of adaption have since slowed (67). Historically, in a sample of several hundred cities, roughly 7.7% deaths are due to baseline (pre-industrial) climates (131) and 37% of warm-season heat related-deaths are due to historical warming (132). The projected future mortality impacts of warming have a broad distribution, due both to the uncertain balance between gains and damages and substantial uncertainty in estimated rates of adaptation (Figure 5B). One projection (57) estimates that warming will contribute to roughly 73 deaths per 100,000 worldwide (high emissions scenario), valued at roughly 3.2% of world GDP (Figure 5B). This impact is distributed unevenly, with low income regions suffering a larger burden (57) (Figure 4B).

Non-thermal impacts of climate change, i.e. the effect of all other factors besides temperature, have been studied less, but some analyses suggest that they also are likely to have major economic consequences. For example, the increasing frequency of wildfires in the US is projected to generate more particulate matter (PM) air pollution, which in turn has many health impacts, including mortality (133, 134). PM-induced mortality has been documented in many contexts around the world (135–137), but linkages to wildfires and/or climate change are less clear globally. In the US, these projected costs amount to $608 billion annually by mid-century, potentially greater than the thermal impacts of climate change in the US (133). New evidence indicates that indirect mortality from tropical cyclones is much larger than their direct mortality (101, 138) (Figure 2I vs 2J), which is also true for urban floods in some contexts (139, 140). There are substantial adverse health impacts from reduced rainfall in agricultural contexts (e.g. (141, 142)), but the potential future impact of these channels is poorly constrained, in part because rainfall projections so uncertain (57).

Evidence increasingly indicates that mental health will be impacted by climate change. Early work indicated that climate disasters affected mental health through stress (e.g. (143)) while recent findings demonstrate effects of temperature across multiple mental health outcome measures (144). The dose-response relationship between temperature and mental health is qualitatively different from the U-shaped mortality response: harm increases roughly linearly with temperature for measures of affect (91), self-reported mental health (98, 144), and self-harm (97, 145) (Figure 2D). Global projections of mental health impacts and their valuation are important areas for future work.

Warming-induced reductions in sleep (146, 147) and exercise (148, 149) are a potential cause of some mental health impacts and directly impact well-being, making these impacts important in their own right. Data from health-tracking devices enable detailed analysis of these outcomes. Individual adverse outcome "events", such as one day with poor sleep or exercise, have limited cost, but the cumulative impact of extended exposure to high temperatures for large populations may have economically significant impact. A nonlinear effect of temperature is projected to redistribute how much populations exercise in different regions and seasons (148, 149). Warming has a more uniform adverse impact on sleep, with a projected impact of inducing poor sleep for roughly two additional weeks per year by 2100 (Figure 4I).

Vector borne diseases are thought to be affected by climate change but are not well studied in economics

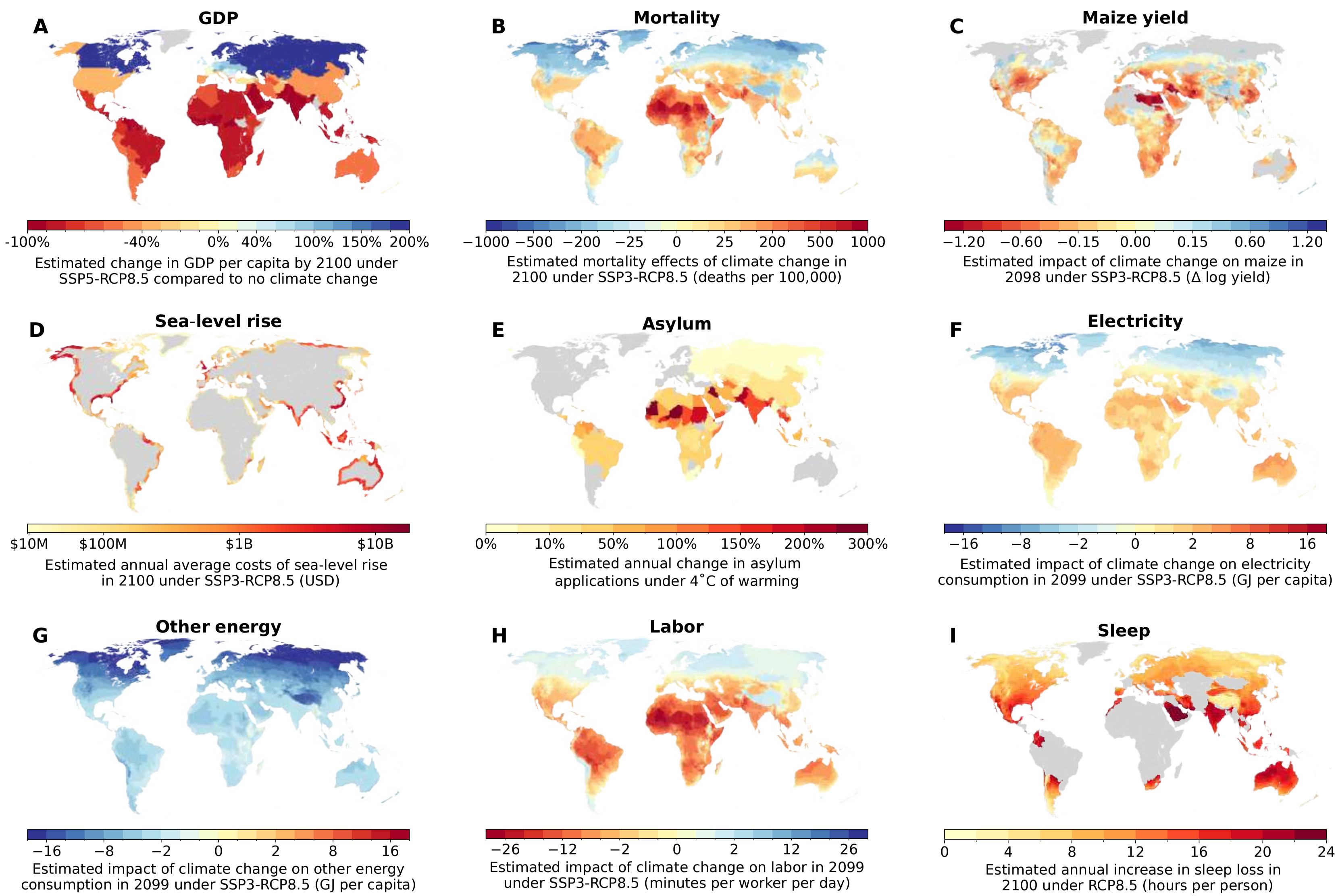

Figure 4: Global projected end-of-century impacts for (A) GDP (61), (B) mortality (57), (C) maize yields (59), (D) sea level rise (150), (E) asylum applications (99), (F) electricity consumption (58), (G) other energy consumption (e.g. heating) (58), (H) labor supply (120), and (I) sleep loss (147). Results are generally shown in a "high emissions" scenario, although model runs vary somewhat; details are in each panel. Each map is reproduced with data from the referenced analyses; figure by Luke Sherman.

using empirical methods. Projections mostly rely on structural epidemiological-ecological models (e.g. ref. (151)). It is thought that climate change will impact the ecological distribution of dengue, malaria, cholera and other vectors based on those models, but the response of populations in terms of disease avoidance, climate adaptation, or medical innovation are mostly unknown. One recent empirical analysis suggests that climate change has likely already increased aggregate malaria incidence in Sub-Saharan Africa slightly, but is likely to reduce it in the long-run due to negative impacts of high temperature on transmission (152). Another recent analysis indicates that rising temperatures have already increased the incidence of dengue by $\sim 18\%$ in 21 tropical countries and projects increases of 40-57% by mid-century (153). This is an important area for future research, which should identify the extent of spatial spillovers, link structural models with behavior, and pin down costs.

Empirically-based estimates of the SCC currently only incorporate thermal impacts on mortality. In those calculations, accounting for adaptation reduces mortality roughly 30% (57). Partial SCC estimates are \$75.4/\$32.5 (in 2024 US\$) for mortality in high/moderate emissions scenarios using a VSL of \$12.2 million and a discount rate of 1.5%. These estimates differ dramatically from prior partial SCC estimates of $<$ \$2.5 from FUND (3% discount rate) that were used by the US Federal Government but did not have an empirical basis (154). In the 2023 scientific SCC update by the US government, mortality represents $\sim 63\%$ of the total SCC (25), qualitatively consistent with prior US-only estimates where mortality was the largest projected cost (66) (note neither estimate accounted for impacts on GDP). Accounting for other health impacts will likely increase this estimate. Mortality costs are a large impact category because lives have high value, although this high value also motivates extensive adaptation which in turn lowers the SCC.

3.3 Conflict

Perhaps the most long-standing concern regarding climate change is that it could trigger violence and social instability, an idea that has accrued much cultural interest. At a high level, a major conclusion from the literature is that climatic factors amplify patterns of violence around the world, throughout history, and at nearly all scales of social organization (32, 33). A key finding is the qualitative consistency of effects from hot and dry conditions for outcomes across the full "spectrum of violence" (155), which ranges from intrapersonal violence (e.g. suicide, discussed above) to interpersonal violence (e.g. domestic violence, sexual assault, homicide) to small-scale intergroup violence (e.g gang killings, riots, ethnic violence) to large-scale organized political violence (e.g. coups, civil conflicts, interstate conflicts) and finally to full scale institutional-, population- and civilization-collapse.

In general, warming and drying tends to exacerbate pre-existing patterns of violence with effects that are proportional to pre-existing rates of violence. Populations with limited baseline violence do not generally express large absolute changes (32). This result suggests that climatic factors do not themselves serve as triggers for violence, which are determined by other patterns of behavior, but instead create ambient conditions more conducive for external triggers to escalate into violent outcomes. This interpretation differs from early speculation that climate change would trigger violent conflicts over water resources, a notion with limited empirical support (156). Instead, we generally see violence in response to thermal conditions, with weaker effects associated with precipitation. Water conflicts have proven difficult to identify and are not a dominant signal in the data.

The dose-response function for most forms of violence is log-linear in temperature, increasing $\sim 11.3\%$ per standard deviation (s.d.) in temperature for intergroup conflict and 2.4% for interpersonal violence (32) (Figure 2E). Effects are roughly 3.5% and 0.4%, respectively, for precipitation. This linearity contrasts with the (inverted) U-shaped relationships for many other thermal impacts. One interpretation of this difference is that the underlying mechanism differs from other impacts, but is similar across forms of violence. The log-linear conflict response results in a somewhat more equitable pattern of impacts from warming, since hot locations and cold locations are affected similarly in percentage terms. However, the overall level of additional harm will reflect pre-existing patterns of conflict, with baseline conflict risk that is generally higher for poorer populations.

Understanding the mechanisms through which climate influences intergroup conflict, in particular, is an important project. Economics, state capacity, psychology, and logistics have all been proposed in the literature as potential mechanisms (32). On economics: changing food prices can trigger conflict (157) and lower national income elevates conflict risk (158) but cash transfers only sometimes reduce climate-related violence (105, 106, 155) and household wealth is not correlated with conflict risk in cross-section (159). On political capacity: governments function less smoothly under extreme climate conditions (160), electorates punish leaders after extremes (148), and lower national revenues (a proxy for state capacity) are associated with higher risks (159). On psychology: growing evidence indicates that psychological channels might play a role triggering or escalating conflicts, including in sports (161), within drug-trafficking organizations (155), among insurgents in occupied Iraq and Afghanistan (162), and in laboratory experiments (163). Little evidence supports the logistics hypothesis, i.e. that climate alters conflict risk by altering the physical constraints governing violent engagement, although it may nonetheless play a role. Together, these findings suggest that multiple channels likely matter in most contexts and policy interventions might be able to mitigate some climate-related conflict, such as through employment programs (105), policies that reduce food price volatility (e.g. grain storage, trade liberalization), or gun control regulations (164).

There is some evidence that coherent changes in the global climate, caused by ENSO, generate an overall impact on conflict that differs from local idiosyncratic weather events (165). This could be due to the aggregate impact of global conditions affecting local markets more than idiosyncratic shocks (63, 166, 167).

Empirical evidence can put the risks of climate-related conflict into perspective. For example, warming in RCP 4.5 is +1°C over 30 years, a trend of 0.033°C / yr. Based on the estimated effect +11.3% intergroup conflict per s.d. in temperature (32) (s.d. = 0.4°C for an average country), this implies (0.033°C / yr) $\times$ (28.25% / 1C) = +0.93% increase in risk / yr. This represents a gradual but meaningful escalation of risk over time, which may be quantitatively large after several decades for locations with substantial baseline levels of risk. The effect is smaller for interpersonal violence (+0.2% / yr).

Similar calculations can be used to understand the potential role of anthropogenic climate change on modern conflicts. For example, anthropogenic enhancement of a drought in Syria was likely to contribute to onset of the recent civil war by 1.1-7.3% (see Appendix D). Climate change did not cause the entire Syrian conflict—but the cost of this fractional enhancement was substantial, given the extraordinary human toll of the resulting violence. This type of risk is expected to grow steadily with future warming.

The first empirically-derived projection of future conflict risk is presented in Ferguson et al. (158), who estimate linkages between temperature, conflict, and GDP growth in Africa and apply them in a coupled conflict-GDP projection. They estimate that conflict risk increases 5.1 percentage points during 2023-2100 due to warming (RCP 7.0). Four-fifths of this effect is driven by interactions with climate-driven changes in GDP.

While the substantial costs to violence and conflict are intuitively clear, full quantification of their welfare impact are challenging to construct (168). Current SCC estimates do not account for the social cost of climate-caused violence, although they should. This will require further developing projections of conflict probabilities and valuing the resulting excess risk.

3.4 Food security

The effect of climate change on agriculture is probably the most heavily studied impact. In early assessments, agricultural impacts were usually estimated to be the largest of any category (5); and an important early contribution of economists was to challenge the so-called "dumb farmer" approach to modeling these impacts, i.e. the assumption that farmers would not adapt to warming, as well as emphasizing that warming would generate some benefits for agriculture in cold regions. All of these points remain considerations for modeling agricultural impacts, but recent empirical findings have tempered our understanding of their importance.

The most important empirical finding, regarding agricultural impacts, was the discovery by Schlenker and Roberts (2009) (51) of a sharp non-linearity in the dose-response relationship between daily temperature and crop yields: end-of-season yields fall sharply for each additional day above a certain temperature cutoff (roughly 29°C). This finding holds for nearly all major staple crops (Figure 2G) (59) and advanced the broader literature methodologically. This "kinked" nonlinear daily dose-response function is consistent (15) with the well-documented smooth, inverted-U dose-response function in response to annual average temperature (118, 169). A concave relationship with seasonal rainfall also holds for most crops, with high and low rain harming yields (59). Recent work indicates that livestock and fisheries production also follow inverted U-shaped patterns with seasonal temperature (170, 171).

Empirical studies have found that temperature is the dominant variable of concern for global agricultural impacts, rather than changing rainfall or other measures of water availability (59, 118, 172–174). Previously, attention had focused on drying as the central challenge of climate change, perhaps because the partial effect of temperature is more difficult for farmers to intuit through observation. In addition, projected changes in precipitation remain highly uncertain and heterogeneous (13), dampening projected impacts. Nonetheless, researchers continue to evaluate different measures of climatic conditions, often combining aspects of temperature and precipitation (e.g. vapor pressure deficit (175), drought indicies (176), soil moisture availability (174), the distribution of rainy days (177), etc). Empirical models generally account for some of these moisture-related variables, but the bulk of global agricultural impacts are nonetheless explained by thermal conditions (59). The effect of CO_2-fertilization is not not well-constrained empirically (178).

