Navigating the ‘Problem from Hell’: A Guide to Climate Damages

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Abstract

Multiple lines of research aim to quantify the economic impacts of climate change. We show that the effects of climate change on economic activity depend on how climate change alters weather across time and space. Changes in contemporary weather have direct effects on output; changes in past weather and in expectations of future weather induce adaptation; and changes in weather elsewhere around the globe introduce a general equilibrium effect. Using this framework, we argue that estimation of climate impacts faces a trilemma. A methodology can have at most two of: (i) robustness to a particular economic model's structure, (ii) interpretation as effects of persistent, widespread, anticipated climate change, and (iii) quasi-experimental identification. We summarize the literature on climate damages in light of the trilemma. A solid body of knowledge has developed around direct effects, and recent work has made substantial progress towards understanding adaptation and spatial spillovers.

Keywords: climate change, damage function, social cost of carbon, adaptation, weather, trade

JEL Codes: C23, C51, F18, O13, Q17, Q51, Q54, R11

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1 Introduction

The economics of climate change is a problem from hell.
– Martin Weitzman, *Review of Environmental Economics and Policy* (2015)

The many unknowns, complex interlinkages, and high stakes make climate change an economic "problem from hell" (Weitzman, 2015, p. 145). Among the many research questions, understanding the economic damages from climate change is of central importance, as it links scientific insights to policy design and evaluation. Climate change destabilizes important physical inputs to the economy, creates global systemic risks, and alters the geographic scope of human activity. Global average surface temperature set a new record in 2024, exceeding 1.5°C (2.7°F) relative to 1880–1900 (Figure 1). And global surface temperature has risen "faster since 1970 than in any other 50-year period over at least the last 2000 years" (IPCC, 2023, p. 4). Accumulated greenhouse gas emissions also cause the seas to rise, precipitation patterns to change, and oceans to acidify, while altering extreme events like hurricanes and wildfires (Hsiang and Kopp, 2018; IPCC, 2021, 2023).

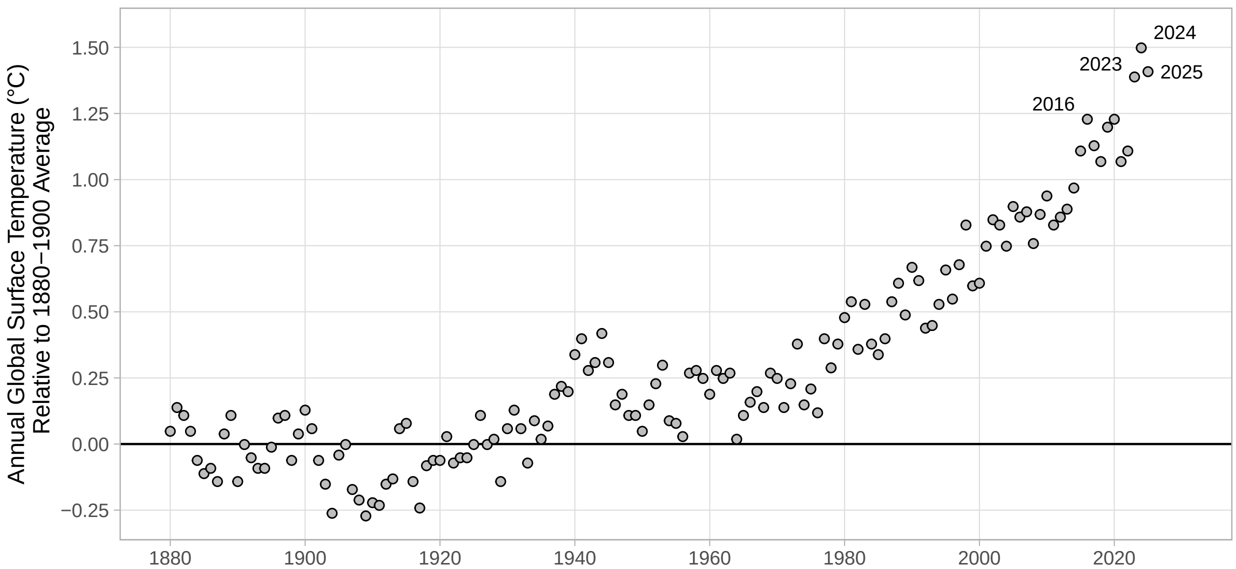
Estimates of damages inform both the stringency of actual climate policies and what policies economists recommend for implementation.[1] Recent syntheses indicate that 3°C of warming relative to pre-industrial global average temperature would, in central projections, persistently lower future GDP by around 3% (Barrage and Nordhaus, 2024) or even 7–13% (Howard and Sterner, 2025). Damage functions are a core component of cost-benefit integrated assessment models (IAMs), which mathematically represent the relationships between the economy and the climate (Kelly and Kolstad, 1999; Nordhaus, 2013; Dietz, 2024). Similar models are used by academics and policymakers to calculate the social cost of carbon (SCC) (Dietz, 2024), the present value of the stream of damages caused by the emission of one additional ton of carbon dioxide. Damage estimates are the critical piece of these values: no damages, no SCC. Damage estimates also inform the emerging legal framework of "loss and damage," which considers how emitters might compensate parties harmed by climate change (UNFCCC, 2012).

The large and growing literature on climate damages uses a variety of conceptual frameworks, modeling choices, and data. Over time, the pendulum has swung between explicit structural modeling and a variety of applied econometric methods, each approach a response to perceived shortcomings of earlier work. Early studies developed simulation models of agricultural impacts. Seeking a more direct link to empirical data, subsequent literature regressed outcomes on long-run average temperature within a cross-section of locations. Seeking identification in the modern causal sense, recent literature regressed outcomes on realized weather for a panel of locations.[2] And the

[1] Although some regions may experience net benefits over some timescales, we use the term "damages" because there is widespread consensus that aggregate global impacts in both the short- and long-term are negative (Howard and Sylvan, 2020).

[2] Throughout, we use "climate" to indicate the distribution of variables such as temperature and precipitation and

Figure 1: Global Average Surface Temperatures



Note: This figure shows annual global surface temperatures relative to the period from 1880 to 1900. Data source: Lenssen et al. (2024); GISTEMP Team (2026); Lemoine, Hausman, and Shrader (2026).

pendulum swings back, seeking counterfactuals more faithful to climate change: a recent strand of literature builds dynamic spatial models that rely on theoretical contributions from trade and macroeconomics.

Why are there so many different approaches? Different strands of the literature—and individual papers from those strands—contribute to different parts of our understanding of the climate change problem and face different limitations. To clarify these tradeoffs, we begin with a simplified model of climate change that is *widespread*, *persistent*, and *anticipated*. We model a two-region world economy experiencing ongoing climate change and expecting climate change to continue. We decompose the effects of climate change on output and on welfare into individual terms that we map into the literature. Some are obvious: local weather may have direct and immediate effects on productivity (for example, heat waves may hurt agricultural production). Others are more nuanced: current capital stocks depend on how agents responded to past changes in weather and to anticipated future changes in weather. And some of the terms involve cross-region spillovers: trade adjusts for direct damages from weather in each region and for the evolution of capital stocks in each region.

We next discuss methods researchers have used to study these effects. Our focus is not so much on the details of estimation (for example, which fixed effects to include in a panel regression) but rather on conceptual questions raised by idealized versions of each method and the trade-offs each

"weather" to indicate realizations of those variables.

method must make when it comes to understanding the channels for climate damage revealed by our conceptual model. We propose three desiderata: we want methods that are informative about widespread, persistent, anticipated climate change; robust to the particularities of an economic model's structure; and well-identified in the econometric sense of potentially recovering unique, causal relationships from data. We argue that, though they each get at some aspect of the problem, no single approach yet satisfies all three. Cross-sectional regression methods are vulnerable to omitted variables bias and their counterfactual calculations capture only local changes in climate; panel regression methods capture weather changes that are localized, one-off, and potentially surprising rather than widespread, persistent, and anticipated; and structural methods require imposing a variety of particular model restrictions that are hard to test. The proliferation of papers using varying methods is a reasonable response to the tension created by the desiderata and is likely to continue. It is imperative that the varied approaches speak to one another.

Although the conceptual challenges we describe are related to challenges in other areas of economics (for example, Heckman, 2000; Nakamura and Steinsson, 2018), they are especially important here given the centuries-long and global nature of climate change. The conceptual challenges have not gone unnoticed by climate economists: debates about the relative merits of various methods of estimating climate impacts are decades old (Cline, 1996; Tol, 2009; Dell, Jones and Olken, 2014; Massetti and Mendelsohn, 2018; Kolstad and Moore, 2020). We argue that these debates recur because they are inherent to the enterprise, a result of the many channels through which climate change impacts the economy and of the trilemma we propose.

We review the recent literature in light of our model and trilemma. We divide papers into broad categories reflecting types of impacts highlighted by our model: estimates of direct damages, papers investigating the scope for adaptation in response to local weather, and papers examining cross-region spillovers. In the direct damages strand, data-driven efforts have led to tremendous advances. These take causal identification seriously, offer granularity across impact categories, and allow for heterogeneity across space. Recent IAMs have incorporated these updated damage estimates (Rennert et al., 2022; EPA, 2023; Barrage and Nordhaus, 2024).

Unfortunately, the recent causal estimates struggle to incorporate adaptation—the set of actions people and society take to respond to climate change—both by people directly affected by climate change and via trade and other general equilibrium effects. Adaptation determines the total damage from climate change by affecting the damages people experience and by being costly in its own right. Adaptation tends to lower total damages (relative to a world without adaptation possibilities), but if a damage estimate fails to include adaptation costs, it may understate total damages (relative to a world where adaptation is costless). Trade and general equilibrium effects determine how global climate change will affect the economy and how effects in climate-exposed sectors spill over to other sectors. Recent work on dynamic adjustment and on spatial spillovers aims to advance understanding of these topics by placing more structure on the problem, albeit at the cost of diminishing the robustness to model structure attainable through purely reduced-form methods.

We conclude with a discussion of next steps, offering some specific suggestions for future research. We discuss what the broad research agenda might look like in an environment of imperfectly known—and even imperfectly knowable—damages. We argue that there will always be room for multiple methodological approaches, and we propose that there are gains from pursuing hybrid methods and using some methods to test the assumptions imposed by others.

2 Conceptual Framework for Climate Change Damages

E'en hell hath its peculiar laws.

– Johann Wolfgang von Goethe, *Faust*

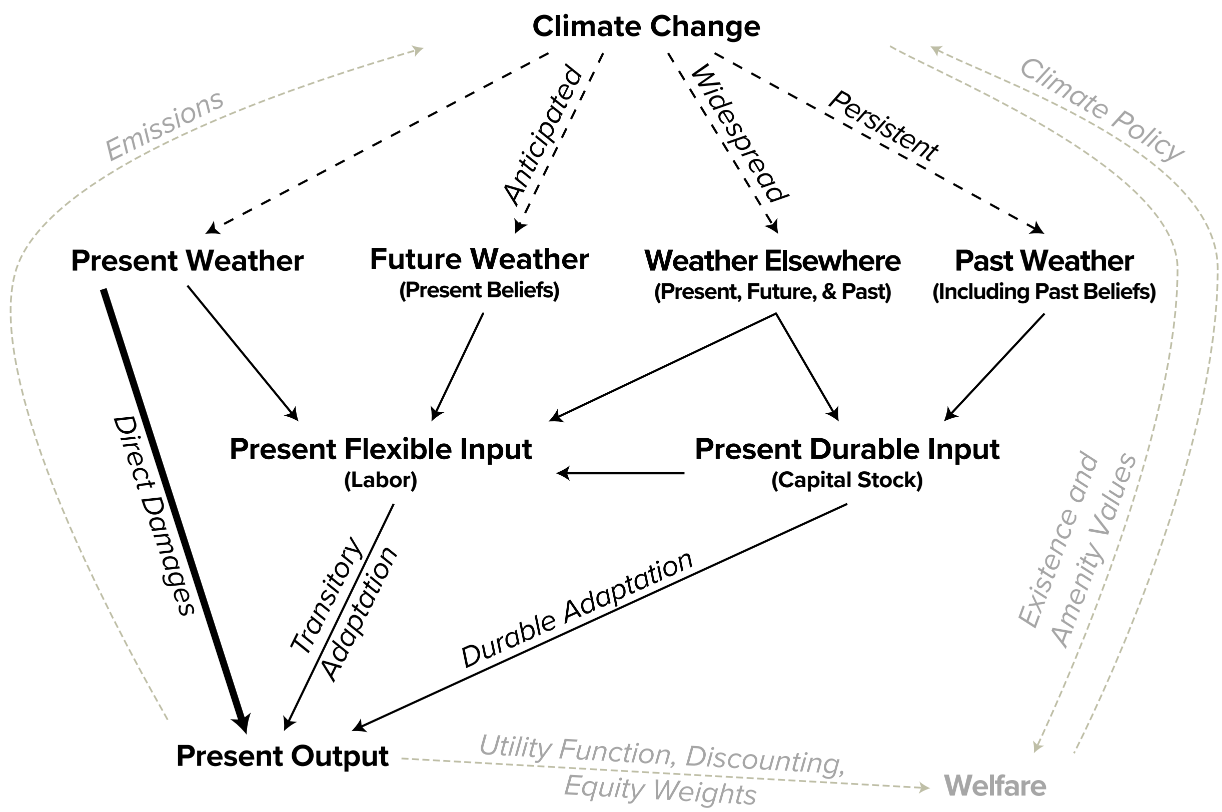
To organize ideas, we develop a conceptual framework of climate change damages that highlights key challenges in estimating climate impacts, illustrated in Figure 2 and formalized in Section A of the Appendix. We focus on the effect of climate change on economic activity (in black). Climate change has been affecting global weather for decades and will continue to unfold for centuries into the future, meaning that at any given time—and relative to a world without climate change—weather is different in the past, present, and future, both locally and elsewhere around the world (dashed black arrows). These changes in weather in turn affect economic output directly (thick black arrow) and also affect output via adaptation, comprising adjustments to both flexible and durable inputs (thin black arrows).

To focus on understanding climate change *damages*, we abstract from many important components of climate change that are relevant to optimal policy (gray arrows in Figure 2): we take climate change as given, rather than endogenizing emissions and climate as IAMs do; we focus on effects on output, largely leaving to the side the issue of translating output into welfare; and we do not address determinants of climate policy.