It is notable that new methods in empirical climate impact modeling are often first demonstrated using agricultural data (54, 95, 179). Attribution of historical climate impacts was one of these innovations, with early evaluations using simple yield models to compute that historical output was reduced by 3.8 and 5.5% (relative to a counterfactual) for maize and wheat during 1980-2008 due to warming (169). More recent work indicates agricultural TFP was reduced 21% during 1960-2015 (180).

Globally, after accounting for measurable patterns of adaptation, the projected impact of climate change on yields are highly heterogeneous due to the nonlinear relationships between crop yields and multiple climate variables (59), with some regions benefiting and others declining (e.g. Figure 4C). These patterns are further complicated by the differing responses of crops. Nonetheless, three generalizable points deserve emphasis. First, the many of the largest impacts tend to be substantial net losses in regions that are currently considered global "breadbaskets". This occurs because of the high concentration of current production in these regions and their near-optimal temperatures today, which causes additional warming to induce sharp yield declines due to the nonlinear dose-response (Figure 2G). Second, because projected yield gains generally occur in regions with currently sub-optimal conditions and low production, aggregated projections tend to be dominated by losses in high-production regions rather than these gains. Global projections indicate a net production loss of 5.4×10^{14}kcal annually per 1°C (59) (equal to 120kcal/person/day, per 1°C; Figure 5C). Third, many locations, particularly low income regions, are projected to experience large and acute losses in agricultural productivity. Importantly, these losses may have large welfare impacts on the affected communities with enduring consequences that are not well-represented by global aggregate damage measures.

Market-based valuations of global agricultural impact, while important, are sometimes misleading in terms of global welfare impacts. For example, a recent estimate suggest that the partial SCC for global staple crop production is roughly \$6 (59) per ton of CO_2. This value is modest largely because global prices for food staples are relatively low. As a result, impacts on global food supply are calculated to have limited impact on wealthy populations because a small fraction of their income is spent on food and staples are highly substitutable in global markets (166). However, because demand for calories is relatively inelastic, reductions in local supply can have dramatic welfare impacts for populations that are isolated from global markets or who cannot increase expenditures to reflect price changes (64, 166). In these contexts, reductions in yields can directly translate into greater hunger and malnutrition; for example, weight-for-height z-scores among children in DHS surveys worldwide declines with temperature in a pattern that reflects crop yields, particularly in rural communities(100) (Figure 2H). Such food insecurity is estimated to currently be growing, due to a confluence of factors that include slowed growth of yields – some of which is due to warming (180) – as well as conflicts that restrict production and trade in food (181).

Mitigating the most extreme welfare impacts of climate change on the global food supply will come down to whether commodities can be efficiently reallocated to regions that suffer acute shortages (64, 81). One challenge to achieving this is that many impacts will be correlated across large regions, so populations with food production shortfalls may need to trade with increasingly distant partners (63). Political actors also tend to restrict food exports when experiencing domestic production shocks, increasing global prices and limiting supply for trading partners (182). Thus, while the mechanics of large-scale trade in food is technologically "solved", with massive ships moving an unprecedented quantity of calories, climate-driven production losses will continue to generate global-scale harms in the absence of further policy innovation. For example, modern El Niño events still cause stunting of low-income children worldwide (142). For these reasons, understanding how global trade in food can expand and maintain openness in a changing climate is a crucial topic for future study.

Future empirical work should also identify how continuous innovation on crop resilience can be sustained (183) and quantify the scale of crop-switching, irrigation and agricultural expansion that can be realistically expected (103, 184, 185).

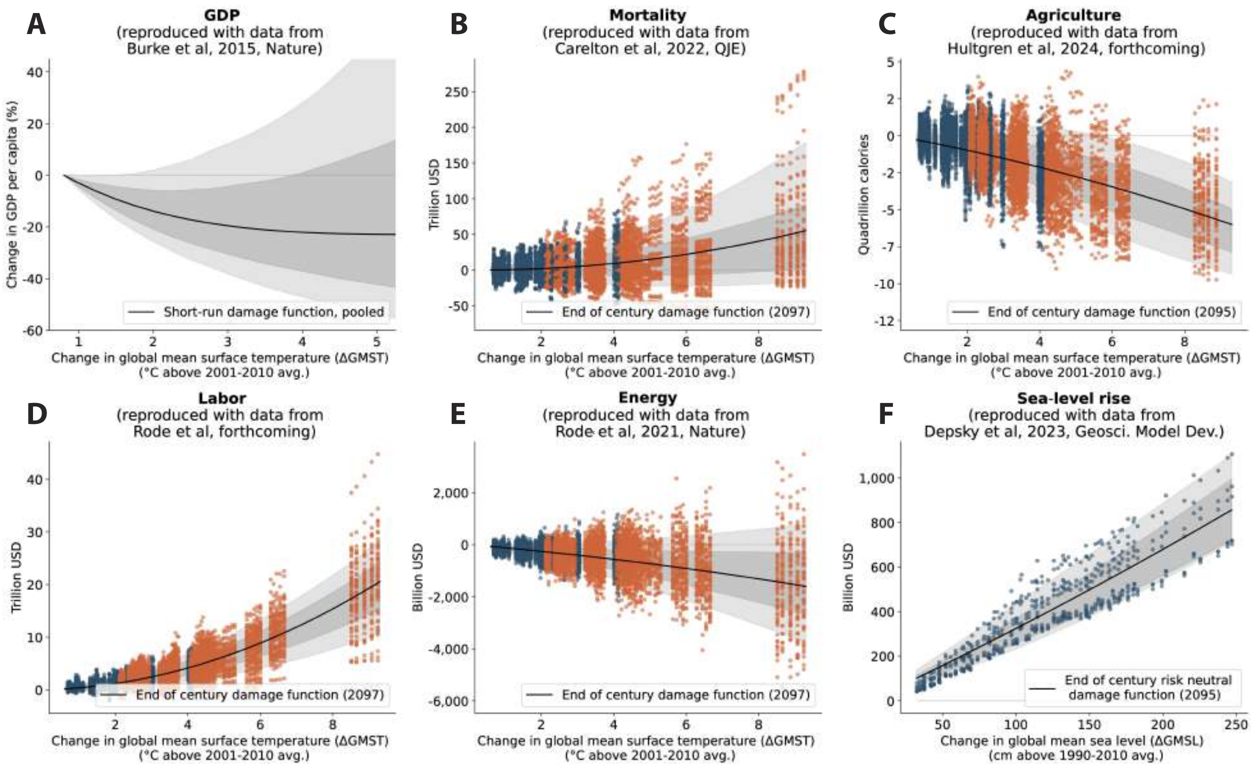

Figure 5: Estimated global "damage functions" describing the joint distribution of global aggregate impacts and change in global mean surface temperature ($\Delta GMST$); reproduced from empirical analyses. Black lines are median estimates, shaded grey bands are 10-90th and 25-75th quantile ranges. Markers indicate individual simulation runs in a moderate (blue) and high (orange) emissions scenario. Damage functions for GDP (61), mortality (57), agriculture (59), labor supply (120), energy consumption (58), and sea level rise (150). Reproductions from referenced analyses; figure by Luke Sherman.

3.5 Disasters

The distribution of floods, droughts, heat waves, wildfires, and tropical cyclones are expected to be altered by climate change. Recent empirical research has identified many impacts of these disasters, and in some cases projected future outcomes.

It is notable, however, that while the increasing frequency, intensity, and costs of disasters are often described in public discourse as the clearest economic consequence of climate change, the opposite is nearer to the truth. The historical and future impacts of climate change via different disasters classes remains largely unknown for three reasons. First, trends in disaster events and total costs are highly confounded by trends in both reporting rates and the number of individuals (or assets) exposed to disaster risk. For example, historical disaster datasets are generally compilations of *ad hoc* records (e.g. newspaper articles) with reporting gaps that change over time (e.g. (186)) and many trends in disaster costs are explained by population and/or economic growth (e.g. (101)). Second, it is more technically challenging to analyze the effect of disaster hazards (e.g. wildfires, inland floods, storm surge) compared to ambient climate (e.g. temperature, precipitation) since they require modeling of complex physical phenomena. Third, it is not always possible to quantify the historical or projected impact of climate change on disasters with precision (13), primarily because disasters are rare events. As a result, the link between climate change and economic risk from disasters at any specific location remains highly uncertain for most hazards.

Where progress has been made, disaster impacts are decomposed into *direct damages*, which occur during the geophysical events (e.g. homes burning in a wildfire), and *indirect damages*, which emerge later as a result of the disaster (e.g. health impacts of wildfire smoke). Empirical analyses have characterized the dose-response for direct damages from some hazards, such as flood depth-damage curves (187) or wind-damage from cyclones (52) (e.g. Figure 2I), as well as indirect damages, such as unearned income (62, 114, 138, 188) or excess mortality in the wake of disasters (101, 133) (e.g. Figure 2J). A general finding is that indirect damages tend to substantially outweigh direct damages (101, 133, 138, 188), sometimes by a factor ≥ 10, and can accrue over many years. Because the discovery of large indirect losses is recent, it is unknown if and how they can be mitigated. This is an important emerging area for research.

Another open question is how risk management systems will respond to climate change. Private insurance markets, public risk-sharing mechanisms (e.g. government disaster assistance), and international risk-sharing (e.g. relief aid) currently support many populations – but coverage is incomplete globally and can be *ad hoc* if relief depends on political actions (189, 190). As the climate changes, some private insurance markets show signs of strain as insurers increase premiums or do not renew policies to limit their exposure to unknown or difficult-to-manage risks (43, 191). There is also growing concern that public risk management systems may not be fiscally sustainable, as demand for services increases while revenues decline and borrowing costs rise (188, 192, 193). Little is known about how international relief aid is changing in response to climate change.

"Risk reduction" is adaptation that reduces disaster vulnerability. Many investments in risk reduction are thought to cost societies less than the protective benefits they generate (188, 194, 195), but nonetheless appear underutilized worldwide. Several theories could explain this low uptake: cost-benefit calculations do not capture the full costs of these investments (e.g. (150)), moral hazard unwinds the benefits from investments (e.g. (196)), the political-economy of decision-making prevents efficient investments (e.g. (197)), or future benefits from investments are heavily discounted (e.g. (52)). Understanding what policies, financial innovations or market structures could support efficient risk reduction globally is a pressing area for future work.

3.6 Migration

High-level assessments of climate change risks almost universally identify human migrations as a major concern, but constraining the scale and scope of potential impacts has remained frustratingly difficult. The net impact of climate change on migration is not predicted by theory. Deteriorating local conditions could encourage individuals to leave or could cause them to become trapped in a context where resources are insufficient to migrate away (198, 199). Empirically determining which influence dominates remains challenging primarily because large, high-quality, standardized data on migration are scarce. In addition, migration is often heavily regulated, making it difficult to detect historical signals and difficult to project, since future regulations are unknown. Overall, findings in the literature span a large range of outcomes, do not tend to generalize, and seem less robust than for the topics above; perhaps due to data quality, heterogeneous responses across differing populations, or the need for alternative modeling approaches.

Country-level studies of domestic migrants dominate the literature, since these limited contexts may have better data. Perhaps the most consistent finding is that long-lasting climatic changes that predict economic declines, such as multiple hot years in a row, are generally associated with adults emigrating (200–202). These migrants are likely pursuing economic opportunities, although other factors, such as amenities, might play a role (201).

Limited global-scale international migration studies also suggest some patterns that diverge based on the income of source countries. Cattaneo and Peri (198) study bilateral migration between 115 countries and find that higher temperatures increase emigration from middle-income countries but decrease emigration from poor countries. Benveniste et al. (199) study 32 demographic groups for subnational units across 168 country censuses and find that responses to climate stressors depend on age and education, with different groups responding in opposite ways. These findings suggest that at low incomes, deteriorating economic conditions reduce the likelihood of departure, effectively trapping populations, but in middle income contexts, populations may have the resources to invest in migrations that will create new economic opportunities.

Many questions remain. Migration depends on long-term beliefs about future conditions (203), which are difficult to measure empirically. Most analyses do not study where departing individuals go, and it is unclear if climate change will meaningfully alter the distribution of destinations since only a few large-sample analyses study moves between two economic environments observed simultaneously (99, 200, 202, 204). It is also unknown if out-migration will affect the probability that remaining individuals depart. The response of local wages and housing prices could discourage additional departures (205–207) but an expanded social networks of migrants can help facilitate out-migration (206, 208). More work is needed to understand the consequences of extended periods of out-migration and the magnitude of total displacement that can be reasonably projected.

A unique analysis by Schlenker and Missirian (2017) (99) studies international asylum seekers requesting amnesty, a particularly vulnerable population. They find that asylum applications respond nonlinearly to temperature (Figure 2F). The authors project that if current patterns persist, asylum applications would increase roughly 190% in 2100 for a high emissions scenario (Figure 4E) but only 30% in a moderate emissions scenario due to the nonlinear dose-response.

Few other empirical studies project migration due to climate change, and nearly none attempt to value the full cost of these moves (150). Is moving costly or beneficial to the mover overall? For example, Deryugina et al (2018) (208) find that many victims of Hurricane Katrina experienced long-run benefits from moving away. At present, migration is essentially never accounted for in SCC estimates.

Lastly, a nascent literature on "managed retreat" studies policies that incentivize migration away from climate hazards (209). These policies might be cost-effective if individuals living in risky locations are a net financial burden to society (210). Managed retreat policies could also prevent individuals from becoming trapped in a location with limited and/or depreciating assets that they cannot liquidate (206). Given the challenges that lie ahead, understanding how to design managed retreat policies is an important area for future investigation.

4 Advances on other major issues

The literature is growing quickly, bringing new insights and raising numerous new questions. Here, I highlight a limited set of recent notable findings – however, I still must omit many important contributions since it is not possible to detail each new major research area here.

4.1 Behavior & Decision-making

A growing literature indicates that climatic conditions directly influence some types of decision-making. For example, in an experimental setting, Almås et al. (2019) (163) find that subjects exposed to hotter conditions exhibited a greater desire to see opponents suffer hardship. This finding aligns with multiple other findings that individuals are more likely to be punitive towards others in hot thermal conditions, such as decisions by judges (211) or professional athletes retaliating violently against opposing teams (161), and findings described in the Conflict section above. These results seem intuitively consistent with higher temperatures inducing more a negative emotional state, indicated, for example, by higher rates of swearing on Twitter (91). Thermal conditions have been hypothesized to alter decision making by altering the physical conditions of neural processes (e.g., (212)), but this lacks definitive evidence. Other patterns of behavior respond to climatological conditions, such as exercise routines (148) and car accidents (213), although these could be due to other factors rather than decision-making.

4.2 Cities

Urban populations, projected to represent 68% of the global population in 2050 (214), face particular challenges from climate change. Some evidence indicates that adverse climate conditions in rural regions generate migration into cities (200, 215), accelerating their growth and potentially straining public systems. Rural climate shocks also elevate urban food prices and increase the risk of urban unrest (157). Urban environments experience a "heat island" effect, compounding the thermal stress experienced by low-income urban populations (216), and they face unique challenges when managing elevated rainfall, since widespread impermeable surfaces can cause damaging urban flooding (83, 139, 140). Due to their dense populations and high concentrations of capital, planners and managers will likely face heightened political pressure to protect urban environments from difficult-to-manage climate pressures, such as SLR (197), hurricanes (52), and water shortages (217). Errors in climate risk management for urban communities will likely generate acute social costs, since impacted populations are large, concentrated, and may contain vulnerable low-income communities. Future work should focus on understanding how improved planning can mitigate these risks and how policies can guide resilient development, particularly in rapidly urbanizing contexts.

4.3 Energy

Climate change will substantially impact the structure of global energy demand. As hypothesized by early assessments (5, 90), warming will reduce global heating demand but increase global demand for cooling (58). Some early models predicted that rising energy demand, particularly in Africa and Asia, represented the largest economic cost of climate change (2, 22); however, empirical analyses now demonstrate that many populations have insufficient resources to consume significant cooling, curbing potential demand. Nonetheless, in well-resourced contexts, average cooling demands will rise modestly with warming (56, 58) (Figure 4F), placing significant new burdens on energy systems during heat waves when cooling demand is synchronized (218). On net, the partial SCC for energy consumption is estimated to be −\$4 per ton of CO_2 (58), since savings from reduced heating (which is widespread, Figure 4G) slightly outweigh costs of new cooling (which is focused in richer contexts; Figure 5E). The magnitudes of these effects indicate that the widely speculated air conditioning-driven feedback loop (i.e. warming → energy demand → emissions → more warming) is probably irrelevant (58, 219).

4.4 Human Capital & Productivity

It has been hypothesized that climate affects the productivity of workers at least since Baron de Montesquieu's 1748 "Spirit of the Laws" (220) and Ellsworth Huntington's 1915 "Civilization and Climate" (221). Research has now tested these ideas with data using modern methods, finding that both mental and physical performance are indeed influenced by climatic conditions, particularly temperature and humidity (45, 119, 222). Many measures of performance decline when thermal conditions exceed a threshold, although this threshold can be altered through adaptation or "acclimation", i.e. the human body adjusting to cope with prolonged exposure to high temperatures. (However, physiologists have established a core body temperature of 40°C as a limit to adaptability; productivity collapses for nearly all individuals from triggering a "safety switch" in the brain (212).) In general, high-skilled workers seem less sensitive to thermal conditions than low-skilled workers (223, 224). Cognitive performance is also affected by thermal conditions (222, 225, 226), perhaps related to effects on judgment-based decision-making discussed above. Probably one of the most consequential recent findings is that learning (227) and other mechanisms for human capital formation (228, 229) are reduced by high temperature exposure. This result suggests a potential pathway for climate change to reshape patterns of economic growth (107). Current global assessments focus on changes in global labor supply due to thermal stress (120), which mirrors spatial patterns of growth (Figure 4H) and is projected to cost roughly \$1.3 trillion per 1°C in global average temperature (Figure 5D).

4.5 Insurance

Globally, insurance coverage for climate-related risks is low and expanding insurance usage is likely crucial for reducing many harms from climate change (27); at the same time, some firms are exiting markets in part due to difficulties associated with climate change. This juxtaposition underscores the importance of understanding climate impacts on insurance markets. Insurance systems were historically designed to be financially sustainable in a stationary climate, so the uncertainty and shifting distribution of risks driven by climate change pose fundamental challenges. Some public and private insurers have responded to changing risks by modifying premiums or shedding policies, passing costs back to consumers (43, 191, 230), which can in turn trigger political backlash. Yet, politicization and heavy regulation can limit the growth and efficiency of insurance markets, when expansion would be broadly beneficial to public finances by reducing reliance on social safety-nets systems (21, 193). Additionally, subsidies are effective at expanding access, especially in poor contexts, but subsidized insurance undermines incentives to adapt (231–233), increasing society's overall exposure to climate risks. Future work should aim to understand how to achieve market expansion (for consumers) and flexibility due to changing risks (for suppliers) through politically viable and financially sustainable reforms.

4.6 Real Estate

A patchwork of new studies indicate that many of the economic impacts of climate change will be capitalized in land values (234, 235). In contexts where information is available and salient, changing perceptions of disaster risk alters real estate values (21, 236). A resulting concern is the possibility that populations become "stuck" in risky locations, because homes with new risks may become difficult to sell (209, 210). Theory predicts that long-term demand changes driven by migration will restructure home prices (84), but there is limited empirical evidence to constrain these projections. Real estate impacts interact with various public policies and investments, such as zoning and defensive infrastructure (233), which can create incentives for politicization of these investments (197) but also motivate careful policy analysis and design. Additionally, because real estate assets are held by individuals with the highest willingness-to-pay, observed prices may reflect the beliefs held by the individuals who are most optimistic about climate risks (77). There is growing concern that mis-pricing or concentration of climate risks in real estate may translate into other systemic risks. Understanding the potential scope of this risk and potential policy remedies is an important area for future empirical investigation.

4.7 Sea Level Rise

Rising seas are an iconic symbol of climate change, but their global economic impact is less clear. Empirical analysis of sea level rise (SLR) is difficult because projected changes do not have modern physical analogs that can be observed. Over the next century, SLR is likely to generate acute impacts for a relatively small number of individuals who live or work within a vertical meter of local high-tide levels (197, 234) (Figure 4D). In many contexts, intermittent flooding of coastal infrastructure may represent the most economically important disruption (83, 237). The slowness and predictability of SLR means defensive investments (e.g. sea walls) and migration are likely effective but costly adaptations. Defensive investments are projected to be used most heavily in Asia, where coastal population densities are high, enabling investments to accrue large benefits that offset the high costs of new infrastructure (150). Estimates for the global partial SCC from SLR are roughly \$3 per ton of CO_2, reflecting a cost of \$3.34 billion per 1 cm of global mean SLR (Figure 5F). This cost is modest because of the limited number of individuals directly affected by SLR.

4.8 Trade

Trade will play an important role in coping with climate change impacts worldwide (81). Particularly for food commodities, market integration can limit the most extreme impacts of climate change (59, 64), e.g. avoiding famines. However, some of the benefits of trade—particularly its ability to limit extreme instances of hunger for poor populations—may be reduced when adverse impacts are widespread, as is expected with changing climate, since the productivity and tradable surplus of otherwise willing trading partners can be impacted simultaneously (63, 182). Historically, some climate disasters disrupted supply chains for manufactured goods and there is evidence that firms can restructure supply chains in response to reduce exposure to climate risks (238). In general, nearly all findings indicate that reducing frictions to trade are important *adaptations* to climate change; however, some current policy trends are to exploit trade barriers to support emissions *mitigation*. Future research may help balance these two countervailing objectives.

5 Some important open questions

Many open questions remain for empirical researchers investigating the impact of climate change. I briefly note a few topic areas where I hope progress can build on our prior understanding. These topics range from narrow-but-important technical issues to expansive open topic areas.

Demographics Population structure and growth is one of the factors driving climate change, however it is less well understood how climate change will affect demographics. Recent evidence indicates that climate can shape birth rates (239) and mortality rates (57, 101), but we lack clarity on how these effects combine to alter population growth and reshape age distributions of the future. Projections of climate change usually assume a demographic scenario (13), but future work should empirically constrain these assumptions and endogenize demographics.

Depreciation Climate is thought to affect the rate at which capital physically depreciates (113), although it is difficult to empirically measure these changes. Given the vast quantity of capital that will be exposed to climate change, we should understand how it will alter depreciation rates.

Divergence Some projections of climate change impacts indicate economic divergence within and/or between countries (61). This result appears at odds with classical models of convergence and has thus generated much debate (71, 109, 122). Understanding the extent, scale, and limits of divergence that has occurred historically, both in association with climatic events and otherwise, should inform and constrain these future projections.

Ecosystems A vast literature in ecology documents that climate change will transform ecosystems worldwide. However, only a few impacts that will likely affect economic outcomes, such as the effect of pests on crops, have been measured empirically. We lack an empirical basis to understand how numerous known ecosystem responses that will influence human outcomes. It is unknown how important this gap in our knowledge is and it represents one of the most urgent areas for investigation.

ENSO as an analog for climate change The El Niño-Southern Oscillation (ENSO) is a major driver of the current global climate (115) and many aspects of the global economy (63, 115, 116, 142, 165, 167, 240, 241). ENSO represents a unique opportunity to study the economic response to auto-correlated and globally coherent climate events, making it a potentially useful analog for answering important questions about the effects of climate change. However, many aspects of ENSO differ in key ways from climate change. It remains unknown how applicable and generalizable effects of ENSO are to climate change projections.

Freshwater resources Recent research has highlighted some important roles of water in economic activities and identified how the functioning of water markets might be improved (242), and it is understood that climate change will alter the distribution and availability of fresh water resources, including precipitation, surface water, and ground water. However, due to data and methodological challenges, our general understanding of the economic impact of these changes lags behind our understanding of other dimensions of climate, such as temperature.

Geoengineering Whether humans should deliberately alter the climate in order to counteract specific aspects of climate change is a profoundly controversial question. Most justifications for geoengineering focus on simple economic arguments about the costs and benefits relative to emissions management strategies. If it is indeed true that geoengineering can eliminate many of the societal impacts described in this article, it surely deserves careful and balanced economic evaluation. However, the degree of scrutiny for such consequential policy proposals should be far greater than, not less than, that of normal economic policies. Given the stakes involved, policy options should be evaluated empirically where possible (e.g. ref. (243)), rather than relying only on simulations and theoretical reasoning (244).

Innovation The unknown path of future technology is one of the weakest elements of any climate change projection. It is hypothesized that climate change will redirect much innovation, but the extent, scale, speed, and likely impact of this response is not well-constrained empirically (109).

Interacting impacts It has been hypothesized that multiple climate shocks that occur in close proximity (either in space and/or time) may result in economic impacts that meaningfully exceeds the sum of their individual impacts. This could be important, for example, if risk management systems draw on common resources, such as a centralized disaster fund. Some lines of evidence suggest these "compound events" may have magnified impacts (63, 114, 117, 158), but these interacting effects have proven difficult to isolate, characterize and constrain empirically. Evidence for how such events can be managed effectively would also be valuable.

Micro-macro reconciliation Analyses of climate impacts using micro and macro data are rarely linked. In general, it is unclear whether empirical findings across scales are consistent, and seemingly inconsistent findings should be explicitly reconciled.

National accounts Over the last decade, there has been meaningful progress in international standards that guide how natural capital is represented in the System of National Accounts (245). Current standards detail how quantities of GHG emissions are tracked, but no guidelines exist to assign prices to these flows. There is also little empirical foundation to describe how climate change will impact the quantity and value of other national capital stocks.

Spatial and temporal auto-correlation Projected changes in the climate are spatially and temporally autocorrelated, and evidence suggests that auto-correlated changes may have greater economic impacts. A fixed count of weather events (e.g. hot days) arranged in different sequences or spatial arrangements can have different economic impacts (63, 114). Because climate change will alter the spatial and temporal auto-correlation of weather, it is important to understand and account for these effects empirically.

Speed of adaptation Most successes in measuring adaptation have focused on cross-sectional patterns, but it remains difficult to empirically quantify how quickly we expect populations to adapt to climate change (67). Some challenges are understanding how populations update their beliefs about the climate, when beliefs translate into actions, and how long it takes for actions to alter vulnerability.

6 Discussion

The view from above Empirical research points toward an increasingly coherent picture of a global economy and society impacted by climate change. In general, aggregate costs of some scenarios may grow large primarily because the global population is persistently exposed to diffuse but chronic losses. Temperature is the most important environmental variable worldwide, both because it has substantial effects and every individual is exposed to it every day. Precipitation, tropical cyclones, wildfires, floods, and SLR have major – often acute – impacts but in more restricted populations. Most outcomes have a nonlinear response to temperature with a minimum or maximum near temperatures traditionally comfortable for people, suggesting linkages to physical processes. A notable exception is the collection of findings with linear responses that depend on human judgement, the use of violence, mental health, and sleep. Populations appear to adapt to climate in many contexts where effects are salient and costs of adaptation are modest, but adaptation is less prevalent than many early predictions. Nonlinear effects can generate inequalities in impacts, which are a dominant feature of many global projections. In numerous contexts, there is evidence that adverse climate events have persistent effects, which is particularly important for GDP where growth effects compound. Trade, insurance, and financial systems help alleviate many impacts that are well-represented in markets, but many non-market impacts – including welfare, unmanaged risk, health, and violence – can exhibit large adverse impacts even in the presence of functioning markets. In hot and low-income regions, several major impact categories (income, health, conflict, food security, and migration) are projected to change in a direction that undermines social stability, raising concerns that these simultaneous changes might destabilize populations and/or institutions.

The importance of empirical analysis A lesson from the trajectory of the literature is that many hypotheses about the response of society to climate changes were incorrect. Of course, falsifying hypotheses is central to all scientific pursuits, but the extent to which data and modern empirics have overturned previous writing in this context is notable. It was previously thought that non-agricultural economic impacts, health, happiness, and conflict impacts were small, that energy, migration, and SLR were dominant, that adaptation would be low-cost and extensive, and that trade and insurance would ameliorate most impacts. Notable policy applications in the US even assumed impacts on agriculture, energy, health, and happiness that were the wrong sign. Impacts on human judgment and human capital, major effects on GDP, and long-term effects of disaster were largely unarticulated. Overall, it appears that understanding the impact of global environmental change on the global population is too difficult for us to intuit, rather it requires data and the discipline of empirical analysis as a compliment to rigorous theory.

Policy The quantification of climate change impacts is central to consequential climate policies. Policy design inevitably involves trade-offs and resource reallocations due to climate policy could become large. For a sense of scale, if the SCC adopted by the US EPA in 2023 ($231 per ton) were applied as a carbon tax to current global emissions (37 billion tons annually), the total cost/revenue would amount to 8% of global GDP. Current policies fall short of this, but many nonetheless represent extraordinarily large investments. If these resources are redirected from other applications, it is essential—both for economic efficiency and as a moral imperative—that the best available scientific evidence justifies the quantities involved. Data and empirical analysis are required to achieve this.

Policy-makers have noted the recent growth of empirical literature covered in this article and an expanding number of local, state, national, and international governments, as well as NGOs, are adopting climate-related policies that are either explicitly motivated by empirical findings or use them directly. This progress is heartening, but unanswered questions asked by all levels of decision-making continue to mature and deepen. Hopefully, the now-flourishing community of researchers can rise to the call and meet this growing need. Navigating our collective future requires guidance that cannot be obtained any other way.

References

1. W. D. Nordhaus, Optimal greenhouse-gas reductions and tax policy in the" DICE" model. The American Economic Review **83**, 313–317 (1993).
2. R. S. Tol, On the optimal control of carbon dioxide emissions: an application of FUND. Environmental Modeling & Assessment **2**, 151–163 (1997).
3. C. Hope, J. Anderson, P. Wenman, Policy analysis of the greenhouse effect: an application of the PAGE model. Energy Policy **21**, 327–338 (1993).
4. J. Weyant et al., Integrated assessment of climate change: an overview and comparison of approaches and results. Climate change **3** (1995).
5. W. D. Nordhaus, J. Boyer, Warming the world: economic models of global warming (MIT press, 2003).
6. N. Stern, Stern Review: The economics of climate change. (2006).
7. W. Nordhaus, Climate change: The ultimate challenge for economics. American Economic Review **109**, 1991–2014 (2019).
8. K. Gillingham, J. H. Stock, The cost of reducing greenhouse gas emissions. Journal of Economic Perspectives **32**, 53–72 (2018).
9. K. C. Meng, Using a free permit rule to forecast the marginal abatement cost of proposed climate policy. American Economic Review **107**, 748–784 (2017).
10. R. S. J. Tol, The economic effects of climate change. Journal of economic perspectives **23**, 29–51 (2009).