To capture the global, *widespread* nature of climate change, we model climate affecting local weather both in a region of interest and elsewhere in the global economy; to capture the *persistent* nature of climate change, we model past periods in which the climate was already changed; and to capture the *anticipated* nature of climate change, we model future periods for which agents know what climate to expect. We model a flexible input (described as labor) and investment into a durable stock input (described as capital), each of which reflect adaptation actions as delineated below.

In the model described in Section A of the Appendix, each of two regions, labeled A and B, produces a consumption good and acts like a price-taker in the global market for its good. A representative consumer in each region has utility for both goods, which motivates regions to trade

Figure 2: Conceptual Framework



Note: This schematic summarizes the components of our conceptual framework. Many papers estimate the direct damages on output from present, local weather (the thick black arrow)—for example, the effect of temperature on agricultural production. Other effects may also be important (thin black arrows): agents make or have made transitory and durable decisions (for example, about labor and investment in capital) in response to present weather, past weather, beliefs about future weather, and weather in other locations (from all time periods). The text describes why some arrows appear (for example, past weather affected past investment choices, which affect today's capital stock, and future weather affects today's labor choices via trade-offs with investment) while others do not (today's capital stock cannot respond to today's weather, and past weather affects today's labor only by affecting today's capital stock). Arrows in grey are important components of climate economics that are outside the scope of our review, which focuses on climate damages.

with each other. Production Y_t^j in region j at time t is determined by weather w_t^j and two stylized inputs. A first input is labor that can be flexibly allocated to either production (ℓ_{Yt}^j) or investment (ℓ_{Kt}^j). A second input, K_t^j, is a predetermined[3] capital stock, which comprises physical, resource, and knowledge stocks. Neither input is mobile across regions.[4]

Any model formalizing the impact of climate change on the economy must specify the stochastic process that generates weather and specify how climate change alters that process. We map global, expected climate to local, realized weather in the following way. Weather in region j and period t is $w_t^j = \theta^j C + \tilde{w}_t^j$. C indexes the global climate, with θ^j scaling a change in global climate to a change in region j's climate. $\tilde{w}_t^j$ is a mean-zero random variable that reflects stochasticity in weather. The joint distribution of $\tilde{w}_t^j$ and $\tilde{w}_t^k$ (weather shocks in region j and weather shocks in the other region k) is independent and identically distributed over time and independent of C.

Within our framework, we study an idealized climate experiment. We compare two worlds that have always had and will always have different climates. This allows us to analyze climate change via comparative statics. The change $\mathrm{d}C$ that we study does not represent a change from one period to the next, it does not represent a difference-in-difference conceptualization in which one world is experiencing an evolving climate while the other is not, and it does not capture uncertainty about what climate change will turn out to be. Modeling climate change in these ways would introduce new terms related to transition costs and to climate risk, but the channels for climate change effects that we identify would remain. Within our experiment, the difference $\mathrm{d}C$ between the two worlds captures *widespread* climate change because it alters weather in every region, captures *persistent* climate change because it alters the history of weather leading up to a given period, and captures *anticipated* climate change because agents understand that it alters the distribution of future weather.

Much empirical work considers the effects of climate change on output, and the damage functions central to integrated assessment models have tied output to temperature. Within our model, the first-order effect of climate change on region A's output is

$$\frac{\mathrm{d}Y_t^A}{\mathrm{d}C} = \underbrace{\frac{\partial Y_t^A}{\partial w_t^A}\theta^A}_{\text{direct damages}} + \underbrace{\frac{\partial Y_t^A}{\partial \ell_{Yt}^A}\frac{\mathrm{d}\ell_{Yt}^A}{\mathrm{d}C}}_{\text{transitory adaptation}} + \underbrace{\frac{\partial Y_t^A}{\partial K_t^A}\frac{\mathrm{d}K_t^A}{\mathrm{d}C}}_{\text{durable adaptation}} . \tag{1}$$

We delineate three channels through which climate change affects output. The first channel is the "direct damage" from altered contemporary weather (thick black arrow in Figure 2): weather is an

[3]As is standard in the literature, there is a one-period lag for the labor that is allocated to investment to generate useful capital.

[4]The formal model could be extended to include features such as migration, weather-exposed capital stocks (including weather-driven depreciation), imperfectly competitive markets, constraints on adaptation, direct valuation of either climate or climate-exposed environmental stocks, climate affecting higher moments of the distribution of weather, learning about climate change, or a richer set of production inputs (to allow for changes in how labor is allocated across production of different goods, for instance).

input to production, and a change in that input can have first-order consequences on production. Direct damages have been the focus of extensive empirical research, as reviewed in Section 4.1. One example is that increased heat waves can reduce contemporaneous agricultural yields.

The other channels are forms of adaptation (thin black arrows in Figure 2; second and third terms on the right-hand side of equation (1)), as follows. The second channel is the transitory response of flexible, endogenous inputs (such as labor) to climate change. For instance, a farmer can change the timing of their planting. The third channel is how past choices have altered today's durable inputs that are fixed in the short run (such as capital stocks). An example is that farmers may have planted perennial crops in prior periods, whether anticipating climate change or in response to past climate change. And these two channels are related to one another. In particular, the transitory adaptation channel also depends in part on past durable input choices. Farmers may have dug wells in past periods, whether anticipating climate change or in response to past climate change, in turn allowing them to more easily water today's crops. Recent empirical research has prioritized a better understanding of adaptation, as reviewed in Section 4.2, although durable responses have been subject to less empirical research than transitory responses.

Section A of the Appendix shows that the adaptation terms in equation (1) combine responses to four different manifestations of climate change (the dashed black arrows in Figure 2): changes in present local weather; in future local weather; in past local weather; and in weather in other locations (present, future, and past).[5] Here we describe how these four kinds of weather all generate transitory adaptation by changing usage of labor, our flexible input. We also describe how two of these manifestations additionally contribute to durable adaptation by changing capital stocks, our durable input.

First, climate change alters contemporary local weather. The change in contemporary local weather may then directly alter the marginal product of labor; may alter the value of labor's marginal product by directly affecting the scale of local output and prices; and may alter expectations of later prices—and thus the incentives to allocate some labor to investment—by affecting investment decisions in the other region B. Some of these responses to contemporary, local changes in weather are the part of transitory adaptation that could be termed *ex post adaptation to a temporary change in local weather*.

Second, climate change affects present beliefs about future local weather. Climate change thereby alters the present incentives to devote labor towards investment versus output. In addition, investment in the other region may depend on present beliefs about local weather in this first region, and investment in this first region may respond to investment in the other region.[6] These responses

[5]If we were analyzing nonmarginal climate change, the adaptation term would contain higher-order terms that would include interactions between response channels.

[6]This mechanism is not explicitly depicted in Figure 2, which does not display investment in other regions.

to anticipated, local changes in weather are the parts of transitory adaptation that could be termed *ex ante adaptation to an anticipated change in local climate*.

Third, climate change is a process that may have been unspooling for quite a long while prior to any given time t. Climate change will then have altered local weather in prior periods (both realized past weather and past beliefs about subsequent weather). Those earlier changes in weather can affect the time t capital stock, in ways that contribute to durable adaptation but also to transitory adaptation via equilibrium choices over the flexible input. Section A of the Appendix shows that the effects of climate change on the time t capital stock ($\mathrm{d}K_t^A/\mathrm{d}C$) comprise the effects of climate change on investment in all earlier periods. As a result, the capital stock contains a memory of transitory adaptation ($\mathrm{d}\ell_{Yt}^A/\mathrm{d}C$) in those earlier periods, and thus of changes in all earlier periods' weather and beliefs. This altered capital stock affects output directly and also affects present labor choices. These responses (which include both ex ante and ex post adaptation) create a history dependence that has not been extensively researched.

Finally, climate change also affects weather elsewhere around the world (see Section 4.3). These changes contribute to both the transitory adaptation and durable adaptation terms in equation (1). These changes in nonlocal weather have temporal dimensions mirroring the foregoing discussion of changes in present, future, and past local weather: current changes in weather elsewhere on the planet affect local prices; anticipated changes in weather elsewhere on the planet affect local investment incentives; past changes in weather elsewhere around the planet affect capital stocks elsewhere around the planet and thereby affect local prices and local investment incentives; and all such changes can affect investment incentives elsewhere around the world and thereby affect local investment incentives. These responses to present, projected, and past changes in other regions' weather can be summarized as *adaptation to changes in other regions' climates*.

We have considered the effects of climate change on output, which in turn required considering the effects of climate change on fixed and variable factors of production. Effects on welfare are also important. In some ways, welfare expressions are simpler: some channels that matter for output may drop out by the envelope theorem. But many channels do remain: for example, the time t capital stock is predetermined as of time t, so past adaptation does not drop out via envelope theorem arguments (see Section A). However, welfare effects also raise thorny questions. Moving from output to welfare requires aggregating welfare across space (distributional weighting), across time (discounting or broader notions of intergenerational justice), across goods (valuing health and non-market environmental goods), across states of nature (accounting for risk, uncertainty, and the chance of catastrophe), and across dimensions of weather (including temperature, precipitation, sea level rise, and storms).[7]

[7] Prior surveys of these issues, which often go beyond the scope of this paper, cover inequality over space (Drupp et al., 2025; Kelleher, 2025); discounting (Dasgupta, 2008; Heal, 2009*a*; Gollier, 2013; Heal, 2017; Millner and Heal,

In sum, recovering the effects of climate change on output within our stylized framework requires recovering the following effects: (i) direct damages on output; (ii) transitory adaptation; and (iii) durable adaptation. The latter two are functions of past, present, and future weather, both in the region of interest and in other regions connected to it by trade networks. Each of the terms delineated above is likely to be nonzero in practice, but some may be relatively small in particular applications. We do not expect that any one empirical paper will nail down every one of these terms. Instead, we propose that a major goal for empirical work should be to establish which terms are likely to be important in which settings. And we propose that each piece of empirical work should be clear about which terms it captures and which terms it excludes and thus to what extent it captures the full effect of climate change. Being clear about which terms are excluded and included is sometimes tricky: for instance, as we discuss below, many empirical papers that appear to be estimating only direct damages may in practice be estimating combinations of direct damages and various types of adaptation, and papers that seek to understand adaptation might be better capturing one or the other of transitory and durable adaptation.

3 Methodological Choices: The Climate Impacts Trilemma

Almost every natural man that hears of hell, flatters himself that he shall escape it. . .
– Jonathan Edwards, *Sinners in the Hands of an Angry God*

Projecting climate change damages requires economists to causally link the distribution of temperature and other climate variables to outcomes in nature and society. We discuss prominent approaches through the lens of a trilemma: researchers desire methods that

(A) **are robust to economic model structure**—they are not overly reliant on particular assumptions about behavior, about functional form, or about the error distribution;

(B) **can be interpreted as the effect of widespread, persistent, anticipated climate change**—not only as the effect of temporary, local weather shocks; and

(C) **are econometrically well-identified**—they find internally valid causal estimates by isolating exogenous variation.

We argue that researchers can have at most two of these; they must accept the possibility of nonrobustness to economic model structure, of mismatch with climate variation, or of econometric confounding.

2023); nonmarket goods (Bastien-Olvera and Moore, 2022); and risk, uncertainty, and catastrophes (Pindyck, 2007; Weitzman, 2007; Pindyck, 2013; Heal and Millner, 2014; Heal, 2017; Lemoine and Rudik, 2017; Jensen and Traeger, 2024).

Figure 3 illustrates the trilemma. It locates six prominent papers from different eras of climate impact estimation within a triangle whose vertices correspond to the three desiderata. A paper that is closer to a given vertex does a better job, in our view, of achieving that desideratum. Section B of the Appendix details why we locate papers where we do.

Early work, typified here by Adams et al. (1988), adopted structural approaches that focused on capturing the widespread nature of climate change and some aspects of the persistence of climate change but were not identified in the modern econometric sense and relied on the assumptions embedded in a particular economic model. Subsequent papers, typified here by Mendelsohn, Nordhaus and Shaw (1994), adopted reduced-form cross-sectional methods that increased robustness to the particulars of the underlying economic model but gave up capturing the widespread nature of climate change and could not fully address omitted variable concerns fundamental to econometric identification. The next wave of papers, typified here by Schlenker and Roberts (2009), adopted reduced-form panel methods that emphasized econometric identification using local short-run weather shocks but, relative to cross-sectional methods, gave up capturing the persistent, anticipated nature of climate change.[8]

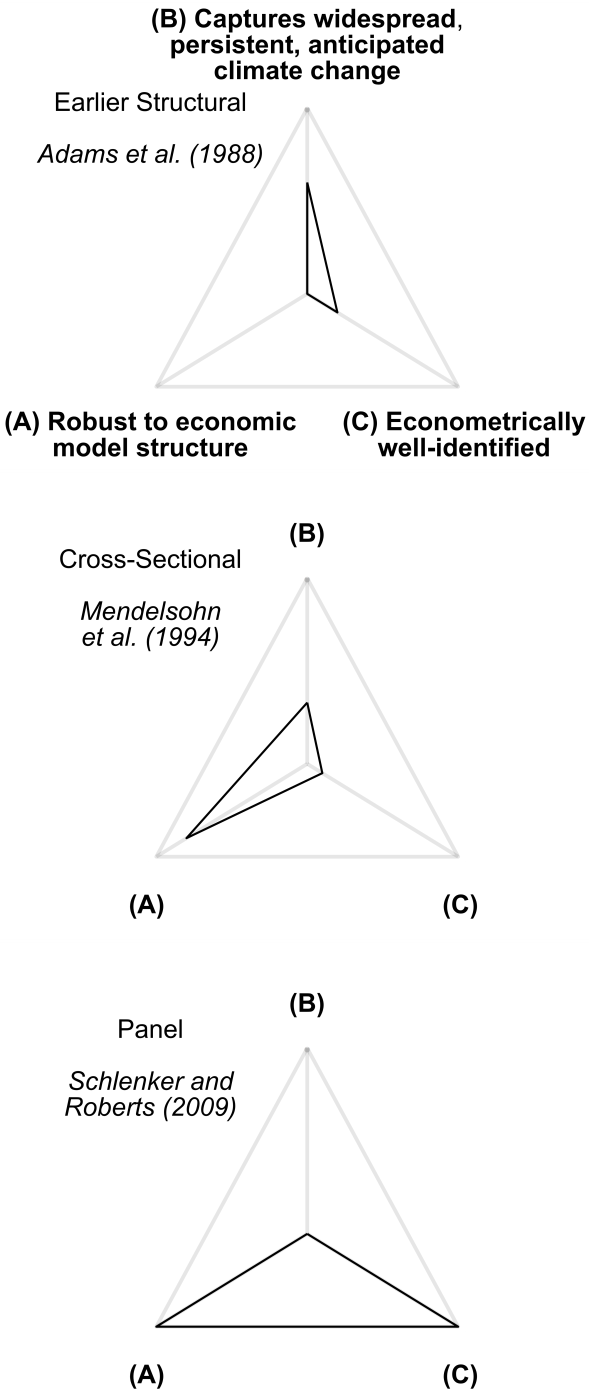
More recent work has responded to the inability of reduced-form panel methods to capture the widespread, persistent, and anticipated nature of climate change. To capture adaptation in response to persistent climate change, Carleton et al. (2022) combined reduced-form panel methods with cross-sectional variation to explore heterogeneity in panel responses, thereby reintroducing omitted variables concerns in identification. Cruz and Rossi-Hansberg (2024) added more structure to better capture the widespread, persistent nature of climate change, at the cost of model robustness. They devoted special attention to dynamics missing in some early structural work. Most recently, Bilal and Känzig (2024) implemented time series methods. These methods are analogous to cross-sectional methods in pulling back on panel identification in order to better capture important aspects of climate change, but whereas cross-sectional methods might capture the persistent nature of climate change, these time series methods might capture the widespread nature of climate change.