11. S. Dietz, in Handbook of the Economics of Climate Change, ed. by L. Barrage, S. Hsiang (Elsevier, 2024), vol. 1.
12. M. Greenstone, presented at the AEA Papers and Proceedings, vol. 114, pp. 1–30.
13. S. Hsiang, R. E. Kopp, An economist's guide to climate change science. Journal of Economic Perspectives **32**, 3–32 (2018).
14. M. Auffhammer, S. M. Hsiang, W. Schlenker, A. Sobel, Using weather data and climate model output in economic analyses of climate change. Review of Environmental Economics and Policy (2013).
15. S. Hsiang, Climate econometrics. Annual Review of Resource Economics **8**, 43–75 (2016).
16. D. Hogan, W. Schlenker, in Handbook of the Economics of Climate Change, ed. by L. Barrage, S. Hsiang (Elsevier, 2024), vol. 1.
17. M. Dell, B. F. Jones, B. A. Olken, What do we learn from the weather? The new climate-economy literature. Journal of Economic literature **52**, 740–798 (2014).
18. T. A. Carleton, S. M. Hsiang, Social and economic impacts of climate. Science **353**, aad9837 (2016).
19. M. Auffhammer, Quantifying economic damages from climate change. Journal of Economic Perspectives **32**, 33–52 (2018).
20. H. O. Pörtner et al., Eds., Climate Change 2022: Impacts, Adaptation and Vulnerability (Cambridge University Press, Cambridge, UK and New York, USA, 2022), ISBN: 9781009325844.
21. S. Hsiang et al., "Fifth National Climate Assessment: Chapter 19. Economics", tech. rep. (US Global Change Research Program, 2023).
22. D. Diaz, F. Moore, Quantifying the economic risks of climate change. Nature Climate Change **7**, 774–782 (2017).
23. T. Carleton, M. Greenstone, A guide to updating the US Government's social cost of carbon. Review of Environmental Economics and Policy **16**, 196–218 (2022).
24. NASEM, Valuing climate damages: updating estimation of the social cost of carbon dioxide (National Academies Press, 2017).
25. EPA, Report on the social cost of greenhouse gases: Estimates incorporating recent scientific advances, 2022.
26. K. Desmet, E. Rossi-Hansberg, Climate change economics over time and space. Annual Review of Economics **16** (2024).
27. T. Carleton, E. Duflo, K. Jack, G. Zappala, in Handbook of the Economics of Climate Change, ed. by L. Barrage, S. Hsiang (Elsevier, 2024), vol. 1.
28. S. Fankhauser, Adaptation to climate change. Annual Review of Resource Economics **9**, 209–230 (2017).
29. S. Hsiang, P. Oliva, R. Walker, The distribution of environmental damages. Review of Environmental Economics and Policy (2019).
30. O. Deschenes, Temperature, human health, and adaptation: A review of the empirical literature. Energy Economics **46**, 606–619 (2014).
31. K. L. Ebi et al., Extreme weather and climate change: population health and health system implications. Annual review of public health **42**, 293–315 (2021).
32. M. Burke, S. M. Hsiang, E. Miguel, Climate and conflict. Annu. Rev. Econ. **7**, 577–617 (2015).
33. S. M. Hsiang, M. Burke, E. Miguel, Quantifying the influence of climate on human conflict. Science **341**, 1235367 (2013).

34. M. Auffhammer, W. Schlenker, Empirical studies on agricultural impacts and adaptation. Energy Economics **46**, 555–561 (2014).

35. T. W. Hertel, D. B. Lobell, Agricultural adaptation to climate change in rich and poor countries: Current modeling practice and potential for empirical contributions. Energy Economics **46**, 562–575 (2014).

36. A. Ortiz-Bobea, in Handbook of agricultural economics (Elsevier, 2021), vol. 5, pp. 3981–4073.

37. M. Auffhammer, E. T. Mansur, Measuring climatic impacts on energy consumption: A review of the empirical literature. Energy Economics **46**, 522–530 (2014).

38. B. A. Bastien-Olvera, F. C. Moore, Climate impacts on natural capital: consequences for the social cost of carbon. Annual Review of Resource Economics **14**, 515–532 (2022).

39. C. Cattaneo et al., Human migration in the era of climate change. Review of Environmental Economics and Policy (2019).

40. H. A. Klaiber, Migration and household adaptation to climate: a review of empirical research. Energy Economics **46**, 539–547 (2014).

41. W. W. Botzen, O. Deschenes, M. Sanders, The economic impacts of natural disasters: A review of models and empirical studies. Review of Environmental Economics and Policy (2019).

42. C. Kousky, Informing climate adaptation: A review of the economic costs of natural disasters. Energy economics **46**, 576–592 (2014).

43. C. Kousky, Understanding disaster insurance: New tools for a more resilient future (Island Press, 2022).

44. G. Heal, J. Park, Reflections—temperature stress and the direct impact of climate change: a review of an emerging literature. Review of Environmental Economics and Policy (2016).

45. R. J. Park, Slow Burn: The Hidden Costs of a Warming World (Princeton University Press, 2024).

46. H. Hong, G. A. Karolyi, J. A. Scheinkman, Climate finance. The Review of Financial Studies **33**, 1011–1023 (2020).

47. F. Zhou, T. Endendijk, W. W. Botzen, A review of the financial sector impacts of risks associated with climate change. Annual Review of Resource Economics **15**, 233–256 (2023).

48. S. Giglio, B. Kelly, J. Stroebel, Climate finance. Annual review of financial economics **13**, 15–36 (2021).

49. R. Mendelsohn, W. D. Nordhaus, D. Shaw, The impact of global warming on agriculture: a Ricardian analysis. The American Economic Review, 753–771 (1994).

50. O. Deschênes, M. Greenstone, The economic impacts of climate change: evidence from agricultural output and random fluctuations in weather. American Economic Review **97**, 354–385 (2007).

51. W. Schlenker, M. J. Roberts, Nonlinear temperature effects indicate severe damages to US crop yields under climate change. Proceedings of the National Academy of Sciences **106**, 15594–15598 (2009).

52. S. M. Hsiang, D. Narita, Adaptation to cyclone risk: Evidence from the global cross-section. Climate Change Economics **3**, 1250011 (2012).

53. A. Barreca, K. Clay, O. Deschenes, M. Greenstone, J. S. Shapiro, Adapting to climate change: The remarkable decline in the US temperature-mortality relationship over the twentieth century. Journal of Political Economy **124**, 105–159 (2016).

54. M. Burke, K. Emerick, Adaptation to climate change: Evidence from US agriculture. American Economic Journal: Economic Policy **8**, 106–140 (2016).

55. G. Heutel, N. H. Miller, D. Molitor, Adaptation and the mortality effects of temperature across US climate regions. Review of Economics and Statistics **103**, 740–753 (2021).

56. M. Auffhammer, Climate Adaptive Response Estimation: Short and long run impacts of climate change on residential electricity and natural gas consumption. Journal of Environmental Economics and Management **114**, 102669 (2022).

57. T. Carleton et al., Valuing the global mortality consequences of climate change accounting for adaptation costs and benefits. The Quarterly Journal of Economics **137**, 2037–2105 (2022).

58. A. Rode et al., Estimating a social cost of carbon for global energy consumption. Nature **598**, 308–314 (2021).

59. A. Hultgren et al., Estimating global impacts to agriculture from climate change accounting for adaptation. Nature **642**, 644–652 (2025).

60. M. Dell, B. F. Jones, B. A. Olken, Temperature shocks and economic growth: Evidence from the last half century. American Economic Journal: Macroeconomics **4**, 66–95 (2012).

61. M. Burke, S. M. Hsiang, E. Miguel, Global non-linear effect of temperature on economic production. Nature **527**, 235–239 (2015).

62. S. M. Hsiang, A. S. Jina, "The causal effect of environmental catastrophe on long-run economic growth: Evidence from 6,700 cyclones", tech. rep. (National Bureau of Economic Research, 2014).

63. J. I. Dingel, K. C. Meng, S. M. Hsiang, "Spatial correlation, trade, and inequality: Evidence from the global climate", tech. rep. (National Bureau of Economic Research, 2019).

64. I. Nath, Climate change, the food problem, and the challenge of adaptation through sectoral reallocation. Journal of Political Economy **133**, 1705–1756 (2025).

65. A. J. Challinor et al., A meta-analysis of crop yield under climate change and adaptation. Nature climate change **4**, 287–291 (2014).

66. S. Hsiang et al., Estimating economic damage from climate change in the United States. Science **356**, 1362–1369 (2017).

67. M. Burke et al., "Are We Adapting to Climate Change?", tech. rep. (National Bureau of Economic Research, 2024).

68. I. W. G. on Social Cost of Carbon, "Technical support document:-technical update of the social cost of carbon for regulatory impact analysis-under executive order 12866", tech. rep. (United States Government, 2013).

69. F. C. Moore et al., Mimi-PAGE, an open-source implementation of the PAGE09 integrated assessment model. Scientific data **5**, 1–8 (2018).

70. K. Rennert et al., Comprehensive evidence implies a higher social cost of CO2. Nature **610**, 687–692 (2022).

71. U. K. Müller, J. H. Stock, M. W. Watson, An econometric model of international growth dynamics for long-horizon forecasting. Review of Economics and Statistics **104**, 857–876 (2022).

72. K. Rennert et al., The social cost of carbon: advances in long-term probabilistic projections of population, GDP, emissions, and discount rates. Brookings Papers on Economic Activity **2021**, 223–305 (2022).

73. F. C. Moore, D. B. Diaz,
Temperature impacts on economic growth warrant stringent mitigation policy.
Nature Climate Change **5**, 127–131 (2015).

74. K. Ricke, L. Drouet, K. Caldeira, M. Tavoni, Country-level social cost of carbon.
Nature Climate Change **8**, 895–900 (2018).

75. W. D. Nordhaus, An optimal transition path for controlling greenhouse gases.
Science **258**, 1315–1319 (1992).

76. D. Acemoglu, P. Aghion, L. Bursztyn, D. Hemous, The environment and directed technical change.
American Economic Review **102**, 131–166 (2012).

77. L. Barrage,
Optimal dynamic carbon taxes in a climate–economy model with distortionary fiscal policy.
The Review of Economic Studies **87**, 1–39 (2020).

78. W. D. Nordhaus, Z. Yang,
A regional dynamic general-equilibrium model of alternative climate-change strategies.
The American Economic Review, 741–765 (1996).

79. T. Hertel, T. Rutherford, "Extending the GTAP data base for analysis of climate change. Final report September 15, 1997–September 14, 1998", tech. rep.
(Purdue Univ., West Lafayette, IN (United States), 1998).

80. T. W. Hertel, Global Trade Analysis: Modeling and Applications
(Cambridge University Press, 1997).

81. A. Costinot, D. Donaldson, C. Smith, Evolving comparative advantage and the impact of climate change in agricultural markets: Evidence from 1.7 million fields around the world.
Journal of Political Economy **124**, 205–248 (2016).

82. K. Desmet, D. K. Nagy, E. Rossi-Hansberg, The geography of development.
Journal of Political Economy **126**, 903–983 (2018).

83. C. A. Balboni, In Harm's Way? Infrastructure Investments and the Persistence of Coastal Cities.
American Economic Review (forthcoming).

84. J.-L. Cruz, E. Rossi-Hansberg, The economic geography of global warming.
Review of Economic Studies **91**, 899–939 (2024).

85. M. L. Weitzman, On modeling and interpreting the economics of catastrophic climate change.
The review of economics and statistics **91**, 1–19 (2009).

86. M. Golosov, J. Hassler, P. Krusell, A. Tsyvinski, Optimal taxes on fossil fuel in general equilibrium.
Econometrica **82**, 41–88 (2014).

87. D. Lemoine, C. Traeger, Watch your step: optimal policy in a tipping climate.
American Economic Journal: Economic Policy **6**, 137–166 (2014).

88. Y. Cai, T. S. Lontzek, The social cost of carbon with economic and climate risks.
Journal of Political Economy **127**, 2684–2734 (2019).

89. M. Barnett, W. Brock, L. P. Hansen, Pricing uncertainty induced by climate change.
The Review of Financial Studies **33**, 1024–1066 (2020).

90. T. C. Schelling, Some economics of global warming. The American Economic Review **82**, 1–14 (1992).

91. P. Baylis, Temperature and temperament: Evidence from Twitter.
Journal of Public Economics **184**, 104161 (2020).

92. W. D. Nordhaus, Geography and macroeconomics: New data and new findings.
Proceedings of the National Academy of Sciences **103**, 3510–3517 (2006).

93. T. Deryugina, S. Hsiang, "The marginal product of climate", tech. rep.
(National Bureau of Economic Research, 2017).

94. P. Mérel, E. Paroissien, M. Gammans, Sufficient statistics for climate change counterfactuals. Journal of Environmental Economics and Management **124**, 102940 (2024).

95. H. Druckenmiller, S. Hsiang, "Accounting for unobservable heterogeneity in cross section using spatial first differences", tech. rep. (National Bureau of Economic Research, 2018).

96. M. Burke, M. Zahid, N. Diffenbaugh, S. Hsiang, Quantifying climate change loss and damage consistent with a social cost of greenhouse gases. Nature (forthcoming).

97. M. Burke et al., Higher temperatures increase suicide rates in the United States and Mexico. Nature climate change **8**, 723–729 (2018).

98. N. Obradovich, R. Migliorini, M. P. Paulus, I. Rahwan, Empirical evidence of mental health risks posed by climate change. Proceedings of the National Academy of Sciences **115**, 10953–10958 (2018).

99. A. Missirian, W. Schlenker, Asylum applications respond to temperature fluctuations. Science **358**, 1610–1614 (2017).

100. R. E. Baker, J. Anttila-Hughes, Characterizing the contribution of high temperatures to child undernourishment in Sub-Saharan Africa. Scientific reports **10**, 18796 (2020).

101. R. Young, S. Hsiang, Mortality caused by tropical cyclones in the United States. Nature, 1–8 (2024).

102. R. Hornbeck, P. Keskin, The historically evolving impact of the ogallala aquifer: Agricultural adaptation to groundwater and drought. American Economic Journal: Applied Economics **6**, 190–219 (2014).

103. N. Hagerty, "Adaptation to surface water scarcity in irrigated agriculture", tech. rep. (Working Paper, 2021).

104. J. T. Mullins, C. White, Can access to health care mitigate the effects of temperature on mortality? Journal of Public Economics **191**, 104259 (2020).

105. T. Fetzer, Can workfare programs moderate conflict? Evidence from India. Journal of the European Economic Association **18**, 3337–3375 (2020).

106. T. Garg, G. C. McCord, A. Montfort, Can social protection reduce damages from higher temperatures? Journal of Environmental Economics and Management **131**, 103152 (2025).

107. S. M. Hsiang, Temperatures and cyclones strongly associated with economic production in the Caribbean and Central America. Proceedings of the National Academy of Sciences **107**, 15367–15372 (2010).

108. M. Burke, V. Tanutama, "Climatic constraints on aggregate economic output", tech. rep. (National Bureau of Economic Research, 2019).

109. I. B. Nath, V. A. Ramey, P. J. Klenow, "How much will global warming cool global growth?", tech. rep. (National Bureau of Economic Research, 2024).

110. R. Colacito, B. Hoffmann, T. Phan, Temperature and growth: A panel analysis of the United States. Journal of Money, Credit and Banking **51**, 313–368 (2019).

111. P. Zhang, O. Deschenes, K. Meng, J. Zhang, Temperature effects on productivity and factor reallocation: Evidence from a half million Chinese manufacturing plants. Journal of Environmental Economics and Management **88**, 1–17 (2018).

112. S. Acevedo et al., The effects of weather shocks on economic activity: How can low-income countries cope. World Economic Outlook (2017).

113. S. M. Hsiang, A. S. Jina, Geography, depreciation, and growth. American Economic Review **105**, 252–256 (2015).

114. S. Miller, K. Chua, J. Coggins, H. Mohtadi, Heat waves, climate change, and economic output. Journal of the European Economic Association **19**, 2658–2694 (2021).

115. S. M. Hsiang, K. C. Meng, Tropical economics. American Economic Review **105**, 257–261 (2015).

116. C. W. Callahan, J. S. Mankin, Persistent effect of El Niño on global economic growth. Science **380**, 1064–1069 (2023).

117. A. Bilal, D. R. Känzig, "The Macroeconomic Impact of Climate Change: Global vs. Local Temperature", tech. rep. (National Bureau of Economic Research, 2024).

118. W. Schlenker, D. B. Lobell, Robust negative impacts of climate change on African agriculture. Environmental Research Letters **5**, 014010 (2010).

119. E. Somanathan, R. Somanathan, A. Sudarshan, M. Tewari, The impact of temperature on productivity and labor supply: Evidence from Indian manufacturing. Journal of Political Economy **129**, 1797–1827 (2021).

120. A. Rode et al., Labor disutility in a warmer world: The impact of climate change on the global workforce. (2022).

121. C. D. Romer, D. H. Romer, The macroeconomic effects of tax changes: estimates based on a new measure of fiscal shocks. American Economic Review **100**, 763–801 (2010).

122. M. Dell, B. F. Jones, B. A. Olken, Temperature and income: reconciling new cross-sectional and panel estimates. American Economic Review **99**, 198–204 (2009).

123. U. S. O. of Management, Budget, Analytical Perspectives: Budget of the United States Government, Fiscal Year 2025 (US Government Printing Office, 2024).

124. C. Bertram et al., NGFS Climate Scenarios Database: Technical Documentation. (2020).

125. E. Nakamura, J. Steinsson, R. Barro, J. Ursúa, Crises and recoveries in an empirical model of consumption disasters. American Economic Journal: Macroeconomics **5**, 35–74 (2013).

126. V. Cerra, S. C. Saxena, Growth dynamics: the myth of economic recovery. American Economic Review **98**, 439–457 (2008).

127. O. Deschênes, M. Greenstone, Climate change, mortality, and adaptation: Evidence from annual fluctuations in weather in the US. American Economic Journal: Applied Economics **3**, 152–185 (2011).

128. M. E. Kahn, The death toll from natural disasters: the role of income, geography, and institutions. Review of economics and statistics **87**, 271–284 (2005).

129. A. Gasparrini et al., Projections of temperature-related excess mortality under climate change scenarios. The Lancet Planetary Health **1**, e360–e367 (2017).

130. O. Deschenes, E. Moretti, Extreme weather events, mortality, and migration. The Review of Economics and Statistics **91**, 659–681 (2009).

131. A. Gasparrini et al., Mortality risk attributable to high and low ambient temperature: a multicountry observational study. The Lancet **386**, 369–375 (2015).

132. N. Scovronick, Y. Guo, Y. Honda, D. Hondula, et al., The burden of heat-related mortality attributable to recent human-induced climate change. Nature climate change **11**, 492–500 (2021).

133. M. Qiu et al., Wildfire smoke exposure and mortality burden in the US under climate change. Nature, 1–3 (2025).

134. C. F. Gould et al., Health effects of wildfire smoke exposure. Annual Review of Medicine **75**, 277–292 (2024).

135. Y. Chen, A. Ebenstein, M. Greenstone, H. Li, Evidence on the impact of sustained exposure to air pollution on life expectancy from China's Huai River policy. Proceedings of the National Academy of Sciences **110**, 12936–12941 (2013).

136. S. Heft-Neal, J. Burney, E. Bendavid, M. Burke, Robust relationship between air quality and infant mortality in Africa. Nature **559**, 254–258 (2018).

137. E. Arceo, R. Hanna, P. Oliva, Does the effect of pollution on infant mortality differ between developing and developed countries? Evidence from Mexico City. The Economic Journal **126**, 257–280 (2016).

138. J. Anttila-Hughes, S. Hsiang, Destruction, disinvestment, and death: Economic and human losses following environmental disaster. Available at SSRN 2220501 (2013).

139. T. Bearpark, A. Rode, A. Patankar, The urban mortality consequences of rainfall and sea level rise. Nature (forthcoming).

140. S. Berggreen, L. Mattisson, "The curse of bad geography: Stagnant water, diseases, and children's human capital", tech. rep. (Working Paper, 2023).

141. S. Maccini, D. Yang, Under the weather: Health, schooling, and economic consequences of early-life rainfall. American Economic Review **99**, 1006–1026 (2009).

142. J. K. Anttila-Hughes, A. S. Jina, G. C. McCord, ENSO impacts child undernutrition in the global tropics. Nature communications **12**, 5785 (2021).

143. J. Currie, M. Rossin-Slater, Weathering the storm: Hurricanes and birth outcomes. Journal of Health Economics **32**, 487–503 (2013).

144. J. T. Mullins, C. White, Temperature and mental health: Evidence from the spectrum of mental health outcomes. Journal of Health Economics **68**, 102240 (2019).

145. T. A. Carleton, Crop-damaging temperatures increase suicide rates in India. Proceedings of the National Academy of Sciences **114**, 8746–8751 (2017).

146. N. Obradovich, R. Migliorini, S. C. Mednick, J. H. Fowler, Nighttime temperature and human sleep loss in a changing climate. Science Advances **3**, e1601555 (2017).

147. K. Minor, A. Bjerre-Nielsen, S. S. Jonasdottir, S. Lehmann, N. Obradovich, Rising temperatures erode human sleep globally. One Earth **5**, 534–549 (2022).

148. N. Obradovich, J. H. Fowler, Climate change may alter human physical activity patterns. Nature Human Behaviour **1**, 0097 (2017).

149. Y. Fan, J. Wang, N. Obradovich, S. Zheng, Intraday adaptation to extreme temperatures in outdoor activity. Scientific Reports **13**, 473 (2023).

150. N. Depsky et al., DSCIM-Coastal v1. 1: an open-source modeling platform for global impacts of sea level rise. Geoscientific Model Development **16**, 4331–4366 (2023).

151. E. A. Mordecai et al., Detecting the impact of temperature on transmission of Zika, dengue, and chikungunya using mechanistic models. PLoS neglected tropical diseases **11**, e0005568 (2017).

152. C. J. Carlson, T. A. Carleton, R. C. Odoulami, C. D. Molitor, C. H. Trisos, The historical fingerprint and future impact of climate change on childhood malaria in Africa. medRxiv, 2023–07 (2023).

153. M. L. Childs, K. Lyberger, M. Harris, M. Burke, E. A. Mordecai, Climate warming is expanding dengue burden in the Americas and Asia. medRxiv (2024).

154. D. Diaz, Evaluating the Key Drivers of the US Government's Social Cost of Carbon: A Model Diagnostic and Inter-Comparison Study of Climate Impacts in DICE, FUND, and PAGE. FUND, and PAGE (October 3, 2014) (2014).

155. C. Baysan, M. Burke, F. González, S. Hsiang, E. Miguel, Non-economic factors in violence: Evidence from organized crime, suicides and climate in Mexico. Journal of Economic Behavior & Organization **168**, 434–452 (2019).

156. A. T. Wolf, Shared waters: Conflict and cooperation. Annu. Rev. Environ. Resour. **32**, 241–269 (2007).

157. E. McGuirk, M. Burke, The economic origins of conflict in Africa. Journal of Political Economy **128**, 3940–3997 (2020).

158. J. Ferguson, M. Burke, E. Miguel, S. Hsiang, Climate change, conflict, and the risk of economic collapse in Africa. Proceedings of the National Academy of Sciences (forthcoming).

159. M. Burke, J. Ferguson, S. Hsiang, E. Miguel, Will Wealth Weaken Weather Wars? American Economic Review **114**, 65–69 (2024).

160. N. Obradovich, D. Tingley, I. Rahwan, Effects of environmental stressors on daily governance. Proceedings of the National Academy of Sciences **115**, 8710–8715 (2018).

161. R. P. Larrick, T. A. Timmerman, A. M. Carton, J. Abrevaya, Temper, temperature, and temptation: Heat-related retaliation in baseball. Psychological Science **22**, 423–428 (2011).

162. A. Shaver, A. K. Bollfrass, Disorganized Political Violence: A Demonstration Case of Temperature and Insurgency. International Organization **77**, 440–474 (2023).

163. I. Almås et al., Destructive Behaviour, Judgement, and Economic Decision-making under Thermal Stress*. The Economic Journal, ISSN: 0013-0133 (Jan. 2025).

164. J. Colmer, J. L. Doleac, Access to guns in the heat of the moment: more restrictive gun laws mitigate the effect of temperature on violence. Review of Economics and Statistics, 1–40 (2023).

165. S. M. Hsiang, K. C. Meng, M. A. Cane, Civil conflicts are associated with the global climate. Nature **476**, 438–441 (2011).

166. M. J. Roberts, W. Schlenker, Identifying supply and demand elasticities of agricultural commodities: Implications for the US ethanol mandate. American Economic Review **103**, 2265–2295 (2013).

167. A. D. Brunner, El Nino and world primary commodity prices: warm water or hot air? Review of Economics and statistics **84**, 176–183 (2002).

168. A. Hoeffler, M. Reynal-Querol, Measuring the costs of conflict. Washington, DC: World Bank.

169. D. B. Lobell, W. Schlenker, J. Costa-Roberts, Climate trends and global crop production since 1980. Science **333**, 616–620 (2011).

170. W. Liu, J. Zhou, Y. Ma, S. Chen, Y. Luo, Unequal impact of climate warming on meat yields of global cattle farming. Communications Earth & Environment **5**, 65 (2024).

171. C. M. Free et al., Impacts of historical warming on marine fisheries production. Science **363**, 979–983 (2019).

172. D. B. Lobell, M. B. Burke, Why are agricultural impacts of climate change so uncertain? The importance of temperature relative to precipitation. Environmental Research Letters **3**, 034007 (2008).

173. J. R. Welch et al., Rice yields in tropical/subtropical Asia exhibit large but opposing sensitivities to minimum and maximum temperatures. Proceedings of the National Academy of Sciences **107**, 14562–14567 (2010).

174. J. Proctor, A. Rigden, D. Chan, P. Huybers, More accurate specification of water supply shows its importance for global crop production. Nature Food **3**, 753–763 (2022).

175. M. J. Roberts, W. Schlenker, J. Eyer, Agronomic Weather Measures in Econometric Models of Crop Yield with Implications for Climate Change. American Journal of Agricultural Economics **95**, 236–243, ISSN: 00029092, 14678276 (2013).

176. M. Auffhammer, V. Ramanathan, J. R. Vincent, Climate change, the monsoon, and rice yield in India. Climatic Change **111**, 411–424, ISSN: 1573-1480 (2012).

177. R. Fishman, More uneven distributions overturn benefits of higher precipitation for crop yields. Environmental Research Letters **11**, 024004 (2016).

178. C. A. Taylor, W. Schlenker, "Environmental drivers of agricultural productivity growth: CO fertilization of US field crops", tech. rep. (National Bureau of Economic Research, 2021).

179. M. Burke, J. Dykema, D. B. Lobell, E. Miguel, S. Satyanath, Incorporating climate uncertainty into estimates of climate change impacts. Review of Economics and Statistics **97**, 461–471 (2015).

180. A. Ortiz-Bobea, T. R. Ault, C. M. Carrillo, R. G. Chambers, D. B. Lobell, Anthropogenic climate change has slowed global agricultural productivity growth. Nature Climate Change **11**, 306–312 (2021).

181. FAO, IFAD, UNICEF, WFP, WHO, "The State of Food Security and Nutrition in the World 2024", tech. rep.

182. A. Hsiao, J. Moscona, K. Sastry, "Food Policy in a Warming World", tech. rep. (National Bureau of Economic Research, Inc, 2024).

183. J. Moscona, K. A. Sastry, Does directed innovation mitigate climate damage? Evidence from US agriculture. The Quarterly Journal of Economics **138**, 637–701 (2023).

184. J. Rising, N. Devineni, Crop switching reduces agricultural losses from climate change in the United States by half under RCP 8.5. Nature communications **11**, 4991 (2020).

185. T. Carleton, L. Crews, I. Nath, Agriculture, trade, and the spatial efficiency of global water use. Working Paper (2023).

186. G. A. Vecchi, T. R. Knutson, Estimating annual numbers of Atlantic hurricanes missing from the HURDAT database (1878–1965) using ship track density. Journal of Climate **24**, 1736–1746 (2011).

187. O. E. Wing, N. Pinter, P. D. Bates, C. Kousky, New insights into US flood vulnerability revealed from flood insurance big data. Nature communications **11**, 1444 (2020).

188. T. Deryugina, The fiscal cost of hurricanes: Disaster aid versus social insurance. American Economic Journal: Economic Policy **9**, 168–198 (2017).

189. S. A. Schneider, S. Kunze, Disastrous discretion: Political bias in relief allocation varies substantially with disaster severity. Review of Economics and Statistics, 1–33 (2023).

190. D. Strömberg, Natural disasters, economic development, and humanitarian aid. Journal of Economic perspectives **21**, 199–222 (2007).

191. J. Boomhower, M. Fowlie, J. Gellman, A. Plantinga, "How are insurance markets adapting to climate change? risk selection and regulation in the market for homeowners insurance", tech. rep. (National Bureau of Economic Research, 2024).

192. L. Barrage, presented at the AEA Papers and Proceedings, vol. 110, pp. 107–112.

193. R. Jerch, M. E. Kahn, G. C. Lin, Local public finance dynamics and hurricane shocks. Journal of Urban Economics **134**, 103516 (2023).

194. A. Aitsi-Selmi, S. Egawa, H. Sasaki, C. Wannous, V. Murray, The Sendai framework for disaster risk reduction: Renewing the global commitment to people's resilience, health, and well-being. International journal of disaster risk science **6**, 164–176 (2015).

195. U. N. O. for Disaster Risk Reduction et al., Global assessment report on disaster risk reduction 2022 (UN, 1901).

196. K. R. Wagner, Adaptation and adverse selection in markets for natural disaster insurance. American Economic Journal: Economic Policy **14**, 380–421 (2022).

197. A. Hsiao, Sea level rise and urban adaptation in Jakarta. Technical Report (2023).

198. C. Cattaneo, G. Peri, The migration response to increasing temperatures. Journal of development economics **122**, 127–146 (2016).

199. H. Benveniste, P. Huybers, J. Proctor, Global climate migration is a story of who and not just how many. Nature Communications **16**, 7752 (2025).

200. P. Bohra-Mishra, M. Oppenheimer, S. M. Hsiang, Nonlinear permanent migration response to climatic variations but minimal response to disasters. Proceedings of the National Academy of Sciences **111**, 9780–9785 (2014).

201. P. Baylis, P. Bharadwaj, J. T. Mullins, N. Obradovich, Climate and migration in the United States. Journal of Public Economics **249**, 105446 (2025).

202. S. Feng, M. Oppenheimer, W. Schlenker, "Climate change, crop yields, and internal migration in the United States", tech. rep. (National Bureau of Economic Research, 2012).

203. L. A. Bakkensen, L. Barrage, Going underwater? Flood risk belief heterogeneity and coastal home price dynamics. The Review of Financial Studies **35**, 3666–3709 (2022).

204. M. Obolensky, M. Tabellini, C. Taylor, "Migration, Climate Similarity, and the Consequences of Climate Mismatch", tech. rep. (National Bureau of Economic Research, 2024).