We next discuss each of these approaches in more detail.[9] To fix ideas, consider a researcher with data on output y_{it} and weather w_{it} in locations i and periods $t \in \{0, ..., T_0\}$. Each method below proposes different ways of using these data to project $\mathrm{d}y_{iT_1}/\,\mathrm{d}C$, where $T_1 > T_0$.

[8] The emphasis on econometric identification of causal effects (desideratum C) at the expense of interpretation for a policy-relevant counterfactual (desideratum B) is broadly familiar in economics (Heckman, 2000; Timmins and Schlenker, 2009).

[9] We leave aside expert elicitation papers, such as Pindyck (2019) and Moore et al. (2024). These remain subject to the trilemma to the extent that experts' views may be informed by the kinds of empirical papers we discuss.

Figure 3: The Climate Impacts Trilemma



Note: This figure visualizes the trilemma described in the main text: at most, a given paper fully achieves two of the three desiderata represented by the corners of this triangle. For six papers that use very different empirical approaches, we plot our subjective assessment of their weakest and strongest points related to the three desiderata. On the bottom left vertex, desideratum (A) refers to whether a paper is robust to economic model structure. At the top vertex, desideratum (B) refers to whether a paper captures widespread, persistent, anticipated climate change. On the bottom right vertex, desideratum (C) refers to whether a paper is econometrically well-identified. Section B of the Appendix contains verbal descriptions of our assessments.

3.1 Cross-Sectional Methods

A first line of inquiry compares outcomes across locations with different climates (for example, Mendelsohn, Nordhaus and Shaw, 1994; Nordhaus, 2006; Dell, Jones and Olken, 2009; Albouy et al., 2016), estimating regressions along the lines of:

$$\bar{y}_i = \beta^{cs}\bar{w}_i + \gamma X_i + \varepsilon_i, \tag{2}$$

with $\bar{y}_i$ and $\bar{w}_i$ indicating averages over time of y_{it} and w_{it}, X_i indicating a vector of covariates, and ε_i indicating an error term. If the error term is uncorrelated with the right-hand side variables, the estimated $\hat{\beta}^{cs}$ captures how changing average weather affects average output.[10]

When applying estimates of β^{cs} to climate change counterfactuals, the researcher implicitly changes historical weather in a given location while holding climates in all other locations fixed. These cross-sectional methods are robust to different models of how a change in local climate affects outcomes. These methods therefore can in principle satisfy desideratum (A).

Cross-sectional methods only partly satisfy desideratum (B). They permit counterfactuals that are clearly interpretable as changes in steady-state local climate.[11] However, to interpret these counterfactuals as changes in global climate, one must assume away all of the trade terms in equation (A-9) (see Gouel, 2025).[12]

Moreover, cross-sectional methods generate well-known econometric concerns and thus do not satisfy desideratum (C). First, climate is not randomly assigned around the planet, so comparing climates across locations does not constitute a natural experiment. As many papers point out, omitted variables that are correlated with climate are always a concern, no matter how many controls are included in X_i (Darwin, 1999; Hanemann, 2000; Schlenker, Hanemann and Fisher, 2005; Deschênes and Greenstone, 2007).

Second, the stable unit treatment value assumption (SUTVA) is unlikely to hold. Neighboring locations generally have correlated climates and contain suppliers, customers, and competitors for each other. Changes in one location's climate are therefore correlated with changes in nearby locations that affect the first location. This raises questions not just of interpretation but also of bias: by treating the neighboring locations as "control" units, the impact on the "treated" location

[10] Many notable papers in this literature are "hedonic" or "Ricardian" studies, which estimate effects on forward-looking metrics such as land value rather than output (Mendelsohn, Nordhaus and Shaw, 1994; Schlenker, Hanemann and Fisher, 2005; Severen, Costello and Deschênes, 2018). For reviews of Ricardian approaches, see Mendelsohn and Dinar (2009), De Salvo, Begalli and Signorello (2014), and Prakash et al. (2024).

[11] With one caveat: cross-sectional comparisons implicitly modify expectations of future weather, but people living with climate change may form expectations differently than people did in the past.

[12] An additional limitation to satisfying desideratum (B) is that timescales can matter: Dell, Jones and Olken (2014) argue that the effects estimated from a cross-sectional regression may be too long-run to be relevant to near-term climate change.

is estimated with bias (Deschenes and Meng, 2018). And as with bias from omitted variables, a SUTVA violation could generate bias that is either positive or negative.

Third, climate change is already happening and therefore is part of the sample researchers work with. For instance, land values should reflect climate change, both already realized and imminent. Severen, Costello and Deschênes (2018) show that cross-sectional estimates of the relationship between land prices and historical climate may not be appropriate for use in climate counterfactuals. They show that the proper calculation requires estimating the relationship between land values and expected future climate.

In sum, cross-sectional methods target the effects of climate change in the absence of flows across space via trade or migration, and they do so without imposing further theoretical restrictions, but they suffer on econometric identification and they miss the widespread nature of climate change. If we could sign the econometric bias in a given application of cross-sectional methods and also sign the bias from ignoring flows across space, then we might use cross-sectional methods to bound the effect of climate change, but these biases unfortunately tend to be of ambiguous sign.

3.2 Panel Methods

Reacting to econometric concerns with cross-sectional estimators, much of the literature in the last decade-plus has adopted methods that estimate the effects of varying a location's weather over time (Schlenker and Roberts, 2006; Deschênes and Greenstone, 2007; Schlenker and Roberts, 2009; Dell, Jones and Olken, 2012; Fisher et al., 2012). These studies typically estimate panel fixed effects regressions:

$$y_{it} = \beta^{panel} w_{it} + \delta_i + \nu_t + \varepsilon_{it}, \tag{3}$$

with δ_i a unit fixed effect to account for time-constant unobservables, ν_t a time fixed effect to account for common shocks across space, and ε_{it} an error term.

Rather than estimating the relationship between average weather and average output over space, this regression estimates the relationship between weather and output within units over time. It aims to isolate causal effects by looking at variation in weather that is unusual for a location and time period. The appeal of panel methods is that they are potentially well-identified, as high-frequency weather is arguably exogenously assigned. And panel methods identify the effects of weather without imposing a fully specified economic model of how weather affects the economy. They therefore aim to satisfy desiderata (A) and (C) when it comes to the effects of local weather.

Yet identification can still be a challenge in practice. For instance, time-varying confounders within a unit may cause omitted variables bias (Fisher et al., 2012; Blanc and Schlenker, 2017; Hogan and Schlenker, 2024). Including finer fixed effects or trends may better control for unobservable confounders, but measurement error may attenuate estimates more severely when useful variation is removed through fixed effects and trends (for example, Arellano, 2003). Researchers therefore face trade-offs in their choice of specification and controls, as mitigating the potential for time-varying confounders risks increasing the fraction of residual variation comprised of measurement error (Auffhammer and Schlenker, 2014; Blanc and Schlenker, 2017; Hogan and Schlenker, 2024).

In addition, weather anomalies are correlated over space (Auffhammer et al., 2013) and time. Following the above discussion of SUTVA violations in cross-sectional methods, the spatial correlation of weather anomalies potentially introduces a bias of unknown sign.[13]

But the primary challenge for panel methods arises in connecting the coefficients from panel regressions to widespread, persistent, anticipated climate change (desideratum (B)). Because example regression (3) does not control for how factor inputs respond to weather, the estimated $\hat{\beta}^{panel}$ captures, in the framework of Section 2,

$$\frac{\mathrm{d}Y_t^A}{\mathrm{d}w_t^A} = \underbrace{\frac{\partial Y_t^A}{\partial w_t^A}}_{\substack{\text{direct}\\ \text{damages}}} + \underbrace{\frac{\partial Y_t^A}{\partial \ell_{Yt}^A}\frac{\mathrm{d}\ell_{Yt}^A}{\mathrm{d}w_t^A}}_{\substack{\text{short-run, myopic}\\ \text{adaptation}}} . \tag{4}$$

Comparing to equation (1) and equation (A-9) of the Appendix Section A, the estimated effect includes the direct damages from weather on output and also the effect on inputs through current weather. By focusing on localized unusual weather, panel methods include adaptation that is short-run and myopic but miss the effect of climate change on past weather, on expectations of weather, and on weather in other locations (see equation (A-9)).[14] Indeed, omitting such adaptation is an oft-discussed drawback of panel methods, related to our discussion at the end of Section 2 (Deschênes and Greenstone, 2007; Dell, Jones and Olken, 2014; Massetti and Mendelsohn, 2018; Kolstad and Moore, 2020; Hogan and Schlenker, 2024). And panel methods do not typically estimate how climate alters output via changes to the incoming capital stock in equation (1). That is, a panel estimator reflects a localized, one-off, and potentially surprising weather change rather than the widespread, persistent, and anticipated change in weather produced by climate change.

To some, omitting much adaptation is a virtue of panel methods: an optimizing agent equates the marginal benefits and marginal costs of adaptation, so adaptation drops out of the full effect of climate change on an optimized object by an envelope theorem argument (for more on this argument, see Hsiang, 2016; Mérel, Paroissien and Gammans, 2024). However, it is important that researchers make clear what the optimization problem is. Otherwise, the envelope theorem argument can be misapplied in practice, as when the left-hand side variable is a choice variable

[13] See Zappala (2024) for recent work focused on SUTVA and Rudik et al. (2022) for a demonstration of that bias.

[14] See Shrader (2023) and Lemoine (2023) on using weather forecast data to capture effects of expectations of future weather in panel regressions.

such as agricultural yields or an intermediate object such as revenue or flow profit rather than an *optimized* object such as the present value of expected profits. In addition, the choice variable needs to be continuous and unconstrained, which is not the case in many adaptation applications (Guo and Costello, 2013).

More generally, the envelope theorem will not justify reducing the effect of climate change on output to equation (4) in a model with a future, a past, and regions interacting through trade (see Section 2 and Section A of the Appendix). In that case, panel methods do not satisfy desideratum (B). A one-off, surprising, and localized weather event differs from climate change in many of the ways that make climate change a hard problem. It is the *persistence* of climate change that makes it potentially so costly while also potentially making adaptation so critical, it is the *anticipated* nature of climate change that is the motivation for current policy, and it is the globally *widespread* nature of climate change that makes trade and migration complicated. To extrapolate panel estimates of altered output or adaptation choices to climate change, we have to assume that these three aspects of climate change are jointly small.

Recent work has turned to "long difference" methods in an attempt to escape the trilemma. Here the timestep of a panel regression is on the order of one to three decades rather than on the order of a day or year (as in Dell, Jones and Olken, 2012; Burke and Emerick, 2016).[15] The goal is to isolate variation due to climate trends. This work generally finds that long difference estimates are, in practice, similar to standard panel estimates (Dell, Jones and Olken, 2012; Burke and Emerick, 2016). This result could reflect a lack of adaptation to longer-run climate trends over and above adaptation to short-run weather shocks, the hypothesis favored by much of the literature. However, the similarity between these estimates is also consistent with another hypothesis. Long differencing does not eliminate the type of weather variation used in conventional panel estimates: at least some part—and frequently the bulk, or even all—of the identifying variation is based on what weather happened to be in the first and final intervals used to construct the difference, apart from any climate change that may have happened. The similarity of long difference estimates to standard panel estimates may then merely reflect that the underlying weather variation dominates any medium-run variation in climate trends (Lemoine, 2023).[16] Moreover, if long-run variation in temperatures is indeed present, it may be driven by latitudinal differences or otherwise correlated with regional patterns and may thus carry omitted variables bias (Kolstad and Moore, 2020; Hogan and Schlenker, 2024).[17]

[15] Repeat-Ricardian models (as in Bareille and Chakir, 2023) are conceptually similar.

[16] Finding stable estimates across varied estimation windows can still be consistent with short-run variation dominating long-run variation, as short-run shocks may induce similar types of identifying variation in each window.

[17] This may be true even with fixed effects. If, for instance, the fixed effects are at the state level, then the residual variation is driven more by geographically larger states that retain substantial within-state variation in latitude and other factors.

In sum, panel methods focus on obtaining well-identified estimates of weather impacts without imposing theoretical restrictions, although identification can be more complicated in practice. From these methods, we learn which types of weather variables are likely to be important channels for climate change. But to interpret their estimates in terms of climate change can require assuming away capital and resource stocks and assuming away flows across space via trade and migration.

3.3 Mixed Panel/Cross-Sectional Methods

Some work mixes panel and cross-sectional methods (Butler and Huybers, 2013; Auffhammer, 2022; Carleton et al., 2022; Hultgren et al., 2025), estimating regressions of the form:

$$y_{it} = \beta^{panel} w_{it} + \gamma^{cs,panel} \bar{w}_i w_{it} + \delta_i + \nu_t + \varepsilon_{it}. \tag{5}$$

This regression extends the benchmark panel regression (3) to include the interaction between a location's average weather and its weather shocks. The estimated $\hat{\beta}^{panel}$ captures short-run effects of weather shocks, and the estimated $\hat{\gamma}^{cs,panel}$ describes how those responses vary with local climate. This regression approach is intended to mitigate concerns about omitted variables bias relative to cross-sectional methods by considering only the cross-sectional component of panel variation, but it does not eliminate omitted variable concerns (Mendelsohn, 2019; Kolstad and Moore, 2020; Carleton et al., 2024; Hogan and Schlenker, 2024). As an example of this critique, Schlenker, Roberts and Lobell (2013) suggest that the reduced sensitivity of agriculture to heat in hotter locations may actually reflect differences in humidity.