205. R. Hornbeck, The enduring impact of the American Dust Bowl: Short-and long-run adjustments to environmental catastrophe. American Economic Review **102**, 1477–1507 (2012).

206. S. Aron-Dine, Rebuild or Relocate? (2024).

207. D. Castellani, The Long-Run Effects of Tropical Cyclones on the U.S. Housing Market. Working Paper (2025).

208. T. Deryugina, L. Kawano, S. Levitt, The economic impact of Hurricane Katrina on its victims: Evidence from individual tax returns. American Economic Journal: Applied Economics **10**, 202–233 (2018).

209. K. J. Mach et al., Managed retreat through voluntary buyouts of flood-prone properties. Science Advances **5**, eaax8995 (2019).

210. R. Young, "The Long-Run Effect of U.S. Flood Hazard Property Buyouts on Migration, Flood Risk, and Household Finance", tech. rep. (Working Paper, 2024).

211. A. Heyes, S. Saberian, Temperature and decisions: evidence from 207,000 court cases. American Economic Journal: Applied Economics **11**, 238–265 (2019).

212. L. Nybo, Cycling in the heat: performance perspectives and cerebral challenges. Scandinavian journal of medicine & science in sports **20**, 71–79 (2010).

213. B. Leard, K. Roth, et al., "Weather, traffic accidents, and climate change", tech. rep. (Resources for the Future Washington, DC, USA, 2015).

214. D. o. E. United Nations, P. D. Social Affairs, "World Urbanization Prospects: The 2018 Revision", tech. rep. (United Nations, 2019).

215. J. V. Henderson, A. Storeygard, U. Deichmann, Has climate change driven urbanization in Africa? Journal of development economics **124**, 60–82 (2017).

216. A. Hsu, G. Sheriff, T. Chakraborty, D. Manya, Disproportionate exposure to urban heat island intensity across major US cities. Nature communications **12**, 2721 (2021).

217. A. C. Abajian, C. Cole, K. Jack, K. C. Meng, M. Visser, "Dodging day zero: Drought, adaptation, and inequality in cape town", tech. rep. (National Bureau of Economic Research, 2025).

218. M. Auffhammer, P. Baylis, C. H. Hausman, Climate change is projected to have severe impacts on the frequency and intensity of peak electricity demand across the United States. Proceedings of the National Academy of Sciences **114**, 1886–1891 (2017).

219. A. C. Abajian, T. Carleton, K. C. Meng, O. Deschênes, Quantifying the global climate feedback from energy-based adaptation. Nature Communications **16**, 3928 (2025).

220. C.-L. de Secondat Montesquieu, C. d. S. baron de Montesquieu, The Spirit of Laws.

221. E. Huntington, Civilization and climate (Yale University Press, 1924).

222. J. Graff Zivin, S. M. Hsiang, M. Neidell, Temperature and human capital in the short and long run. Journal of the Association of Environmental and Resource Economists **5**, 77–105 (2018).

223. M. Burke, V. Tanutama, S. Heft-Neal, M. Hino, D. Lobell, "Game, sweat, match: Temperature and elite worker productivity", tech. rep. (National Bureau of Economic Research, 2023).

224. N. H. Mackworth, Effects of heat on wireless operators. British Journal of Industrial Medicine **3**, 143 (1946).

225. R. J. Park, Hot temperature and high-stakes performance. Journal of Human Resources **57**, 400–434 (2022).

226. E. Fesselmeyer, The impact of temperature on labor quality: Umpire accuracy in Major League Baseball. Southern Economic Journal **88**, 545–567 (2021).

227. R. J. Park, A. P. Behrer, J. Goodman, Learning is inhibited by heat exposure, both internationally and within the United States. Nature Human Behaviour **5**, 19–27 (2021).

228. A. Isen, M. Rossin-Slater, R. Walker, Relationship between season of birth, temperature exposure, and later life wellbeing. Proceedings of the National Academy of Sciences **114**, 13447–13452 (2017).

229. R. Fishman, P. Carrillo, J. Russ, Long-term impacts of exposure to high temperatures on human capital and economic productivity. Journal of Environmental Economics and Management **93**, 221–238 (2019).

230. P. Sastry, I. Sen, A.-M. Tenekedjieva, When insurers exit: Climate losses, fragile insurers, and mortgage markets. Fragile Insurers, and Mortgage Markets (December 23, 2023) (2023).

231. F. Annan, W. Schlenker, Federal crop insurance and the disincentive to adapt to extreme heat. American Economic Review **105**, 262–266 (2015).

232. T. Deryugina, B. Kirwan, Does the Samaritan's dilemma matter? Evidence from US agriculture. Economic Inquiry **56**, 983–1006 (2018).

233. H. Druckenmiller, Y. Liao, S. Pesek, M. Walls, S. Zhang, Removing development incentives in risky areas promotes climate adaptation. Nature Climate Change **14**, 936–942 (2024).

234. M. Benetton, S. Emiliozzi, E. Guglielminetti, M. Loberto, A. Mistretta, Does Climate Change Adaptation Matter? Evidence from the City on the Water (SSRN, 2023).

235. D. Fairweather, M. E. Kahn, R. D. Metcalfe, S. S. Olascoaga, "Expecting climate change: A nationwide field experiment in the housing market", tech. rep. (National Bureau of Economic Research, 2024).

236. M. Hino, M. Burke, The effect of information about climate risk on property values. Proceedings of the National Academy of Sciences **118**, e2003374118 (2021).

237. M. Hino, S. T. Belanger, C. B. Field, A. R. Davies, K. J. Mach, High-tide flooding disrupts local economic activity. Science Advances **5**, eaau2736 (2019).

238. C. Balboni, J. Boehm, M. Waseem, Firm adaptation and production networks: Structural evidence from extreme weather events in Pakistan. (2023).

239. A. Barreca, O. Deschenes, M. Guldi, Maybe next month? Temperature shocks and dynamic adjustments in birth rates. Demography **55**, 1269–1293 (2018).

240. P. Cashin, K. Mohaddes, M. Raissi, Fair weather or foul? The macroeconomic effects of El Niño. Journal of International Economics **106**, 37–54 (2017).

241. S. C. Smith, D. Ubilava, The El Niño Southern Oscillation and economic growth in the developing world. Global environmental change **45**, 151–164 (2017).

242. W. Rafey, Droughts, deluges, and (river) diversions: Valuing market-based water reallocation. American Economic Review **113**, 430–471 (2023).

243. J. Proctor, S. Hsiang, J. Burney, M. Burke, W. Schlenker, Estimating global agricultural effects of geoengineering using volcanic eruptions. Nature **560**, 480–483 (2018).

244. E. National Academies of Sciences, Medicine, et al., Reflecting sunlight: Recommendations for solar geoengineering research and research governance.

245. United Nations, European Union, Food and Agriculture Organization of the United Nations, International Monetary Fund, Organisation for Economic Co-operation and Development, The World Bank, System of Environmental-Economic Accounting 2012 Central Framework.

Appendix

A An Adaptation Primer

Broadly speaking, adaptations are actions that individuals take to maximize their well being, conditional on their climate. This could involve individuals protecting themselves from the adverse impacts of climate change or taking advantage of new opportunities created by climate changes. An important development in recent literature is a more complete understanding of adaptation (1). Many pre-empirical writings in economics emphasized that adaptation had the potential to reduce the global impact of climate change, but quantifying this potential was beyond reach. In current frontier research, many researchers are now measuring the scale and scope of real-world adaptation and using these values to understand how much adaptation will influence climate change impacts, essentially building projections of adaptation that are then used to modify a baseline impact projection.

Adaptation enters the basic framework of the dose-response function by modifying vulnerability:

$$vulnerability = baseline\_vulnerbility \cdot (1 - adaptation) \tag{3}$$

For harms (benefits), *adaptation* is positive (negative) and pushes vulnerability toward (away from) zero. In general, *adaptation* is thought of as a latent variable that is not directly observed, but influences *vulnerability*, which can be measured. The literature sometimes refers to a theoretical benchmark of "full adaptation" as a situation where $adaptation = 1$ and a population is completely insulated from the effects of the hazard, i.e. $vulnerability = 0$.

Adaptation costs If technologies exist that can fully protect a population from a hazard, why are not all populations fully adapted? Some early literature assumed that adaptation costs would "vanish in the long run". If correct, this assumption implied that (i) all populations should fully utilize frontier adaptation technologies, which would result in (ii) vulnerability being identical everywhere. However, empirical measurements have since overturned this assumption. Consistent quantification of physical hazards in econometric analyses has enabled comparable measurements of vulnerability in different populations. This revealed that not all populations were fully utilizing frontier adaptation technology.

Hsiang and Narita (2012) (2) initially demonstrated large differences in vulnerability to tropical cyclones across countries, pointing out that such differences could coexist in equilibrium if there were unobserved costs that prevented some populations from adapting as much as others. Carleton et al (2022) (3) noted that these adaptation costs should be bundled into the total damage of climate change because they represent forced spending that would not occur in the absence of these changes. Following this approach, one can take the expectation of Equation 1 from the main text, substitute Equation 3, and introduce adaptation costs to obtain:

$$\begin{aligned} E[impact] = & [baseline\_vulnerbility \cdot (1 - adaptation)] \cdot weather\_hazard \cdot prob(weather\_hazard) \\ & + adaptation \cdot adapt\_cost \end{aligned} \tag{4}$$

where $adapt\_cost$ is a marginal cost of additional adaptation (fixed costs are also possible). Hsiang and Narita (2012) (2) showed these costs were sufficient to generate heterogeneity in estimated vulnerability because the cyclone climate (expressed here as $prob(weather\_hazard)$) differed across countries. Optimizing populations will only adapt up to a level where the cost of marginal adaptations equal their expected marginal benefit. Since these benefits are determined by the climate (e.g. defensive investments are more valuable when hazards are more common), the climate of each country will determine the overall level of adaptation that is undertaken (e.g. more cyclones $\rightarrow$ greater adaptation). Thus differences in climate generate differences in the degree of unobserved adaptation, which in turn causes differences in estimated vulnerability.

Adaptation costs cannot usually be directly observed, similar to adaptation, but recent advances have allowed researchers to account for these costs. For example, Deryugina and Hsiang (2017) (4) point out that in general equilibrium, adaptations are a reallocation of resources away from a baseline use (e.g. spending on education) and towards adaptation (e.g. spending on protective infrastructure). This implies that impacts

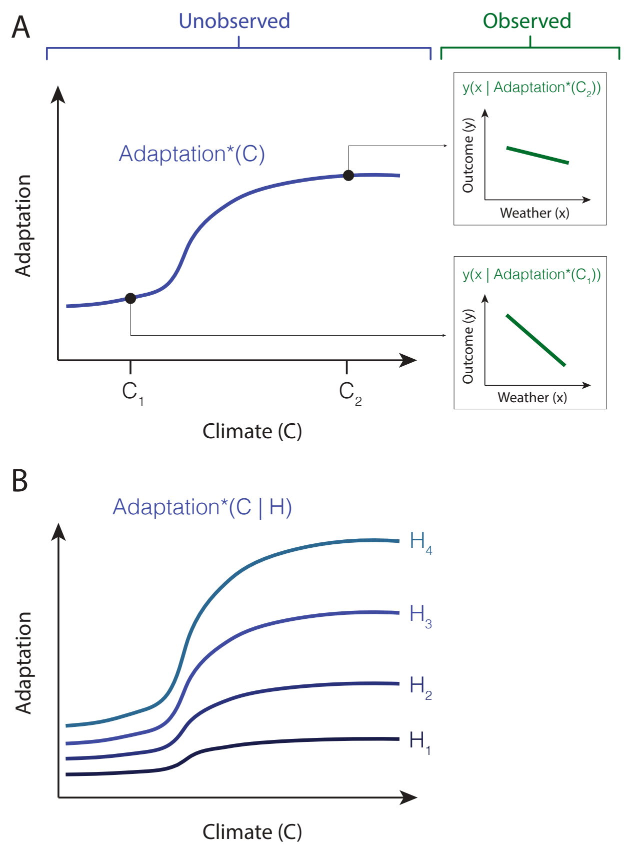

Figure A.1: (A) An example optimal adaptation schedule $Adaptation^*(.)$ as a function of climate C (blue line). Adaptation is an unobserved latent variable, but different levels of adaptation influence the vulnerability of an observed outcome y in response to an observed weather hazard x (green inset panels). (B) The optimal adaptation schedule may change conditional on covariate H (e.g. income).

of climate on total revenues (i.e. GDP) implicitly include all adaptation costs for actions that are priced in the market. For cases where the outcome of interest is not GDP, Carleton et al. (2022) (3) developed a general approach to account for unobserved adaptation costs explicitly, by integrating marginal costs that are assumed to be equal to measurable marginal benefits.

Optimal adaptation Because adaptation is costly, the level of adaptation for a population ($adaptation$) depends on their climate (C). For every (counterfactual) climate C that a population could face, there exists an optimal degree of adaptation $adaptation^*(C)$ they could undertake (Figure A.1A). In principle, Equation 4 can reflect any values of the a vector located in the $adaptation \times climate$ space; but in practice, we only expect to observe populations along the optimal adaptation schedule $adaptation^*(C)$ in equilibrium. This latent schedule is not directly observable, but is inferred from changes in the measurable marginal impact of weather (i.e. $\frac{\partial}{\partial x} y(x|adaptation^*(C))$, inset "Observed" panels of Figure A.1A).

Of course, the optimization of adaptation will be influenced by the availability of income (3), technology (5) or other factors (e.g. discount rates (2)). This means that $baseline_vulnerability$ and $adaptation_cost$ in Eq. 4 could be made functions of some covariates H. This would in turn generate different adaptation schedules ($adaptation^*(C|H)$) for different values of these covariates (Figure A.1B). This fact has tremendous importance for the global structure of climate change impacts, since populations have very different access to resources and adaptation technology will evolve and progress in the coming century. Thus, the global distribution of climate change impacts is influenced by the degree of adaptation in all locations, which reflects local climate, income, and technology, in addition to other possible factors. Attempting to account for these simultaneously represents the frontier of much modern empirical research.

Measuring adaptation There are two general approaches to studying adaptations empirically. First, it may be feasible to study adaptation actions directly, treating them as an outcome. For example, if individuals use irrigation to protect against drought and irrigation is observable, it is possible to study when, why and how much irrigation is used (6, 7).

Second, it is possible to study the overall net impact of adaptations by measuring how protective they are. This approach has two strategies. In cases where a specific type of adaptation is observable and there is exogenous variation that affects its usage (e.g. a policy intervention), it may be possible to identify how vulnerability changes when the specific adaptation is employed. Historically, analyses using this approach have relied on quasi-experiments, such as the staggered roll-out of public programs (5, 8–10), but increasingly field experiments are being used to test the efficacy of particular adaptation technologies (see (1) and references therein).

Alternatively, and perhaps more commonly, the specific adaptations undertaken are not know. For most hazard-outcome pairings, there exist many potential adaptations. For example, farmers may respond to warming temperatures by changing planting or harvesting dates, altering fertilizer use, switching crop varieties, using irrigation, or altering crop spacing, in addition to other actions (11). Because of this large number of potential actions, *adaptation* is often modeled as a latent vector (one element per action), that is optimized by agents based on their climate (12). Because these actions are unobserved, the literature has focused instead on developing techniques to model the net consequences of all actions and investments expressed in *adaptation* – in terms of benefits and, more recently, costs – without modeling the intermediate adaptive adjustments explicitly. To circumvent the need to model these adaptive actions explicitly, researchers commonly rely on the fact that adaptation (which is not observable) depends on the climate (which is observable). Equation 4 are then reformulated to versions of

$$E[impact] = f(weather(climate), adaptation^*(climate)) \tag{5}$$

where $f(.)$ is a generalization to allow for various forms. This empirical approach, formalized in Hsiang (2016) (12), uses information about the climate as a proxy (or sufficient statistic (13)) for all forms of adaptation in $adaptation^*$. In practice, this strategy uses empirical models that condition vulnerability on climate: the impact of weather hazards is allowed to interact with these climate measures. In some implementations these interactions are complex, allowing a nonlinear response to weather hazards to continuously and smoothly evolve through different climate conditions (3, 4, 11, 14, 15).

As described above, factors other than climate (e.g. income, technology) also influence vulnerability. In some cases, these factors enable populations to adapt, such as accessing building materials that protect against tropical cyclones. However, in other cases, these factors enable behaviors or investments that individuals prefer in their own right and where reductions in vulnerability are an ancillary benefit, such as installing air conditioning for comfort and experiencing its protective health benefits unintentionally. For both reasons, global analyses condition measurements of local vulnerability on both climate and other factors (e.g. income) for a more complete model of adaptation. Although, recent work advocates only considering adjustments associated with climate to be considered forced adaptations in response to climate change (3).

B Types of quantities used to characterize impacts

Many metrics are used to characterize empirical estimates of global climate impacts, which results in a diversity of nomenclature. Below I briefly describe and compare several metrics.

Dose-response functions vs. Damage functions *Dose-response functions* characterize the effect of a *local* hazard, such as exposure to a heat wave, on *local* outcomes, such crop yields (e.g. Figure 2). *Damage functions* summarize *global* outcomes based on the level of *global* climate change, usually indexed to a change in global mean surface temperature (ΔGMST). Empirical analysis usually aims to estimate dose-response functions directly from data (17). Damage functions were a theoretical concept in the early IAM literature (18, 19), however Burke et al (2015) (20) and Hsiang, Kopp, Jina, Rising, et al (2017) (21) demonstrated how to construct empirically-based damage functions by projecting outcomes using empirical dose-response functions, aggregating the projections, and indexing them against ΔGMST. Figure 5 shows examples of this procedure applied to six example outcomes (each is discussed in a following section). Damage functions are

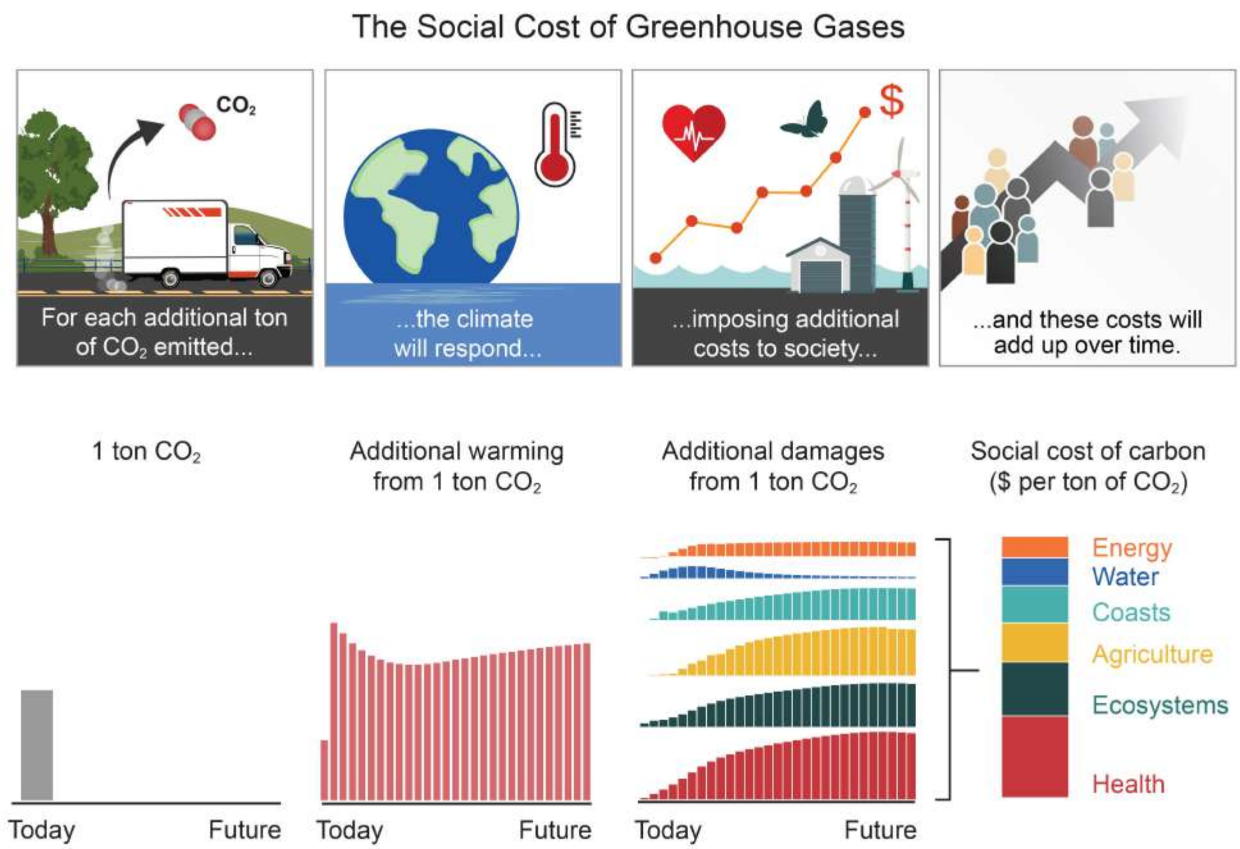

Figure A.2: The social cost of greenhouse gases is a monetary estimate of the total economic impact of an additional greenhouse gas emission today. Reproduced Figure 19.5. from the Fifth National Climate Assessment by the US Global Change Research Program (16). Original Caption: The social cost of greenhouse gases provides an estimate of the economic benefits to society of mitigating emissions, which can then be compared against the costs of doing so. This conceptual illustration shows how the social cost of reducing emissions of a particular greenhouse gas is computed. From left to right, the effect of one ton of carbon dioxide (CO_2) emitted into the atmosphere is illustrated in terms of additional warming or other physical impacts like sea level rise; these changes are translated into costs and benefits expected in representative market sectors such as agriculture, energy services, and water and coastal resources, as well as nonmarket impacts to human health and ecosystems; lastly, impacts that occur around the world and into the future are added up into a single measure using weights that reflect preferences around time, risk, and equity. The values shown in the figure are illustrative and may differ from estimates used for regulatory purposes.

succinct global summaries and are necessary to efficiently compute the cost of marginal emissions, but they generally obfuscate any unequal distribution of damages.

Monetized vs. In-kind impacts Many impacts are reported in monetized units, but some impacts that are of interest to society and economists are challenging to convert into dollar-equivalent values, such as civil conflicts, suicides, hours of sleep, or the dislocation of populations. As a result, these analyses usually report impacts using in-kind units and these findings are omitted from broader monetized assessments (16).

Top-down vs. Bottom-up Two strategies are used to understand how impacts add up. The "bottom-up" approach enumerates many effects (e.g. crop losses and health impacts), and then integrates them to compute an overall picture of damages (21–23). In contrast, the "top-down" approach views the economy as a whole and tries to understand how aggregate measures (e.g. GDP) respond to climate changes (18, 24, 25). The bottom-up approach is generally more laborious but it is able to capture many non-market impacts that are not normally included into aggregate economic measures (e.g. human health), while the top-down approach is relatively complete for the portion of the economy captured by national statistics and it captures the costs and benefits of adaptation to climate change (4).

Patchwork vs. Unified global analysis Global impact estimates are either assembled from a patchwork of national or regional studies or result from a single unified global analysis of harmonized global data. The patchwork approach was historically more viable, but faced critical challenges when large regions were missing data or modeling approaches differed across regions. Recent major efforts have compiled new databases of sub-national observations for unified global analyses of agriculture (11), energy (14), mortality (3, 26), labor supply (27), economic output (28, 29). These data collection efforts are costly, but subsequently can enable a more complete and consistent picture of impacts worldwide. Challenges for this new strategy include quality control for these new global data sets (30), systematic missingness of data from particular regions (e.g. often Subsaharan Africa (3, 11, 29)) and the flexible econometric models used to account for heterogeneity in the diverse global sample can be complex and challenging to implement (e.g. refs. (3, 11)).

Historical Attribution Attribution analyses estimate the impact that historical climate [changes] have had on a population (e.g. refs. (31–33)). These studies compare observed historical outcomes to an unobserved counterfactual history in which the climate were different (e.g. no climate change). A small but growing number of studies compute the overall burden or benefit provided by a baseline climate (i.e. ignoring climate changes) (17, 34).

Scenario-based projections Many analyses use empirical results to project impacts in particular future climate change scenarios. Figure 4 illustrates ten different examples of these projections in a high-emission scenario for different outcomes (each is discussed in a following section). Standardized scenarios that describe socioeconomic trends and emissions schedules have been agreed upon by the Coupled Model Intercomparison Project (CMIP) and adopted by the IPCC (35). These scenarios allow climate modeling teams to standardize their inputs when comparing climate model runs. There have been multiple iterations of these scenarios and they were not developed using standard economic tools (see ref. (36) for a discussion); thus, an important advance has been the development of some scenarios that use modern tools (e.g. (37)) and are now used in key analyses (38).

Optimal policy projections Equilibrium IAMs can develop projections for an optimal policy scenario, subject to the structure of that model. Unlike scenario-based projections that are run with exogenously determined scenarios, optimal emissions policies are endogenous. Some optimal policy projections use model components that have an empirical basis (e.g. ref. (39)), but it is uncommon for them to be empirically-based since closure of these models generally requires more parameterization than current empirical studies can provide.

Social Cost of Carbon and other GHGs The "social cost of carbon/GHGs" (SCC or SC-GHGs) is the total net present value of social costs (or benefit) that results from emitting one additional ton of CO_2 (or other GHG) at a specific moment in time (38, 40). This differs from projections of the flow of total future costs because (1) the SCC is the effect of a marginal emission, rather than the total effect of all emissions and (2) all future impacts are collapsed, via a discount rate, into a single value. Recent empirically-based bottom-up analyses have generally focused on a single outcome category (e.g. agriculture, mortality) and report a "partial SCC" for that outcome (3, 14, 41). Partial SCCs can then be integrated into a total SCC measure. The SCC metric is relevant to emissions mitigation policies since it allows benefits from emissions reductions to be compared to abatement costs, however a challenge is assuming a discount rate and inequality aversion parameter (42).

Loss & Damage A frontier research area is in the use of empirical economics to characterize "loss and damages" (L&D). The notion of L&D is that populations should be compensated by historical emitters for climate damages from historical emissions, included damages that have already occurred. L&D is a legal concept, agreed to by the parties to the UNFCC in the Paris Agreement, but a legal quantitative definition does not yet exist. Economists are well-positioned to formalize this concept and provide the intellectual structure and accounting framework that could enable in a coherent, consistent, and fair implementation of the idea in various contexts. Burke et al (2023) (43) proposed the first formal economic framework for L&D, using an approach similar to calculating the SCC. This is an important area of future work in economics.

C Additional discussion of methodological considerations

Distributions of hazard

Estimates of vulnerability (elements in $\mathbf{B}$ in Eq. 2) are combined with projected changes in the physical climate ($\Delta\mathbf{x}$) to compute impacts. Information regarding $\Delta\mathbf{x}$ originates in the climate science community, but usually requires additional transformations in order to link with empirical economic analyses (12). In global economic analyses, the spatial distribution of changing hazards requires attention (36, 44). For example, 2°C of warming in GMST does not result in 2°C of warming for nearly any location (see below). In many cases, the structure of global impacts is primarily determined by the spatial distribution of environmental changes $\Delta\mathbf{x}$ rather than variation in vulnerability β— i.e. the details of physical processes can sometimes matter more than socioeconomic or econometric nuances. Below are additional issues of note to economists.

Hazard likelihood Changes in the likelihood of hazards is how changes in the climate alter projected outcomes. Once hazard likelihoods are accounted for, the structure of projected impacts often differ from ideas expressed in theoretical analyses or public dialogue. These outlets often focus on salient events, such as extreme weather phenomena that have high costs but which occur infrequently (e.g. 1-in-1000 year floods). In contrast, many of the most economically important impacts of climate change result from small changes in the likelihood of extremely common but less salient events (e.g. moderately cold days (3)). Much of the overall distribution of costs from climate change can be explained by changes in the frequency of non-extreme events, specifically because they are common.

Estimating non-marginal effects via many marginals Empirical analysis of climate change impacts is sometimes challenging because its goal is often to estimate differences in outcomes between states of the world that are very different (e.g. the difference in outcomes in a future with and without climate change) but economic tools are generally well suited to study marginal changes. How should economists characterize the difference in outcomes that result from non-marginal differences in the distribution of hazards in different climate change scenarios, but using the identification strategies that are designed to estimate marginal effects? A key insight from the literature has been to think of future conditions as resulting from many incremental changes in hazard distributions (3, 4, 12, 13). This empowers researchers to estimate well-identified marginal effects and then integrate them to compute non-marginal counterfactuals.

One intuitive motivation for this strategy is to consider how climate change actually unfolds. For example, currently, a very small amount of climate change occurs every day. Specifically, global mean surface temperature is presently warming by roughly $\frac{5}{100{,}000}$°C per day (0.019°C per year). Since each day, or year, is incrementally different from the last, we can model those incremental changes sequentially and then integrate them. A future with and without climate change may be starkly different in non-marginal ways, but we can calculate the scale of this divergence analogously to how it will actually emerge in the real world: through the gradual accumulation of many small daily effects.

Hazards and inequality It is often incorrectly asserted that poor populations will experience the greatest climate changes. Growing evidence indicates that poorer populations may be more adversely affected by some climate changes, but not necessarily because they experience larger changes in hazards. In many cases, intensified exposure to future hazards is actually greatest for higher income populations (45). Nonetheless, poor populations often experience greater harm due to their greater vulnerability – a result of a nonlinear dose response function or an inability to adapt (16, 45).

Linking global to local climate changes The global nature of climate change raises interesting economic questions, such as the extent to which it represents an uninsurable aggregate risk (46, 47). However, a change in Global Mean Surface Temperature (ΔGMST) is not directly relevant for most practical empirical applications. ΔGMST summarizes global changes using a single metric, but it does not describe the experience of any individual or population. 1°C of ΔGMST almost never corresponds to 1°C of local warming at a location, rather local climate change at each location is a function of ΔGMST. Thus, ΔGMST should be thought of as an index value that corresponds with a set of ordered states for each location, but those states and the scaling of ΔGMST to transitions between them depend on the location. "Pattern scaling" is an approach used to link local empirical measurements to global projections that accounts for these location-specific linkages (21). This approach maps a spatial pattern of coefficients that are used to re-scale ΔGMST to approximate projected local changes:

$$\Delta Local\_Temperature_{it} = \gamma_i \cdot \Delta GMST_t$$

where γ_i represents the pattern of coefficients across locations indexed by i.

Quantification of uncertainty

One additional and important, but often overlooked, role for empirical analysis is to quantify uncertainty. In climate change projections, uncertainty strongly influences decision-making (46, 49–52) (e.g. risk is priced) and estimates of uncertainty are critical (even if the distribution of estimated impacts spans zero). In many contexts related to climate change, accurately describing ranges of plausible outcomes is equally valuable to, if not more valuable, than presenting a central projection. Thus, empiricists working on climate change should consider characterizing uncertainty as one of their core responsibilities, in addition to constructing estimates of central tendencies.