The main conceptual question is whether we can mitigate the limitations of panel methods with respect to desideratum (B) by bringing in both the estimated $\hat{\beta}^{panel}$ and $\hat{\gamma}^{cs,panel}$. Identification to the side, the literature sometimes interprets the difference in the effects of weather between hotter and colder locations as evidence of adaptation. Phrased another way, the question is whether $\hat{\gamma}^{cs,panel}$ includes the terms in equation (1) that are missing from $\hat{\beta}^{panel}$ in equation (4), thereby making the experiment more comparable to that targeted by cross-sectional methods and to the actual effects of climate change.

Formally, the estimated $\hat{\gamma}^{cs,panel}$ from regression (5) is the cross-derivative of output with respect to weather and climate. $\hat{\gamma}^{cs,panel}$ therefore describes heterogeneity in the marginal effect of a one-off, surprising, localized weather shock. Such information may be useful when projecting consequences of nonmarginal climate change (Dell, Jones and Olken, 2012; Lemoine and Kapnick, 2016; Carleton et al., 2022; Hultgren et al., 2025). However, this cross-derivative is not part of the missing adaptation terms from equation (1), which are formally derived in Section A of the Appendix (see equation (A-9)). For instance, panel methods miss how past responses to weather and current responses to anticipated weather affect labor, capital, and output today. The formal expressions for these terms are not cross-derivatives of anything in equation (4) with respect to C.

Intuitively, the idea behind regression (5) is that long-run average weather captures adaptation that an agent makes with respect to their climate. The interaction with realized weather is then intended to capture how the effect of a local weather shock is altered by adaptation. The problem is that there are adaptation responses to climate change that impact output (or welfare) regardless of their mediating impact on current weather responses. For instance, imagine that climate change only mattered by depreciating capital stocks. In that case, $\hat{\beta}^{panel}$ and $\hat{\gamma}^{cs,panel}$ would both be zero because contemporary weather would have no immediate effect on production, but climate change would still eventually matter for production via the accumulation of capital consequences.

As another example, Schlenker, Roberts and Lobell (2013) imagine a case where agricultural yields are exactly zero in hot counties. Then the effect of heat on yields would be zero in those counties, which in equation (5) would suggest a high degree of adaptation. If we applied that zero marginal effect of heat to cold counties as they warm over time, then it would appear that adaptation would completely offset any negative effect of climate change. However, we would be missing the action in the fixed effects, which are also zero in hot counties. These would, if they were identified, suggest that climate change would in fact *eliminate* yields in cold counties. In both examples, regression (5) suggests no effects of climate change even though real-world effects could be large.

3.4 Time Series Methods

A few papers have relied on time series variation, putting global temperature (or other aggregated temperature) on the right-hand side of a regression equation (Bansal and Ochoa, 2011; Bansal, Kiku and Ochoa, 2016; Bilal and Känzig, 2024; Müller et al., 2025). This approach estimates a reduced-form relationship between global temperature variation and production and can thus satisfy desideratum (A).

The time series approach is the mirror image of the cross-sectional approach: whereas the cross-sectional approach aims to capture long-run effects by risking spatially-varying confounds, the time series approach aims to capture effects of nonlocal weather by risking time-varying confounds, whether common or unit-specific. And it does so with few data points compared to a standard cross-sectional analysis.

Three challenges for identification relate to isolating the component of global temperature changes that are true *shocks*. First, to attain desideratum (C), one has to believe that the temperature shock is not correlated with other drivers of the economy. As with the cross-sectional literature, mitigating omitted variables bias requires a suite of controls, and one can never be sure that one has included all necessary controls. Second, to attain desideratum (B), one has to believe that climate change causes a similar spatial pattern of weather changes as does the variation in global temperature used by the analyst (for instance, across low- versus high-income countries). Finally, to attain desideratum (B), one has to believe that the time series method (such as the filtration used to isolate shocks) reflects how agents really do form expectations over future weather. But there is a tension here. If the method does successfully isolate shocks, then the variation in global temperature used by the analyst is unlikely to match the persistent and anticipated nature of global climate change. But if the method does not successfully isolate shocks, then it does not attain desideratum (C), as it is not identified in the econometric sense.

3.5 Structural Methods

Many of the first attempts at estimating damages were structural models of agricultural production, which could include trade and long-run adaptation (Adams et al., 1988; Easterling et al., 1993; Rosenzweig and Iglesias, 1994). Some recent papers work to capture the spatial structure of climate change by directly modeling trade and migration flows (see Desmet and Rossi-Hansberg (2024) and Section 4.3 below). Other recent work attempts to capture the temporal structure of climate change by directly modeling adaptation investments (Fried, 2022; Hsiao, 2023; Balboni, 2025). In each case, a study specifies a model $M(w_{it}, C; \beta^{struct})$ that describes how something in the economy responds to weather or to expectations of weather. This model may be a system of equations or an optimization problem. It contains specific functional forms that are parameterized by a vector β^{struct}. The model implies an output response function m:

$$y_{it} = m\left(w_{it}, C; \beta^{struct}\right).$$

The parameters β^{struct} may be calibrated to data, drawn from theory, or estimated by fitting model output to moments of the data.

In principle, a properly specified and well-calibrated model yields a response function $m(\cdot, \cdot)$ that captures all of the channels derived in Section 2. Moreover, this method is capable of going beyond the local analysis of Section 2 to model the process of transitioning from one climate to another. Because the counterfactual construction is directly under the modeler's control, it can satisfy desideratum (B), although in practice many models do abstract from temporal or spatial effects. And the estimation might be done in an econometrically sophisticated way that attempts to satisfy desideratum (C) (Low and Meghir, 2017; Nakamura and Steinsson, 2018), although in practice many parameters are assumed or calibrated rather than estimated, and the identification challenges familiar from other methods arise here too.

However, these methods suffer on desideratum (A). They are only as good as the structural assumptions made about how economic outcomes respond to weather. We saw above that we would have to make strong assumptions about flows across space and about capital stocks to project climate impacts from cross-sectional or panel methods. Such projections therefore do impose a particular type of model behind the scenes, and that model might be restrictive or even unrealistic (trade and capital stocks are clearly important in the real world!). Paraphrasing and adapting Kleven (2021), cross-sectional and panel estimates of climate impacts are in fact "structural", in the sense of requiring theoretical restrictions in order to be interpretable in terms of climate change. Fully structural methods have the advantage of making their model assumptions explicit. However, fully structural models have to make many particular modeling choices. It can be difficult to evaluate the robustness of their conclusions to a broad class of alternate models. In contrast, cross-sectional and panel methods estimate the response function directly and thus are potentially robust to a broad set of underlying models.

In sum, structural methods can attempt counterfactuals beyond the reach of the other methods but are hard to verify as robust to a particular model structure. The natural experiment used in reduced-form research (weather shocks) is not externally valid for the question of policy interest (about climate change) (see also Nakamura and Steinsson, 2018). Imposing more structure can allow for construction of counterfactuals better resembling persistent, widespread, anticipated climate change—but at the cost of stronger assumptions on functional form and potentially weaker identification of causal effects. Estimates from natural experiments and structural approaches can therefore complement each other. Progress could be made in using moments in empirical data to discriminate among the models used to simulate climate impacts.

3.6 Structurally-Motivated Reduced-Form Methods

Some recent work attempts to combine the econometric identification and model robustness of panel methods with the advantages of structural methods for evaluating counterfactuals. These hybrid approaches specify an economic model but do not specify every functional form within that model. They impose enough theoretical restrictions to derive policy terms that are estimable from microeconomic empirical methods but impose few enough such restrictions that the results remain compatible with a set of structural models. These approaches are in the spirit of the minimal structure called for by Marschak's Maxim (Heckman, 2010) and in the spirit of sufficient statistics approaches in the public economics literature (Chetty, 2009; Kleven, 2021).[18]

Rudik et al. (2022) use migration choices to identify how intertemporal value changes with the climate. Migration is a forward-looking activity that reveals agents' assessments of intertemporal value in different regions. Using an envelope theorem argument, Rudik et al. (2022) show that when migration is optimized, the responses of migration shares to temperature shocks identify the

[18] Some have used envelope theorem arguments to justify using panel methods to obtain sufficient statistics for climate change impacts, but these arguments often start from restricted economic environments. The methods considered in this section start from more general environments, analogously to Kleven (2021).

effect of climate change on intertemporal value. They use these reduced-form estimates to validate their structural model, which imposes stronger restrictions on the economic environment.

Lemoine (2023) considers the effects of climate change on outcomes that are not subject to the envelope theorem. This paper aims to analytically derive the true effect of climate change within a dynamic environment, analytically derive the effects captured by coefficients from panel methods, and bound the true effect of climate change from functions of those estimated coefficients. Through this method, an empirical researcher recovers estimates of dynamic adaptation channels from a reduced-form regression.

Relative to structural methods, the researcher gives up some experimental control (falling shorter on desideratum (B)), as they are limited to counterfactuals attainable with panel methods' coefficients, but the researcher does gain a degree of model robustness (improving on desideratum (A)) and potentially improved identification (desideratum (C)). Relative to panel methods, the results are no longer as robust to the whole class of models that restrict the roles of spatial flows and capital stocks (falling shorter on desideratum (A)) but the results speak more directly to the effects of climate change (improving on desideratum (B)). In the future, these hybrid methods may be used as a check on whether persistence or spatial flows are important, and differences with structural methods may indicate when functional form assumptions are important.

3.7 Summary

We have seen that no one method has threaded the needle between being able to demonstrate robustness to the particulars of an economic model's structure; being able to capture the widespread, persistent, and anticipated nature of climate change; and being identified by data in the econometric sense. We argue that this trilemma is inescapable. Researchers must either try to extract the most comparable counterfactuals they can from the data they have or build a model to construct the counterfactual. In terms of individual desiderata, Figure 3 shows that papers have had the hardest time capturing all of the temporal and spatial dimensions of climate change (desideratum (B)). The way in which climate change affects all sectors, locations, and time periods is one of the reasons it is "a problem from hell." Early work tried to capture some of these dimensions of climate change without much focus on identification, work in the 2000s and 2010s emphasized identification at the cost of interpretability in terms of climate impacts, and recent work has attempted to blend identification with the economic forces that motivated early work. We believe that the recent increase in methodological diversity is healthy for the field and look forward to increased cross-fertilization and cross-checking across methodological approaches.

4 Evidence on Channels for Climate Damages

The conceptual model in Section 2 and the analysis in Section A of the Appendix show that the effects of climate change manifest through multiple channels: the direct damages from changes in local weather; agents' adaptation responses to past, present, and expected changes in local weather; and adaptation to changes in other locations' weather that spill over through trade or other spatial flows. Section 3 describes various methods used to identify some or all of these channels, highlighting the tradeoffs associated with each approach. We now review the literature on each of these three broad channels. Many of these papers span multiple channels; the goal is not to pigeonhole papers but rather to clarify how various strands relate to our theoretical model and to the methodological challenges we have highlighted.

4.1 Direct Damages

I heard many things in hell.

– Edgar Allen Poe, *The Tell-Tale Heart*

Much of the existing literature studies the immediate and direct damages from weather on economic outcomes. These papers aim to recover $\partial Y_t^A / \partial w_t^A$—for instance, the impact of weather on GDP or sectoral output—from the right-hand side of equation (1). They then scale these estimates by a modeled change in climate, θ^A, to project direct damages. We begin with the example of agricultural outcomes, typically measured via yields (i.e., output conditional on land inputs). We also review a closely related literature that examines the effects of weather on other measures of economic activity, in some cases reflecting productivity and in some cases reflecting a mix of output effects and adaptation actions.

Multiple excellent reviews have summarized the state of knowledge on direct damages (Dell, Jones and Olken, 2014; Carleton and Hsiang, 2016; National Academies of Sciences, Engineering, and Medicine, 2017; Auffhammer, 2018; IPCC, 2023). In their review, Carleton and Greenstone (2022) identify over 400 empirical studies published between 2010 and 2021. We do not comprehensively review the entire literature. Rather, we highlight key innovations in the estimation of these effects, and we discuss how, in some cases, identifying direct damages is inextricably linked to identifying adaptation and spillovers.

4.1.1 The Causal Revolution Comes to Climate Economics

Since the Dell, Jones and Olken (2014) review, progress has been made estimating the immediate and direct damages from weather on output using causal methods. This literature has applied methods and frameworks from the causal identification revolution that swept through applied microeconomics (Angrist and Pischke, 2010), in this case with the goal of deriving plausibly causal damage estimates using more comprehensive data and modern computing.

A rich literature that clearly aims to estimate direct damages is the one on climate impacts in the agricultural sector (for reviews, see Carter et al., 2018; Ortiz-Bobea, 2021; Bezner Kerr et al., 2022). We begin our review with that sector both because of the importance of climate impacts on agriculture and because of the way it exemplifies many important issues.

In an influential paper, Schlenker and Roberts (2009) leverage weather shocks in a fixed effects framework to estimate the impact of changes in temperature exposure across growing seasons on rainfed U.S. agricultural yields. (A reviewer pointed out that this exercise has an exceptionally long pedigree, with a closely related statistical analysis of the nonlinear effects of temperature on corn yields, Wallace (1920), conducted a century ago.) Schlenker and Roberts (2009) analyze effects on corn, soybean, and cotton yields. A key insight—and a running theme through much of the subsequent literature—is that the impacts of weather shocks are nonlinear. Up to a point, warmer weather improves crop yields. But very hot temperatures cause yields to decline steeply. The paper projects the effects of climate change by predicting changes in yields from the combination of the estimated temperature-yield relationship and warmer weather distributions. It projects severe U.S. crop yield declines under global warming because the relatively large, negative effect of more frequent hot temperatures outweighs the modest gain in yields from less frequent cold temperatures.

Schlenker and Roberts (2009) presage many of the debates that would follow: they qualitatively discuss—but do not estimate—the effect of adaptation, of other atmospheric variables like precipitation and CO_2 (for crop fertilization), and of price changes and other spillovers, as well as related consequences for food security. These debates followed in part because, as discussed in Section 3, their panel methods satisfy only two of the three desiderata (robust to economic model structure and well-identified, but not capturing widespread, persistent, anticipated climate change).