This mandate has two notable implications for common practice. First, empiricists should not deliberately make elective assumptions that mechanically reduce uncertainty (e.g. (53)), since this misrepresents true uncertainty to any decision-maker. Second, empiricists should not only focus on findings that seem "statistically significant" by comments metrics, whether it is a parameter or projection, since this can lead to a selective view of results that under-represents true uncertainty (since more uncertain results may be less significant). Adopting these practices may require shedding deeply ingrained habits.

Criticisms of the empirical approach

As the empirical literature on climate change has grown, criticisms of the approach have emerged. Perhaps the most important critique is that the modern populations studied may be different in important ways from future populations. This concern has three elements that should be considered separately. First, future populations may develop unprecedented technologies that fundamentally alter their relationship to

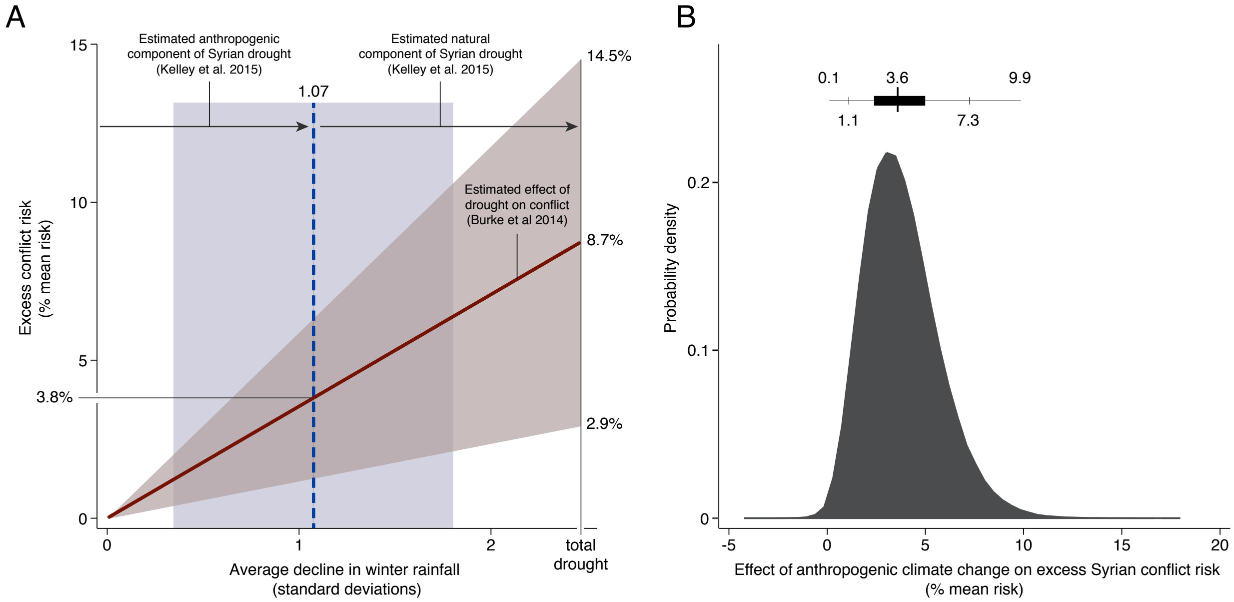

Figure A.3: Attributing excess conflict risk in Syria to the component of drought caused by humans. (A) The 2007-2010 drought (measured in standard deviations of historical variability) has a natural component induced by climate variability (D_0) and a trend component that has been attributed to anthropogenic climate change in ref. (48) (D', dashed blue w. 95% CI). Ref. (25) uses meta-analysis of 17 harmonized studies to estimate that each standard deviation in persistent drought generates 3.54% (±1.2%) excess conflict risk (red w. 95% CI, slope = β). Combining these estimates allows us to attribute a component of excess conflict risk in 2008 due to anthropogenic climate change (mean estimate: 3.8%). (B) Combining uncertainty in the estimated size of the anthropogenic component of drought (48) and uncertainty in the sensitivity of conflict to drought (25), we construct the probability distribution of excess conflict risk in 2010 Syria attributable to anthropogenic climate change. Median, interquartile range, 90-centile range and 99-centile range indicated by box-whisker. Reproduced from Burke and Hsiang (2025).

the climate. The likelihood of such a transformation is unknown and it seems unlikely that all populations would have equal access to such technologies; nonetheless, this issue remains a major intellectual challenge to all research on climate change (not only empirical analyses). Second, future populations may use existing technology to adapt more than previous generations did, altering the relationship between climate and the economy. As discussed above, major advances modeling adaptation now allow frontier analyses to project adaptation, although that is a new development. However, some analyses find (15) the extent of historical adaptation is often limited, indicating that projections without adaptation may sometimes be a reasonable approximation. Third, the distribution of traits in future populations (e.g. income) may lie outside the range of modern populations. In these cases, models that account for adaptation based on modern samples might not be representative of future populations. Although, global studies analyzing this issue (3, 11, 14) find that most future populations having a reasonable analog in modern samples and only the richest/hottest locations are outside of historical experience.

Probably the most misguided critique of the empirical literature is that data-driven projections into the future are less reliable than corresponding theory-based projections. This claim often motivates the application of models that are primarily theory-based. However, to my knowledge, there exists no evidence that theory-based projections of climate impacts are more accurate than empirically-based projections; rather, the notion remains a theory.

D Additional discussion of prior findings

Consistency of Dell et al (2012) with nonlinear effects of temperature on GDP

Important early work by Dell et al. (2012) (24) made a critical contribution by focusing on the persistence of temperature effects on GDP. Dell et al. assumed a linear functional form that differed by income group, with poor countries exhibiting a large negative effect of warming and wealthy countries exhibiting a smaller effect. Those findings ultimately are consistent with the nonlinear form reported in later analyses, since income is strongly correlated with the baseline temperature (54). Dell et al.'s pooled sample of rich countries straddles the peak of the nonlinear dose-response (shown in Figure 1A) – resulting in a flatter estimate in a linear model – while a pooled sample of poor countries is concentrated at hotter temperatures with more negative marginal effects, even when linearized.

Elevation of civil conflict risk in Syria attributable to anthropogenic climate change

Burke and Hsiang (2025) estimate how much anthropogenic enhancement of a drought in Syria was likely to contribute to onset of the recent civil war (55). Combining empirical estimates (+3.5% risk per s.d. in precipitation (25)) with counterfactual climate modeling estimates (climate change increased the drought magnitude by +1.07 s.d. (48)), they estimate that anthropogenic climate change increased the *ex ante* risk of the Syrian conflict by 1.1-7.3% (Appendix Figure A.3). These statements do not support the claim that climate change *caused* the entire Syrian conflict *per se*—although the cost of this fractional enhancement might be viewed as substantial, given the extraordinary human toll of the resulting violence. Note that, regardless of its current magnitude, this type of enhancement is expected to grow steadily with future warming.

Appendix References

1. T. Carleton, E. Duflo, K. Jack, G. Zappala, in Handbook of the Economics of Climate Change, ed. by L. Barrage, S. Hsiang (Elsevier, 2024), vol. 1.
2. S. M. Hsiang, D. Narita, Adaptation to cyclone risk: Evidence from the global cross-section. Climate Change Economics **3**, 1250011 (2012).
3. T. Carleton et al., Valuing the global mortality consequences of climate change accounting for adaptation costs and benefits. The Quarterly Journal of Economics **137**, 2037–2105 (2022).
4. T. Deryugina, S. Hsiang, "The marginal product of climate", tech. rep. (National Bureau of Economic Research, 2017).
5. A. Barreca, K. Clay, O. Deschenes, M. Greenstone, J. S. Shapiro, Adapting to climate change: The remarkable decline in the US temperature-mortality relationship over the twentieth century. Journal of Political Economy **124**, 105–159 (2016).
6. R. Hornbeck, P. Keskin, The historically evolving impact of the ogallala aquifer: Agricultural adaptation to groundwater and drought. American Economic Journal: Applied Economics **6**, 190–219 (2014).
7. N. Hagerty, "Adaptation to surface water scarcity in irrigated agriculture", tech. rep. (Working Paper, 2021).
8. J. T. Mullins, C. White, Can access to health care mitigate the effects of temperature on mortality? Journal of Public Economics **191**, 104259 (2020).
9. T. Fetzer, Can workfare programs moderate conflict? Evidence from India. Journal of the European Economic Association **18**, 3337–3375 (2020).
10. T. Garg, G. C. McCord, A. Montfort, Can social protection reduce damages from higher temperatures? Journal of Environmental Economics and Management **131**, 103152 (2025).

11. A. Hultgren et al.,
Estimating global impacts to agriculture from climate change accounting for adaptation.
Nature **642**, 644–652 (2025).

12. S. Hsiang, Climate econometrics. Annual Review of Resource Economics **8**, 43–75 (2016).

13. P. Mérel, E. Paroissien, M. Gammans, Sufficient statistics for climate change counterfactuals.
Journal of Environmental Economics and Management **124**, 102940 (2024).

14. A. Rode et al., Estimating a social cost of carbon for global energy consumption.
Nature **598**, 308–314 (2021).

15. M. Burke et al., "Are We Adapting to Climate Change?", tech. rep.
(National Bureau of Economic Research, 2024).

16. S. Hsiang et al., "Fifth National Climate Assessment: Chapter 19. Economics", tech. rep.
(US Global Change Research Program, 2023).

17. T. A. Carleton, S. M. Hsiang, Social and economic impacts of climate. Science **353**, aad9837 (2016).

18. W. D. Nordhaus, Optimal greenhouse-gas reductions and tax policy in the" DICE" model.
The American Economic Review **83**, 313–317 (1993).

19. R. S. J. Tol, The economic effects of climate change. Journal of economic perspectives **23**, 29–51 (2009).

20. M. Burke, S. M. Hsiang, E. Miguel, Global non-linear effect of temperature on economic production.
Nature **527**, 235–239 (2015).

21. S. Hsiang et al., Estimating economic damage from climate change in the United States.
Science **356**, 1362–1369 (2017).

22. D. Diaz, F. Moore, Quantifying the economic risks of climate change.
Nature Climate Change **7**, 774–782 (2017).

23. R. S. Tol, On the optimal control of carbon dioxide emissions: an application of FUND.
Environmental Modeling & Assessment **2**, 151–163 (1997).

24. M. Dell, B. F. Jones, B. A. Olken,
Temperature shocks and economic growth: Evidence from the last half century.
American Economic Journal: Macroeconomics **4**, 66–95 (2012).

25. M. Burke, S. M. Hsiang, E. Miguel, Climate and conflict. Annu. Rev. Econ. **7**, 577–617 (2015).

26. A. Gasparrini et al.,
Projections of temperature-related excess mortality under climate change scenarios.
The Lancet Planetary Health **1**, e360–e367 (2017).

27. A. Rode et al.,
Labor disutility in a warmer world: The impact of climate change on the global workforce. (2022).

28. M. Burke, V. Tanutama, "Climatic constraints on aggregate economic output", tech. rep.
(National Bureau of Economic Research, 2019).

29. L. Wenz, R. D. Carr, N. Kögel, M. Kotz, M. Kalkuhl,
DOSE–Global data set of reported sub-national economic output. Scientific Data **10**, 425 (2023).

30. T. Bearpark, D. Hogan, S. Hsiang, Data anomalies and the economic commitment of climate change.
Nature **644**, E7–E11 (2025).

31. D. B. Lobell, W. Schlenker, J. Costa-Roberts, Climate trends and global crop production since 1980.
Science **333**, 616–620 (2011).

32. F. V. Davenport, M. Burke, N. S. Diffenbaugh,
Contribution of historical precipitation change to US flood damages.
Proceedings of the National Academy of Sciences **118**, e2017524118 (2021).

33. N. S. Diffenbaugh, M. Burke, Global warming has increased global economic inequality. Proceedings of the National Academy of Sciences **116**, 9808–9813 (2019).

34. R. Young, S. Hsiang, Mortality caused by tropical cyclones in the United States. Nature, 1–8 (2024).

35. L. Touzé-Peiffer, A. Barberousse, H. Le Treut, The Coupled Model Intercomparison Project: History, uses, and structural effects on climate research. Wiley Interdisciplinary Reviews: Climate Change **11**, e648 (2020).

36. S. Hsiang, R. E. Kopp, An economist's guide to climate change science. Journal of Economic Perspectives **32**, 3–32 (2018).

37. U. K. Müller, J. H. Stock, M. W. Watson, An econometric model of international growth dynamics for long-horizon forecasting. Review of Economics and Statistics **104**, 857–876 (2022).

38. EPA, Report on the social cost of greenhouse gases: Estimates incorporating recent scientific advances, 2022.

39. L. Barrage, presented at the AEA Papers and Proceedings, vol. 110, pp. 107–112.

40. NASEM, Valuing climate damages: updating estimation of the social cost of carbon dioxide (National Academies Press, 2017).

41. K. Rennert et al., Comprehensive evidence implies a higher social cost of CO2. Nature **610**, 687–692 (2022).

42. C. Gollier, in Handbook of the Economics of Climate Change, ed. by L. Barrage, S. Hsiang (Elsevier, 2024), vol. 1.

43. M. Burke, M. Zahid, N. Diffenbaugh, S. Hsiang, Quantifying climate change loss and damage consistent with a social cost of greenhouse gases. Nature (forthcoming).

44. M. Auffhammer, S. M. Hsiang, W. Schlenker, A. Sobel, Using weather data and climate model output in economic analyses of climate change. Review of Environmental Economics and Policy (2013).

45. S. Hsiang, P. Oliva, R. Walker, The distribution of environmental damages. Review of Environmental Economics and Policy (2019).

46. M. L. Weitzman, On modeling and interpreting the economics of catastrophic climate change. The review of economics and statistics **91**, 1–19 (2009).

47. J. I. Dingel, K. C. Meng, S. M. Hsiang, "Spatial correlation, trade, and inequality: Evidence from the global climate", tech. rep. (National Bureau of Economic Research, 2019).

48. C. P. Kelley, S. Mohtadi, M. A. Cane, R. Seager, Y. Kushnir, Climate change in the Fertile Crescent and implications of the recent Syrian drought. Proceedings of the National Academy of Sciences **112**, 3241–3246 (2015).

49. M. Golosov, J. Hassler, P. Krusell, A. Tsyvinski, Optimal taxes on fossil fuel in general equilibrium. Econometrica **82**, 41–88 (2014).

50. D. Lemoine, C. Traeger, Watch your step: optimal policy in a tipping climate. American Economic Journal: Economic Policy **6**, 137–166 (2014).

51. Y. Cai, T. S. Lontzek, The social cost of carbon with economic and climate risks. Journal of Political Economy **127**, 2684–2734 (2019).

52. M. Barnett, W. Brock, L. P. Hansen, Pricing uncertainty induced by climate change. The Review of Financial Studies **33**, 1024–1066 (2020).

53. R. G. Newell, B. C. Prest, S. E. Sexton,
The GDP-temperature relationship: implications for climate change damages.
Journal of Environmental Economics and Management **108**, 102445 (2021).

54. W. D. Nordhaus, Geography and macroeconomics: New data and new findings.
Proceedings of the National Academy of Sciences **103**, 3510–3517 (2006).

55. S. Hsiang, M. Burke, Attributing excess conflict risk in Syria to anthropogenic climate change, 2025, arXiv: 2510.02650, (https://arxiv.org/abs/2510.02650).