4.1.2 Parallels in Other Outcomes

Agriculture is not the only sector of the economy impacted by climate change. A robust literature estimates other impacts. Outcomes considered in this literature include energy use, labor productivity, climate amenities, capital costs, morbidity, mortality, and conflict. These outcomes do not correspond directly to output effects ($\partial Y_t^A/\partial w_t^A$)—in fact, changes to energy and healthcare use are adaptation effects—but they do illuminate mechanisms by which sectoral or aggregate output could be impacted in direct and immediate ways. We discuss these papers as part of the direct damages literature in line with how they have tended to situate themselves, before turning to a more comprehensive review of the adaptation literature.

Estimates for energy use or expenditures were, along with agricultural impacts, some of the earliest causally-identified impact estimates. Like the agricultural papers, much of this research shows U-shaped effects: going from very cold to moderately cold temperatures would bring benefits (in the form of reduced expenditures on heating), but beyond a threshold—in this case driven by ideal temperatures for human comfort—damages would be incurred because of increased expenditures on cooling. This nonlinearity implies that the direct effects of temperature on well-being are context-specific. They vary not only in magnitude but in sign, depending on a region's baseline temperature, on the region's mix of heating and cooling technologies, and on the time horizon of warming projections used. Davis and Gertler (2015), Auffhammer, Baylis and Hausman (2017), and Li, Pizer and Wu (2019) show that in countries as varied as Mexico, the U.S., and China, electricity expenditures are expected to rise with global warming because of increased air conditioning needs, but Wenz, Levermann and Auffhammer (2017) project decreases in electricity demand in Northern Europe. Rode et al. (2021) provide global estimates that account not only for electricity for space cooling and heating but also other fuels used for space heating. They project that energy expenditures will fall over the next century under either moderate- or high-emission scenarios, with electricity use increasing in most countries but outweighed by reduced consumption of other fuels (and with even reduced electricity use in a few northern countries).

A number of papers estimate labor market effects. This work originates with Graff Zivin and Neidell (2014), who estimate the effect of temperature on labor supply. Subsequent papers have estimated effects on human capital accumulation (Graff Zivin, Hsiang and Neidell, 2018; Park et al., 2020; Park, Behrer and Goodman, 2021) and on productivity or earnings (Behrer et al., 2021; Somanathan et al., 2021). This literature generally finds that heat stress lowers labor supply, labor productivity, and exam performance. Like the agricultural, energy, and mortality outcomes, labor productivity and learning may exhibit nonlinear effects, with damages increasing beyond 18 or so degrees Celsius (65 degrees Fahrenheit). A focus of much of this literature has been on distributional effects, with greater vulnerabilities for students in school districts without air conditioning and for outdoor workers. These results are consistent with inequality in the ability to adapt to heat and potentially in the ability to adapt to climate change, topics we return to below.

Some outcomes are more closely related to welfare effects, such as pleasure associated with climate amenities. Albouy et al. (2016) use cross-sectional methods and a hedonic framework to show that prime-aged U.S. households on average favor a daily average temperature of 18 degrees Celsius (65 degrees Fahrenheit) and that this preference shows up in their willingness to pay to live in warmer areas. Sinha, Caulkins and Cropper (2018) conduct a similar cross-sectional analysis within a static discrete choice framework that allows for moving costs. They find that U.S. households who tend to prefer milder winters also tend to prefer milder summers. Sinha, Caulkins and Cropper (2021) compare the hedonic and discrete choice approaches.

A finance literature parallels this direct damages line of research. Among other topics (see Giglio, Kelly and Stroebel, 2021), this literature considers how physical climate risks may differentially affect the cost of capital (Anttila-Hughes, 2016; Acharya et al., 2022), the riskiness of debt (Painter, 2020; Huynh and Xia, 2021; Nguyen et al., 2022; Goldsmith-Pinkham et al., 2023), or the value of coastal real estate (Bernstein, Gustafson and Lewis, 2019; Baldauf, Garlappi and Yannelis, 2020; Keys and Mulder, 2020; Bakkensen and Barrage, 2022).

4.1.3 A Recent Focus on Mortality

Since the Dell, Jones and Olken (2014) review, there has been an increased emphasis on mortality effects, which can be one of the largest contributors to total damages and which may carry special ethical significance.

Hot and cold weather both impact mortality. The increase in heat-related mortality around most of the world is projected to outweigh the reduction in cold-related mortality, leading to an overall increase in global mortality under projected climate change (Carleton et al., 2022). The Carleton et al. (2022) analysis is notable for its massive data collection (covering nearly 40 percent of the world's population) and its monetization of mortality impacts along with adaptation costs (see Section 4.2.2). Even more global data would be helpful for future analyses: lower-income countries and Southern hemisphere countries (including nearly all of Africa) tend to be missing. The authors project a large impact of climate change on mortality by the end of the century, valued at three percent of GDP in 2100. The authors also document spatial heterogeneity, as they project warming to lead to many more deaths in some countries than in others, based on how the temperature-mortality relationship varies with countries' climates and incomes. A limitation of the analysis is that it is unable to explore specific mechanisms: it leverages vital statistics data from many countries around the world, but these do not always have harmonized covariates.

Other papers have investigated mechanisms. Potential mechanisms for mortality effects include heat stress, disease, crime and conflict, suicides, and agricultural losses affecting subsistence or income. (We discuss mechanisms for offsetting those effects below when we review the adaptation literature.) Hsiang, Burke and Miguel (2013) and Burke, Hsiang and Miguel (2015*a*) summarize the literature on weather effects on crime and conflict, showing increases in both interpersonal crime and civil war with high temperature shocks. Some potential mechanisms are physiological: heat can increase aggression. Other potential mechanisms relate to income loss. Carleton (2017) and Burke et al. (2018) estimate effects of heat on suicide. Carleton (2017) finds that effects in India are driven by heat shocks during the growing season, consistent with weather-related shocks to agricultural income.

Morbidity is more challenging to study comprehensively because of the large number of non-fatal health outcomes that could potentially be affected. A large epidemiology literature studies morbidity from extreme heat (Bell, Gasparrini and Benjamin, 2024; Zhou et al., 2025). Economics papers estimating morbidity impacts include studies of hospital admissions (White, 2017; Karlsson and Ziebarth, 2018) and on-the-job injuries (Dillender, 2021). As with mortality, warming in some cases is projected to reduce morbidity. For instance, cold weather-induced illnesses may decrease, or some locations' temperatures may move away from the ideal temperature for malaria-carrying mosquitoes, although other locations potentially become more suitable for these mosquitoes (IPCC, 2022).

4.1.4 Effects on Aggregate GDP

We have thus far focused on the direct damages from weather in individual sectors, reflecting the bulk of the literature. However a smaller set of papers estimates the effects of temperature shocks directly on economic aggregates, such as national GDP (Dell, Jones and Olken, 2012; Burke, Hsiang and Miguel, 2015*b*; Newell, Prest and Sexton, 2021) or regional output and income (Deryugina and Hsiang, 2017; Colacito, Hoffmann and Phan, 2019; Kalkuhl and Wenz, 2020; Barker, 2022; Lemoine, 2023, 2025). As with disaggregated impacts, some of these papers have found U-shaped relationships that imply benefits in some places but costs at the global level. However these effects are estimated with much less precision than many of the disaggregated impacts and may not be robust to empirical choices (Newell, Prest and Sexton, 2021).

The literature has made progress on a fundamental question about whether climate change has a temporary or permanent effect on the growth rate of GDP. Following Casey, Fried and Goode (2023), we use the term "level effect" to mean that a permanent change in climate causes a temporary effect on GDP growth (but a permanent effect on the level of GDP—hence the name) and the term "growth effect" to indicate a permanent effect on GDP growth (implying a growing effect on the level of GDP).[19] The answer to this question is crucial: projecting impacts over the next 100 years results in very different damage estimates depending on whether the economy rebounds to its original level, stays at a permanently lower level, or grows at a permanently lower rate. Empirical approaches have tested—to the extent possible given limited time series data—for these different dynamic consequences of temperature. Nath, Ramey and Klenow (2024, p. 5-6) find that "a permanent change in a country's temperature has persistent medium term growth effects that eventually recede into long run level effects." Bastien-Olvera, Granella and Moore (2022) similarly find persistent effects. Other papers have used modeling frameworks to discipline the analysis (Kahn et al., 2021). Using an extended Solow growth model, Casey, Fried and Goode (2023) show that capital dynamics complicate interpreting regressions of output on temperature

[19]We note that key papers in this literature sometimes use these terms differently, and even inconsistently, in part because they analyze different time horizons (short-term effects versus the medium-term transition between states versus long-run/permanent effects); in part because they are sometimes unclear on whether the temperature shock they are modeling is temporary or permanent; and in part because limited time-series data can severely hamper the ability to separately identify temporary, permanent, and transition effects. Greater clarity and consistency of how each paper defines growth versus level effects may help resolve the outstanding questions in this area.

as evidence for either growth or level effects and that regressions using total factor productivity can better distinguish between level and growth effects. Implementing this regression, they find evidence of level effects (see also Harding et al., 2023).

4.1.5 Moving Forward With Direct Damages Estimation

Future empirical work could consider multiple dimensions of weather simultaneously and could seek empirically grounded estimates of non-weather impacts, such as from ocean acidification (see Doney et al., 2009). Existing work in economics that goes beyond temperature and sea level rise includes work on precipitation (Damania, Desbureaux and Zaveri, 2020; Palagi et al., 2022; Kotz, Levermann and Wenz, 2022; Hultgren et al., 2025); the interaction between temperature and humidity (Barreca, 2012; Wilson et al., 2024); the role of tropical cyclones (Bakkensen and Barrage, 2025; Ferreira, 2024); the role of soil moisture (Proctor et al., 2022); and the effect of a variety of climate variables on agriculture, including wind, humidity, evaporation, and CO_2 fertilization (Zhang, Zhang and Chen, 2017; Toreti et al., 2020).

In summary, weather matters. It matters directly for output and productivity in key sectors like agriculture as well as for health and mortality. The bulk of the literature has implied much higher direct damages from climate change than was previously believed. A missing component, though, is that these papers are generally unable to address the potential importance of adaptation effects and general equilibrium effects.[20] Moreover, these papers may even be mixing up adaptation and spatial spillovers with direct damages: the interpretation of a coefficient on, for instance, current temperature is complicated by the possibility that realized temperature correlates with drivers of adaptation such as forecasted or prior local temperature (Shrader, 2023; Lemoine, 2023) and with direct damages in other locations and sectors that spill over through trade and production networks (Rudik et al., 2022; Zappala, 2024; Lemoine, 2025). We next turn to emerging literatures on adaptation and spatial spillovers.

4.2 Adaptation

But in hell the torments cannot be overcome by habit.

– James Joyce, *A Portrait of the Artist as a Young Man*

Consider again a central challenge facing us when estimating damages: greenhouse gas emissions today cause changes to the climate that manifest within a decade and are essentially permanent from the perspective of economic decision-making. To fully understand damages, we need to know not only how the climate affects the economy today but also how those effects will change over the

[20] In principle, even non-market outcomes such as mortality could be affected by weather elsewhere, because all sorts of relevant goods are traded.

very long run. This implies all sorts of economic questions. How much time will people spend inside versus outside if the world is 3°C hotter? Will those indoor spaces be air conditioned? How will technological change, structural change, or other aspects of economic growth affect our sensitivity to the climate? How can policy hasten or hinder these changes? Seeking answers to these questions is the purview of the study of climate change adaptation.

Adaptation is contingent on all of the things that affect our ability and willingness to act, including the costs and benefits of action, beliefs, the availability of technology, and constraints. Despite a handful of existing reviews specifically on adaptation (Fankhauser, 2010, 2017; Massetti and Mendelsohn, 2018; IPCC, 2022; Carleton et al., 2024), and despite years of calls for more research on adaptation (Fisher and Hanemann, 1993; Mendelsohn, Nordhaus and Shaw, 1994; Hanemann, 2000; Burke et al., 2016), there are still many open questions in this area. Like Carleton et al. (2024), we divide these questions broadly by their policy import: how does adaptation affect the amount of damage from climate change and therefore the optimal mitigation path, and how can policy affect adaptation? Before turning to the challenges and progress on these two questions, we first clarify what is and is not climate adaptation.

4.2.1 Defining Adaptation

There are many definitions of "adaptation" to be found in the literature. As the model in Section 2 formalizes, we use adaptation to refer to actions that are taken in response to realized or anticipated changes in the climate. These actions can involve transitory responses, as denoted by the $\mathrm{d}\ell^A_{Yt}/\,\mathrm{d}C$ term from equation (1), and can show up in durable investments, captured by the $\mathrm{d}K^A_t/\,\mathrm{d}C$ term from equation (1).

Our definition of adaptation excludes actions that are *not* taken in response to changes in the climate. Many argue that societies will become less exposed to climate as they grow richer, making climate change less of a problem over the coming centuries (Ausubel, 1991; Schelling, 1992). For example, households are likely to adopt air conditioning because of both climate change and income growth (Davis and Gertler, 2015). We call the former effect "adaptation" and consider it part of the effect of climate change (and thus a function of today's emission decisions), and we call the latter effect an exogenous change in damages and consider it part of the background we must project when analyzing climate change (Carleton et al., 2024). Some studies estimate the sensitivity of the economy to temperature changes over time or space (Turner et al., 2012; Bleakley and Hong, 2017; Heutel, Miller and Molitor, 2021; Carleton et al., 2022; Burke et al., 2024). These studies can be important for determining that there is scope for adaptation and, under the assumption that the historical changes in sensitivity are caused by repeatable adaptations or other trends, for constructing projections of climate damages in the distant future. However, the detected changes need not themselves reflect adaptation, as they could be due to variation in non-climate factors.

Our definition does broadly capture *anything* an agent does to deliberately adjust to a changing climate. This leaves many actions to consider. Thinking just about the decisions a farmer might make to adapt to a hotter climate, they could make longer-term investments such as purchasing and learning to grow heat-resistant seed varieties; they could take short-term actions like changing the frequency of watering, pest control, or weeding; or they could engage in myriad other activities. It would be a daunting task to understand *all* of these adaptation actions, but for the goal of studying how adaptation affects damages (and therefore optimal mitigation policy), one does not need to delineate each of these individual actions. Instead, one needs to know how much damage is left over after people adapt and the aggregate cost of adaptation.

4.2.2 Understanding Adaptation to Project Damages

To project future damages and determine the appropriate stringency of mitigation policy, we need to estimate how evolving adaptation will affect damage. This effort is complicated by the interplay of the two. Expected future damages determine the incentive of agents to adapt, in turn affecting the damages that should be expected (Kahn, 2015). Because of the many challenges involved in projecting agents' decisions, climate change damage projections in the literature often do not explicitly represent adaptation (Nordhaus, 1992; Schlenker and Roberts, 2009).

Researchers have made progress identifying and characterizing adaptation actions. Some work explicitly links changes in behavior to weather variation, using that link to infer behavioral change under climate change. Examples of these actions include time use (Graff Zivin and Neidell, 2014), employment (Downey, Lind and Shrader, 2023), use of healthcare (Mullins and White, 2020), and migration (Missirian and Schlenker, 2017). Other work examines changes to the economy that have had the effect of changing our sensitivity to the climate, without explicitly decomposing those changes into adaptation per se versus exogenous changes. Examples include Barreca et al. (2016), who examine air conditioning adoption; Rising and Devineni (2020), who examine crop switching; and Sloat et al. (2020), who examine farm relocation. A third set of papers seeks to characterize overall adaptation benefits and costs, without specifying individual actions. Examples include Carleton et al. (2022) and Shrader, Bakkensen and Lemoine (2023) on mortality, and Hultgren et al. (2025) on agriculture. Finally, structural models that include adaptation actions have been used to assess both the effectiveness and cost of adaptation, albeit while needing to specify the set of adaptation options (Bareille and Chakir, 2024).

Much of the work cited above studies responses, whether short- or long-run, to short-run weather shocks. All such responses are part of overall adaptation, but responses to longer-run changes in weather are also needed to provide a complete picture. Lemoine (2023) shows that the bias from assuming that long-run adaptation is identical to short-run adaptation depends on whether actions are intertemporal substitutes (as when accessing depletable resources) or intertemporal complements (as under adjustment costs). A classic example is irrigation for agriculture (Auffhammer and Schlenker, 2014; Blanc and Schlenker, 2017). In the short run, greater irrigation can help farmers maintain production through a drought. But if climate change makes dry conditions occur with greater frequency, water for irrigation might run out, removing irrigation as an available adaptation action. In this depletable resource case, short-run adaptation estimates *overstate* the amount of adaptation in the long run. The reverse can also be true. In the face of adjustment costs, agents will generally adapt more to a permanent shock compared to a temporary shock. Short-run adaptation estimates may then *understate* the amount of adaptation in the long run. In the irrigation example, agents may install new irrigation systems or drill deeper wells when they either experience or anticipate experiencing regularly hot, dry conditions (for empirical work in agriculture, see Hornbeck and Keskin, 2014; Hagerty, 2022). Determining how much adaptation is of the depletable resource type versus the adjustment cost type is important for projecting future climate damages.

Researchers have made more progress studying adaptation in the context of persistent, anticipated changes in the probability of extreme events. When climate change makes these events more likely, adaptation can include investing in resilience. Fried (2022) and Bakkensen and Barrage (2025) study how households adapt to storm risk. The former models how households and firms invest in adaptation capital such as a seawall that mitigates damage from a storm and analyzes the interaction between adaptation investment and disaster aid policies. The latter demonstrate that greater storm risk increases precautionary savings and, potentially, growth in between storms, even as realized storm strikes destroy capital. The effects of climate change on storm risk encompass both channels, whereas cross-sectional and panel regressions tend to emphasize one or the other. Firms can also increase resilience to extreme weather by diversifying the locations of their plants (Castro-Vincenzi, 2024), by diversifying their supply chains (Balboni, Boehm and Waseem, 2024; Castro-Vincenzi et al., 2024; Pankratz and Schiller, 2024), by establishing bank credit lines (Brown, Gustafson and Ivanov, 2021), and by using financial derivatives tied to weather outcomes (Pérez-González and Yun, 2013). However, even where firms allocate capital efficiently ex ante, extreme weather can make capital inefficiently distributed ex post (Liu and Xu, 2025).

Directed technical change in response to climate change is also a form of long-run adaptation. For projections of climate change damage over hundreds of years, such adaptation is likely to be especially important. But it is also especially hard to investigate using any single empirical approach. Plant breeders and farmers have been able to adapt to substantially different geographic climates, but this adaptation takes time (Olmstead and Rhode, 2008, 2011), at least with breeding techniques available in the past. Moscona and Sastry (2023) show that recent U.S. crop breeding efforts have been directed towards crops that have been more exposed to extreme heat. These crop innovations are a form of adaptation. The model in Moscona and Sastry (2023) indicates that this adaptation does substantially reduce the effects of climate change on U.S. agriculture. Future work could consider tradeoffs between traits that enable climate adaptation and other traits and how these tradeoffs interact with farmers' preferences over the mean and variance of yields (Gollin, 2011).

Beyond the responses discussed above, there are further nuances: (1) climate change affects volatility in both weather and climate; (2) potential tipping points raise questions about the scope and speed of adaptation; and (3) history dependence of economic systems may constrain or facilitate adaptation.

An agent facing risk or ambiguity from climate change may invest in shorter-lived capital stocks or may invest in resilience to a wide variety of potential different climates (Fankhauser, Smith and Tol, 1999). Such decisions can be affected by the expectation of having forecasts before extreme events occur (Millner and Heyen, 2021). For instance, more accurate forecasts of weather and seasonal climate can reduce risk and facilitate shorter-run adaptation (Shrader, 2023; Downey, Lind and Shrader, 2023; Burlig et al., 2024). Financial markets can also be important tools through which agents achieve financial resilience: investors may choose their portfolios so as to financially hedge climate risks (Engle et al., 2020), homeowners may choose mortgages that implicitly insure them against sea level risks (Bakkensen, Phan and Wong, 2025), and countries may use disaster insurance to spread the cost of rebuilding capital stocks after natural disasters and may use catastrophe bonds to reduce borrowing costs that were elevated by disaster risk (Phan and Schwartzman, 2024).

Climate change also has the potential to trigger large changes in the earth system via tipping points, causing large or catastrophic damages and raising questions about the efficacy of different adaptation strategies. A small literature has studied damages from tipping points in simulation models. In some papers, tipping points cause exogenously specified damages that do not depend on adaptation (e.g, Cai, Lenton and Lontzek, 2016; Cai and Lontzek, 2019). In other papers, the damages induced by triggering a tipping point emerge endogenously from changes in the earth system and economic reactions to them. Some of these papers model the process of tipping, varying in whether the path of future climate is optimized using that knowledge (Nordhaus, 2019*b*) or whether that process is taken as exogenous (Dietz et al., 2021). In other of these papers, the tipping process is a stylized switch in the dynamics of the climate system, with the focus on uncertainty and learning about that switch (Lemoine and Traeger, 2014, 2016). Adaptation is possible both in advance of happening to flip the switch and in reaction to having flipped it. The potential need for large adjustments to the capital stock in response to having crossed a tipping point may make early warning signals—and ex-ante adaptation based on them—especially important.

The final nuance introduced by the dynamic nature of adaptation is in the way past responses to weather can constrain or facilitate actions taken in the present and future (the durable adaptation term in Section 2). The history of local weather can affect the local capital stock both through ex post adaptation and through local beliefs about climate change—although these effects may not have yet added much to the effects of climate change on local income (Lemoine, 2025). Fried (2022) estimates that adaptation investments to storm risk already comprise 1% of the U.S. capital stock and projects that climate change could roughly double that amount. Hsiao (2023) demonstrates a feedback loop when governments cannot commit to their future adaptation plans: public adaptation investments in the form of sea walls can spur private capital investment that justifies subsequent public adaptation investments. Balboni (2025) shows that adaptation to current coastlines constrains the benefits of investing in road networks that would be less vulnerable to future flooding. As discussed below in Section 4.3.2, Desmet et al. (2021) show how the dynamics of innovation and migration make the damages from a given amount of sea level rise depend on the history of how the seas rose to that point.

4.2.3 The Many Roles of Adaptation Costs

Beyond adaptation actions and their benefits, the costs of adaptation are important to study because they constrain adaptation actions, thus determining how much damage will occur, and because they constitute a potentially avoidable cost of climate change. Early work on climate damages did account for adaptation costs within simulation models, but the level of adaptation was fixed exogenously (Fankhauser and Tol, 1996). In more recent literature, costs of adaptation have not received as much empirical attention as the benefits of adaptation.

Costs are challenging to observe in relevant datasets. Two of the most-studied climate impacts—agricultural yields and mortality—illustrate this challenge. In both cases, the economic outcome is relatively well-measured across many countries around the world, permitting estimates of direct damages and adaptation benefits. In contrast, the costs of inputs in the agricultural sector are not as widely observed, and the range of adaptation actions that affect mortality is not well-established, much less the costs of those actions.[21]

In response to this challenge, Carleton et al. (2022) and Hultgren et al. (2025) back out adaptation costs from their estimated marginal benefits. Their approach assumes that agents optimize fully and completely to every instant's climate along a trajectory of climate change—and do so without needing to care that an instant's climate holds only for that instant.[22] In that case, they show that we

[21]Consider, for instance, that shifting when activities take place during the day is likely to be a simple but important adaptation to prevent heat-related mortality. Yet standard approaches to the valuation of time based on wage rates would say that such time-shifting has no net cost.

[22]More precisely, this approach assumes that: (i) adaptation is an optimized, continuous choice that is made in the absence of constraints and is not primarily biophysical; (ii) adaptation is a function of climate but not of weather realizations; and (iii) adaptation is completely transient. Under these assumptions, (1) agents maximize an adaptation trajectory pointwise and (2) the adaptation trajectory chosen by an agent experiencing a change in climate over time is equivalent to the adaptation trajectory reconstructed from agents living in different climates today. (See Section C of the Appendix for a formal derivation, and see Mérel, Paroissien and Gammans (2024) for a critique of how this approach treats weather variability.) In practice, Carleton et al. (2022) do estimate positive net benefits to adaptation. They argue that adaptation becomes inframarginal at later points in time. However, if adaptation is a stock that accumulates rather

can proxy each agent's experience of climate change over time by the experiences of agents who currently live in a sequence of different climates (we provide an alternative formalization of their argument in Section C of the Appendix). In other words, identification of adaptation comes from assuming that differences observed across space provide a valid proxy for the effect of differences in climate that agents will face over time. The experiences of agents who currently live in a sequence of different climates can in turn be recovered from a regression like equation (5), subject to usual caveats about omitted variables bias.

Richer data on costs would allow for direct estimation of the marginal costs of adaptation. Recent work by Du Puy and Shrader (2024) pursues this agenda for the agricultural sector in France, a setting with particularly complete data on costs. The paper finds that marginal costs of adaptation are low in the year a temperature shock arrives but the cost of adapting to the past shock gradually rises over subsequent years. This finding highlights the intertemporal tradeoffs involved in adaptation decisions. This intertemporal complexity becomes particularly important when adaptation involves capital investments or migration, a point exemplified by potential adaptation to sea level rise (Fried, 2022; Hsiao, 2023; Balboni, 2025). Data on additional sectors and locations would allow for further estimates along these lines.

The empirical work above focuses on private costs of adaptation, and others have discussed whether private costs of adaptation would or would not, based on envelope theorem logic, enter social cost of carbon calculations. However, some adaptation actions may impose substantial externalities, which would not be subject to the envelope theorem unless internalized by policy. In particular, Deschenes (2022) shows that the external pollution-related costs of adaptation to heat through electricity use may be quite large in comparison to the private costs.

Finally, adjustment costs are an especially understudied class of adaptation costs. Adjustment costs include costs incurred in the process of transitioning from one equilibrium climate to another. They therefore always increase the cost of climate change relative to a world where adjustment is possible but costless. Adjustment costs also include the costs of handling more volatile weather within a given climate (see Downey, Lind and Shrader, 2023, for the construction sector) and of learning about the new climate (Kelly, Kolstad and Mitchell, 2005). Adjustment costs mean that hot weather can be beneficial for agriculture when typical but deleterious when unusual (Kelly, Kolstad and Mitchell, 2005). Responses of county-level income to weather shocks are consistent with adjustment costs in aggregate capital stocks and therefore with long-run adaptation exceeding short-run adaptation (Lemoine, 2023). In the big picture, climate change may amount to a massive adjustment cost problem, as the new climate may or may not be objectively inferior to the original one in terms of the eventual, super-long-run economic and ecological equilibrium (Quiggin

than being completely transient, then forward-looking agents should choose adaptation in awareness of the trajectory of climate change and the derivation no longer holds.

and Horowitz, 1999, 2003; Kelly, Kolstad and Mitchell, 2005). With that view, understanding adjustment costs becomes crucial to understanding climate damages.

4.2.4 Adaptation Policy

Public policy can affect adaptation. It is therefore important to understand the effectiveness of adaptation in different contexts, opportunities for policy to encourage adaptation, and how policy might inadvertently stymie adaptation. Adaptation has received far less policy focus than mitigation, but as climate change continues, this balance is likely to shift.

Successful adaptation policy faces multiple challenges. Fankhauser, Smith and Tol (1999) observe that timely adaptation requires a combination of information, incentives, and capacity. More accurate information, available further in advance of climate shocks, can help agents smooth their adjustment over time, and reductions in adjustment costs can also help lower the cost of adaptation.

In addition, good adaptation policy requires going beyond the total benefits or costs of adaptation that are relevant to the study of mitigation. Deciding which adaptation actions to promote requires information on the tradeoffs involved in different actions. To inform policy, research needs to address the effectiveness, costs, and market failures surrounding these different adaptation options. For instance, the literature on coastal erosion has maintained a particular focus on policy and on dynamic adjustment (Gopalakrishnan et al., 2016). Carleton et al. (2024) review the adaptation literature, focusing particular attention on studies that inform adaptation policy and the ways research in this area can be strengthened.

Policy can impede adaptation or even induce apparent maladaptation.[23] Scholars have long discussed how agricultural policies, in particular, may impede adaptation (Lewandrowski and Brazee, 1993). Distortions to adaptation have been studied for subsidized agricultural, fire, and flood insurance, subsidized defensive investments, and agricultural price support policies (Kousky, Luttmer and Zeckhauser, 2006; Wagner, 2022; Obolensky, 2024; Baylis and Boomhower, 2023; Fried, 2022; Hsiao, Moscona and Sastry, 2024).

4.3 Spillovers: Trade, Migration, and More

Hell is—other people!

[23] Maladaptation refers to actions that make agents more vulnerable to climate shocks (Barnett and O'Neill, 2010; Schipper, 2020). Fankhauser and Tol (1996) also apply the term to mismatches between adaptation and the current climate due to imperfect information about climate change or due to a fast rate of climate change. Hornbeck and Keskin (2014) document a case where farmers adapt to increased availability of groundwater by growing crops that *increase* their sensitivity to the climate. This behavior can be welfare-maximizing for an agent even as it increases climate damage.

– Jean-Paul Sartre, *No Exit*

The literatures on direct damages and adaptation largely focus on how climate change in a location impacts output and welfare by altering weather in that same region. But markets link inputs and outputs across space via trade and migration. The effects of climate change on some particular region therefore must account for how climate change's effects on weather in other regions spill over into the first region (see Deschenes and Meng, 2018). In the model of Section 2, the impact of climate change on variable inputs in region A ($\mathrm{d}\ell^A_{Yt}/\,\mathrm{d}C$ from equation (1)) depends, via trade, on how climate change impacts current, past, and future weather in other locations (see equation (A-9)). A relatively mature literature, dating to at least Kokoski and Smith (1987) and summarized in Tol (2009), studies climate change within general equilibrium models. An emerging literature leverages advances in spatial economics to analyze trade and migration in a fashion that is both fine-grained and causally informed.[24] For a recent review dedicated to the new spatial-climate literature, see Desmet and Rossi-Hansberg (2024); for a recent review of dynamic spatial models with an emphasis on climate change applications, see Desmet and Parro (2025); for a macro-oriented review covering trade, migration, and capital reallocation, see Bilal and Stock (2026); and for reviews of migration and climate change, see Millock (2015), Berlemann and Steinhardt (2017), and Cattaneo et al. (2019).

4.3.1 Spatial Linkages Missed by the Direct Damages Literature

As early as Cline (1996), it has been argued that the direct damages papers described in Section 4.1 assume constant prices and thus miss welfare impacts that could come from equilibrium effects on relative prices. This can lead to underestimation of climate damages, if assuming constant prices leads the researcher to ignore changes in consumer welfare. Conversely, ignoring substituting behavior on the part of consumers can lead to overestimation of climate damages. Gouel (2025) summarizes these arguments in the context of trade in the agricultural sector.

A recent spatial literature naturally incorporates price effects, as it models the optimization behavior of both supply- and demand-side agents in a general equilibrium framework. Desmet and Rossi-Hansberg (2015) develop a calibrated spatial endogenous growth model, with iceberg costs of trade. They explore the implications of a coarse border between the global North and global South that hinders trade and migration. The authors argue that trade in goods directly protects against climate damages, and that trade responds as climate change impacts comparative advantage

[24] A distinct literature studies how the spatial distribution of climate change affects optimal and feasible mitigation policies (Nordhaus and Yang, 1996; Brock, Engström and Xepapadeas, 2014; Krusell and Smith, 2022). Benveniste, Oppenheimer and Fleurbaey (2020) integrate international migration into an IAM and study the costs of restrictive border policies. They determine migration from a reduced-form gravity model. The papers we discuss below explicitly represent migrants' decision problems.

around the world.[25] Within their stylized model, the authors show that the evolution of comparative advantage can lead high latitudes to specialize in agriculture and low latitudes to specialize in industry. Although this model is too stylized to yield ballpark estimates of climate impacts, it does suggest that general equilibrium channels should not be ignored.

4.3.2 Trade and Migration as a Form of Adaptation

Costinot, Donaldson and Smith (2016) seek to understand the interaction of climate change and trade within the agricultural sector. The authors estimate their model with fine-scaled agricultural data on ten major crops for 50 countries (subsequently extended by Gouel and Laborde (2021) to include more crops and countries). The authors calibrate crop productivity to output from an agronomic model. The agronomic model has perfect, costless adaptation in the use of inputs for growing each crop, and the authors' model has perfect, costless adaptation in the choice of crop to grow. The authors conduct counterfactual analyses in which they turn off either trade or cross-crop adaptation. Within their model, the ability to adapt to climate change by switching crops reverses much of the damages from a warming world. In contrast, trade flows do not have a substantial impact on climate damages. Intuitively, reconciling their model with the relatively small agricultural trade flows observed in the data requires large trade costs (or a strong preference for domestic products). When they turn off trade adjustments, they implicitly raise trade costs to infinity. Because their calibrated trade costs are already large, their calculated effect of trade is relatively small.[26] An idealized comparison of frictionless trade with a no-trade-adjustment scenario would be more in keeping with their idealized adaptation counterfactual.

Desmet et al. (2021) emphasize how the evolution of comparative advantage mitigates climate damages. The authors leverage the model of Desmet, Nagy and Rossi-Hansberg (2018) to calibrate the impact of sea level rise. Within their model, innovation is local and correlated across locations. Labor can move across locations and is a source of new ideas. As discussed below, model assumptions make optimal innovation and migration choices equivalent to myopic ones, so that agents are unconcerned about future climate change when making either choice.

In their model, innovation and migration responses greatly reduce aggregate losses from coastal

[25] Krusell and Smith (2022) model how trade in capital ownership rights via a global bond market can similarly protect against climate damages.

[26] Their no-trade-adjustment scenario is hard to interpret as a pure change in trade costs because it fixes each crop's *share* of a country's exports. This counterfactual therefore does allow trade in crops to evolve with climate change, with the pattern of that adjustment restricted by the assumption of fixed shares. By including some trade adjustment in level terms, their no-trade-adjustment scenario again favors finding a small role for trade when compared to their reference scenario. Gouel and Laborde (2021) show that turning off trade adjustment is much more costly when the counterfactual instead fixes *bilateral* import shares. In this case, each country buys food from each other country in the same proportion as before, as opposed to constraining only each country's crop-level exports while allowing those exports to be reallocated across countries.

flooding by reallocating economic activity. In particular, the slow nature of sea level rise allows innovations to accumulate in clusters further inland. As people and innovative activities relocate, they increase inland stocks of knowledge, which in turn makes inland locations even better at innovating in later periods. These dynamics were missing from earlier studies of sea level rise with static computable general equilibrium models (Bosello, Roson and Tol, 2007). These dynamics mean that damages in a future year are determined by the full history of sea level rise, not just by the contemporary level of sea level rise. More gradual trajectories allow coastal knowledge stocks to migrate before they are lost. The authors argue that the loss of agglomeration economies in coastal locations is partly offset by the appearance of agglomeration economies in inland locations and by the ability of inland knowledge stocks to compound. Importantly, these estimates ignore the possibility that climate change may introduce new frictions in housing markets and new political economy considerations that may hinder efficient movements. Others have found such factors to be empirically important to sea level rise (Bakkensen and Barrage, 2022; Hsiao, 2023; Balboni, 2025).

Costinot, Donaldson and Smith (2016) and Desmet et al. (2021) also emphasize spatial heterogeneity of impacts, with implications for global inequality. Both papers find regions with benefits from climate change, regions with moderate losses, and regions with substantial losses. Spatial heterogeneity is not in itself a new finding: we described above how many direct damages papers also find unequal outcomes across regions, and some integrated assessment model have long included regional damages. The contribution of the recent literature is to show that impacts vary not just mechanically with baseline climate, income, or the rate of warming but also with how changes in climate around the world change comparative advantage and factor distribution. In Desmet and Rossi-Hansberg (2015), lower latitudes become more industrial not because they get better at making stuff but because they become less agriculturally productive even as higher latitudes become more agriculturally productive. And in Desmet et al. (2021), inland places each gain a little not because sea level rise benefits them directly (indeed, there is no direct effect of sea level rise on inland places) but because economic activity moves inland in response to realized sea level rise. Capturing the evolution of comparative advantage and factor distribution requires a modeling framework that links locations to each other.

4.3.3 Agriculture and Trade

Some have argued that impacts on agriculture have limited importance to developed countries—and potentially to a future, richer world—because agriculture comprises a small share of GDP (Nordhaus, 1991; Schelling, 1992). However, demand for agricultural goods is highly inelastic and production of some crops is very spatially concentrated. As a result, weather shocks in particular locations can have major impacts on consumers worldwide via agricultural markets (Cline, 1996;

Roberts and Schlenker, 2010).

The direct damages literature summarized in Section 4.1 has made progress estimating how weather impacts agricultural productivity, but along the way it lost an older focus on how local shocks can propagate through agricultural markets. Early work embedded crop responses in trade models and concluded that adjustments through trade would substantially buffer impacts on agricultural productivity and that agricultural price changes would affect which countries are winners and losers from climate change (Kane, Reilly and Tobey, 1992; Tobey, Reilly and Kane, 1992; Reilly and Hohmann, 1993; Reilly, Hohmann and Kane, 1994). Early work also emphasized the potential for large welfare impacts stemming from relative price changes driving increases in hunger and food insecurity (Rosenzweig and Parry, 1994; Cline, 1996).

A recent literature has undertaken a more complete appraisal of agricultural impacts, emphasizing the role of trade and the incidence of impacts on the developing world (reviewed by Gaigné and Gouel, 2022). Building on longstanding insights (from, for instance, Adams et al., 1998), Moore et al. (2017) show that the price changes induced by widespread climate change are critical for its incidence. When crop productivity decreases, the corresponding increase in crop prices tends to benefit agricultural exporters (and in particular tends to benefit farmers). An analysis that treated climate change as only a localized shock would miss this effect on prices (see also Cline, 1996). Consistent with this story, Lemoine (2025) estimates that purely local extreme heat reduces income by more in more agricultural U.S. counties, whereas these same counties are less exposed than other counties to income loss from widespread extreme heat.

In a hybrid approach that combines reduced-form causal inference and trade modeling, Dingel and Meng (2025) show that spatial correlation in crop productivity induced by the El Niño Southern Oscillation (ENSO) increases gains from trade in more productive countries and reduces gains from trade in less productive countries. That spatial correlation thereby increases cross-country inequality in welfare.

Some scientists believe that it is technically possible (albeit potentially costly) to adapt enough to offset global food losses from moderate climate change (see Vermeulen, Campbell and Ingram (2012, p. 210), although IPCC (2022) projects stronger constraints). In that case, trade barriers loom large as a source of regional food losses. Several papers show that reducing barriers to trade could be an especially important form of adaptation policy in agriculture. In general, trade adjusts to changes in comparative advantage, which in turn depend on how agricultural productivity changes in comparison to productivity in manufacturing and services.

Nath (2025) shows that trade barriers become especially costly for countries whose populations are close to subsistence levels. He shows with panel regressions that climate change should reduce productivity in non-agricultural sectors of poorer countries by less than prior literature suggested agricultural productivity would fall. One might therefore expect poorer countries to substitute towards non-agricultural production and import more food, but trade barriers can hinder this adjustment. Moreover, when consumers with nonhomothetic utility functions place a high premium on having enough food to meet a subsistence need, Nath (2025) shows that the combination of reduced local agricultural productivity and an inability to trade can actually lead poorer counties to specialize in agriculture *even more* under climate change.[27]

Other work shows that trade barriers are important determinants of how agricultural markets adapt to climate change. Conte (2022) shows that, within sub-Saharan Africa, climate change will cause less migration and generate less unequal outcomes if agricultural trade barriers can be reduced. To ground counterfactuals in policy rather than idealized experiments, this paper simulates reducing migration and trade barriers from their estimated levels within sub-Saharan Africa to estimated levels within the European Union.

Agricultural and trade policies may interact with climate change (Lewandrowski and Brazee, 1993; Reilly, 2011). Hsiao, Moscona and Sastry (2024) empirically study how agricultural trade barriers serve as endogenous policy choices. They show in reduced-form regressions that agricultural support responds differently to temporary shocks to local and foreign food production, with local extreme heat shocks leading to pro-consumer local policies such as reduced tariffs and additional export restrictions and foreign extreme heat shocks leading to pro-producer local policies that support output.[28] Because climate change is widespread, it is a priori unclear which type of policy response dominates. When they use their estimated responses to short-run weather shocks to investigate long-run climate change, governments' responses to the effects of climate change on foreign producers improve welfare whereas governments' responses to the effects of climate change on domestic producers worsen welfare, primarily by changing trade policies. Simulations suggest that agricultural policy responses on net increase losses from climate change.

These recent papers are closely related to Costinot, Donaldson and Smith (2016). They embed reduced-form evidence in a static model that allows them to discuss spatial spillovers. They take the details of agriculture seriously but represent the rest of the economy in a more stylized fashion. Another strand of recent literature is more closely related to Desmet et al. (2021). It is more thoroughly structural, which allows for more comprehensive coverage at the cost of more particular assumptions about the economic environment. We turn to it next.

[27] In a model with homothetic (Cobb-Douglas) preferences, Conte et al. (2021) find that a cluster of agricultural specialization would emerge in sub-Saharan Africa in the absence of climate change but that climate change shifts this cluster elsewhere. These losses are not compensated by specialization in non-agricultural production, due to the low initial productivity of the non-agricultural sector relative to its productivity in other regions and to the relatively low optimal temperature for the non-agricultural sector.

[28] Their empirical design does not distinguish between direct reactions to unfavorable weather and strategic reactions to others' reactions to unfavorable weather. Their estimated reactions are a composite of these potential policy drivers.

4.3.4 Broadening the Analysis of Spatial Linkages

The early spatial spillovers papers tend to focus on one or two spatial spillovers and to construct models in which the expectation of future climate change is irrelevant to decision-making. New and ongoing work attempts to broaden these models.

Cruz and Rossi-Hansberg (2024) develop an integrated assessment model that adds costly trade to the representations of migration and innovation from Desmet et al. (2021). They find that global losses from warming are just about equally split between hits to amenities and hits to productivity. Within their model, migration is a more important channel of adjustment than trade: because most trade is local and climate change is spatially correlated, trade is of limited utility for adaptation.[29]

Rudik et al. (2022) abstract from innovation and investment in order to introduce production networks (i.e., input-output linkages among sectors and locations) and households who account for future climate change when migrating. They find a roughly 3 percentage point loss to U.S. welfare from climate change, driven by hits to amenities that overwhelm gains to productivity. The global losses are substantially larger. In both cases, a substantial portion of the welfare loss comes from within-year temperature extremes. Adaptation makes U.S. losses around 1 percentage point smaller than they otherwise would be, and forward-looking behavior by households accounts for around a quarter of the adaptation benefit.

Bilal and Rossi-Hansberg (2023) study the effects of storms and heat waves in the U.S. They abstract from costly trade and innovation in order to introduce forward-looking capital investment and forward-looking migration. They show that storms substantially reduce welfare by depreciating capital. They also show that making households and firms ignorant of future climate change would alter migration flows by reducing the incentive to move, both directly and by misallocating capital investment towards exposed regions.

All three of these papers tie their models' parameterization to causally-informed reduced-form estimation. By inverting their model and solving the resulting system of equations, Cruz and Rossi-Hansberg (2024) obtain the grid cell-level amenities and productivities that rationalize gridded population and economic data in 1990, 1995, 2000, and 2005. They then regress these parameters on temperature within a panel environment in order to estimate damage functions.[30] Rudik et al. (2022) express their model's equilibrium conditions for trade and migration in a form amenable to panel estimation of the effects of temperature on, respectively, productivity and amenities. Bilal and Rossi-Hansberg (2023) invert a steady-state in their model to recover a set of parameters conditional on investment and migration elasticities. They pin these elasticities down by indirect inference,

[29]Burzyński et al. (2022) project that climate-induced migration will be small relative to other migration pressures and that it does not greatly help the people most severely affected by climate change.

[30]The temperature variable in Cruz and Rossi-Hansberg (2024) differs from nearly all other literature: they use winter (January or July, depending on the hemisphere) temperature over a decade. Most other literature uses annual temperature constructed from all months.

seeking to make event study responses within their model consistent with event study responses in the data. Those responses are expressed in relative terms (i.e., relative to income per capita and investment), which permits them to use responses in level terms to identify damage functions.[31]

Importantly, these three papers imply different magnitudes of global climate damages, although direct comparison is complicated by the fact that they examine different end-point years and different temperature change scenarios. Rudik et al. (2022) estimate that U.S. welfare is reduced by 3% and global welfare by 21% by 2100 for RCP 4.5 (i.e., with global warming of around 2.5 to 3°C). Bilal and Rossi-Hansberg (2023) estimate that U.S. welfare is reduced by more than 10% for both workers and capitalists by 2100 for a global temperature increase of 4°C. Cruz and Rossi-Hansberg (2024) estimate that global welfare is reduced by 10% by 2200 but for RCP 8.5 (i.e., with global warming of around 7°C by 2200). More work is needed to yield a consensus on how various adaptation mechanisms and spatial spillovers interact and to be able to quantify global damages under different emission pathways.

4.3.5 Limitations of Early Work

The early spatial spillovers papers each introduce new spatial considerations to adaptation and impacts. To do so, they dramatically simplify the time dimension of adaptation, with the effect of climate via past and future weather assumed to be zero.

Costinot, Donaldson and Smith (2016) optimize static adaptation decisions using an agronomic model. A limitation of their approach is that it has zero cost to adjusting which crops are planted.[32] Because their data are purely cross-sectional, they cannot estimate any such adjustment costs. In their no-adaptation scenario, Costinot, Donaldson and Smith (2016) hold crop shares fixed (implicitly increasing the cost of adjusting crop choices from zero to infinity) while farming inputs are still re-optimized.

In Desmet and Rossi-Hansberg (2015), innovations become available to all firms in a location (and diffuse to firms in nearby locations) after one period, so that innovation decisions are not forward-looking.[33] And migration is costless when feasible, so workers can optimally choose where to locate in a myopic fashion. As a consequence, no actors in the model make forward-looking decisions that account for the trajectory of warming. That is, decisions are dynamic in the

[31] SUTVA may not hold in a general equilibrium context, so Bilal and Rossi-Hansberg (2023) do not just feed reduced-form regression coefficients into their model. Instead, they replicate the regression within their model and match its coefficient.

[32] Discussing an early analysis of agricultural damages that used analogous assumptions, Fisher and Hanemann (1993, p. 142) observe, "It is our hunch that some of the most important impacts of climate change arise because of the effect on capital stocks which, if not destroyed, are rendered prematurely obsolete. The costs of these effects depends critically on their timing relative to the normal replacement cycle of the affected capital."

[33] The rents here accrue to land rather than firms, but the endpoint of static innovation decisions mimics the endpoint of assuming one-period patents in the macro-climate literature (as in Acemoglu et al., 2012).

sense that they evolve with warming but are not dynamic in the sense that they do not depend on beliefs about how variables such as temperature will evolve in subsequent periods.

Desmet et al. (2021) introduce costly migration, but their economic environment makes all migration and innovation decisions optimally equivalent to myopic decisions: migration imposes flow costs of staying away from one's original home (as opposed to one-time moving costs) that are independent of any prior moves (as opposed to resetting to one's most recent home), and innovations again diffuse freely across time periods. These assumptions make the anticipation of future sea level rise irrelevant within the authors' model. Moreover, the postulated migration cost structure means that labor suffers no direct losses from slowly moving in step with sea level rise rather than waiting to move inland in fewer, larger steps. These migration incentives slow the formation of economic clusters deep inland but, via the spatially correlated specification of productivity, permit coastal knowledge stocks to migrate inland along with the labor force. Similar dynamics were at play in earlier analyses of sea level damage. Fisher and Hanemann (1993, p. 139) state that such analysis "implicitly assumes a smooth and efficient adjustment process that minimizes the damage: after tract A . . . is flooded, tract B becomes shoreline, and everybody dutifully moves over one tract to the right. Regrettably, this does not describe the world as we know it. . . . The inability to respond effectively is a cost of doing business that has to be included in any estimate of the economic impacts of global climate change."

The more recent papers generalize some of these assumptions, leading to some qualitatively different results. For instance, Bilal and Rossi-Hansberg (2023) find a smaller value of migration than in prior work with households whose optimization leads them to ignore the future. Part of this is because people will not move as much in models that do not assume that moving costs can be reversed in a subsequent move, and part of this is because the net benefits from adjusting migration are smaller once migration patterns are intertemporally optimized.[34]

4.3.6 Potential Progress for Spatial Work

Progress is being made, and can continue to be made, on understanding the spatial consequences of climate change.

Existing papers each abstract from potentially important channels, whether production networks, costly trade, capital investment, or the forward-looking nature of migration or innovation. It is not yet clear which of these channels are more quantitatively important and more critical to include going forward. Moreover, because these models are estimated using their own equilibrium conditions,

[34] In an alternative approach that yields a higher value of migration, Baluja (2024) combines a structural model of migration and wages, microdata on households, and climate modeling data (for variation in expected weather) to study the role of beliefs about future climate change in driving climate migration within Mexico. The use of microdata allows for estimation of heterogeneity within the population, particularly in the costs of migrating (see also Mathes, 2025).

it is unclear how abstracting from some channels affects a model's calibration of other channels. For instance, estimates of local productivities may be sensitive to whether equilibrium conditions account for trade, investment, or innovation.

Second, recent papers are limited by the data available. Papers that undertake gridded global analyses typically use the G-Econ database, which contains estimates of economic output at the 1-degree longitude by 1-degree latitude scale (Nordhaus, 2006). These estimates are constructed by multiplying grid-level population by per-capita output, where the latter is taken from regional output data (for instance, at the level of political subdivisions for high-income countries, but at the urban versus rural level for lower-income countries). The estimates of output in much of the world are thereby tied to proportional scaling rules of varying coarseness.

Systematic errors in gridded or subnational data could propagate into estimated model parameters, an issue that has affected analyses using the DOSE subnational GDP dataset (Bearpark, Hogan and Hsiang, 2025). In addition, spatial autocorrelation must be carefully accounted for in inference when using fine-grained data (Schötz, 2025). When subnational—especially downscaled—data do not accurately represent the true underlying variation, bias can ensue. In other cases, model equations require data on variables such as population flows that restrict the geographic scope of the application (Rudik et al., 2022). And data at the resolution of individuals or properties will have restricted geographic coverage (Hsiao, 2023; Baluja, 2024). In contrast to economic data, many weather variables are fairly well-measured on fine grids with comprehensive geographical coverage (see Auffhammer et al., 2013), although quality is lower in places like Africa with lower density of weather monitoring infrastructure (Dinku, 2019).

Third, there are many ways to specify temperature variables (for model selection, see Akyapı, Bellon and Massetti, 2025; Hultgren et al., 2025). Papers should be clear about why they make particular functional form and aggregation decisions.[35] In addition, a substantial fraction of real-world impacts may be determined not by the level of temperature in a given year but by how fast temperature is changing (Fankhauser and Tol, 1996) or by the variability of temperature (Kelly, Kolstad and Mitchell, 2005; Lemoine and Kapnick, 2016; Kotz et al., 2021; Linsenmeier, 2023). The rate and variability of warming become especially important when models have adjustment costs.

Fourth, the papers in the spatial spillovers literature tend to emphasize the dynamic aspects of spatial variables such as migration over the dynamic aspects of other forms of adaptation such as local capital investment. Yet not only are the past and future terms in equation (A-9) potentially relevant in their own right, the spatial effects of interest to this literature should comprise dynamic adaptation in other locations.

[35] For instance, Colacito, Hoffmann and Phan (2019) relate impacts to summer temperature whereas Cruz and Rossi-Hansberg (2024) relate impacts to winter temperature.

Fifth, these papers tend to work with tractable special cases, but it could be important to generalize some assumptions. For instance, the few papers that study climate change in the context of production networks assume Cobb-Douglas forms (for instance, Rudik et al., 2022; Zappala, 2024). Permitting complementarities would change the degree to which effects on one location or sector are transmitted to others and also change the pattern of that transmission (see Baqaee and Farhi, 2019).

Sixth, these papers tend to treat spatial linkages as reflecting first-order concerns about comparative advantage. However, spatial linkages may also reflect second-order, insurance motivations. For instance, in Castro-Vincenzi et al. (2024), firms trade to diversify risks, which has the side effect of amplifying inequality in climate impacts. And in Balboni, Boehm and Waseem (2024), firms adjust the number and composition of their suppliers with an eye towards how flood-prone their suppliers are and also how flood-prone their connecting routes to those suppliers are.

Seventh, these papers could do more to transparently identify key parameters. In particular, much work in the new spatial-climate literature identifies trade and migration costs with the residuals implied by observed trade and population patterns. These residuals are determined by the rest of the model. There can even be enough free parameters to fit the data perfectly. In that sense, the trade and migration costs that are so critical to this literature are closer to calibrated than empirically identified. In addition, these residuals are not structural. They are a reduced-form composite of multiple structural elements, and some of those structural elements may be endogenous to climate change. For instance, tariff policies are likely a critical component of calibrated trade barriers, but Hsiao, Moscona and Sastry (2024) show that these tariff policies themselves respond to weather shocks. Future work should consider ways of identifying migration and trade costs from variation in data, which may require using microeconomic data. Such work has been undertaken at the level of individual countries (Baluja, 2024; Mathes, 2025), but undertaking it at the global level will require novel modeling choices or novel empirical approaches.

Finally, one primary motivation for constructing a structural model is to be able to evaluate novel policy counterfactuals. To date, many papers focus on constructing damage estimates and measuring channels by taking, for instance, migration or trade costs to arbitrarily high or low levels (for an exception, see Conte, 2022). Future work could seek to calibrate the parameters of policy counterfactuals to match relevant real-world policies.

4.4 The Social Cost of Carbon and Policy Updates

Researchers have been working to update the social cost of carbon (SCC) to reflect the wealth of new evidence on climate damages. The SCC monetizes the reduction in welfare from emitting one more unit of carbon dioxide along a predefined emission pathway, based on embedding damage estimates into a larger model that takes a stand on the elements depicted in gray in Figure 2 and described in footnote 7 (Nordhaus, 2014, 2019*a*). In the absence of other externalities or fiscal considerations, the SCC equals the optimal carbon tax along the optimal emission pathway. The SCC is widely used in policy evaluation, both for formal cost-benefit analysis by administrative agencies and in the academic literature. Around 15 years ago, the U.S. government undertook a significant interagency effort to develop a SCC that could harmonize various governmental applications (Greenstone, Kopits and Wolverton, 2013; Metcalf and Stock, 2017). Its central value was $21 per ton of CO_2 (2007 U.S. dollars, around $34 in 2025 dollars), with sensitivity analysis conducted at higher and lower values (which were tied to discount rate and damage considerations). This central value was applied in subsequent regulatory analyses and informed legal challenges (Metcalf and Stock, 2017).

Over the subsequent decade, there were widespread calls for methodological and conceptual updates to the federal government's SCC estimate. Most notably, the National Academies (NASEM) released a report with detailed recommendations (National Academies of Sciences, Engineering, and Medicine, 2017). One recommendation was to break integrated assessment models up into modules (corresponding to socioeconomic projections, climate models, damages, and discounting) so that individual components could be independently updated by subject-area experts.

One team of researchers, Rennert et al. (2022), implemented the NASEM recommendations, releasing the open-source model GIVE (Greenhouse gas Impact Value Estimator). This model uses damage estimates based on existing publications. For example, the agricultural damages are based on Moore et al. (2017), which we discussed above. A second team, the Climate Impact Lab (CIL), estimated damages for various parts of the economy. Above we have discussed their estimates of damages due to energy costs (Rode et al., 2021), mortality (Carleton et al., 2022), and agriculture (Hultgren et al., 2025). The damage estimates from these two teams of researchers make different choices about how to navigate the trilemma discussed in Section 3.

Policymakers have paid close attention to these empirical and conceptual updates. In 2023, the U.S. Environmental Protection Agency released new estimates of the SCC, based on a meta-analysis (Howard and Sterner, 2017) as well as inputs from GIVE and CIL. These SCC estimates leverage some of the damage estimates we evaluate in the preceding sections. Environmental policy bodies in Germany and Switzerland have used the GIVE model to produce SCC estimates but have made different normative choices around, for instance, distributional weighting (UBA, 2024; Ecoplan and INFRAS, 2024).[36] The U.S. EPA analysis gives a central SCC estimate of $190 per ton of CO_2 (in 2020 dollars) for emissions in 2020 using a near-term discount rate of 2%, or around $240 per ton of CO_2 in 2025 dollars. They also give a wide distribution of possible values, in their Figure

[36]Policymakers in some countries including the U.K. and France instead follow an emissions target-abatement cost approach to try to avoid the issue of uncertainty in damages (RFF and NYSERDA, 2021), although determining an appropriate target makes grappling with damages unavoidable.

3.1.1 (EPA, 2023).

5 Room for Future Work

Long is the way
And hard, that out of Hell leads up to Light.

– John Milton, *Paradise Lost*

Dell, Jones and Olken (2014) proposed that future work should emphasize spatial spillovers, mechanisms, and longer-run effects. We have described recent, initial progress on the first of these goals, aiming to capture the widespread nature of climate change. We have described some progress on the second of these goals, with a need for more progress in order to reinforce causal understanding. And we have highlighted the importance of the third of these goals for capturing the anticipated and persistent nature of climate change. In addition to these high-level goals carried over from Dell, Jones and Olken (2014), we here propose concrete directions for future work. We begin with what we see as primarily extensions of existing analysis and proceed to areas more conceptually distinct from the bulk of existing literature.

Impacts on Infrastructure and Other Durables. Whereas direct damages have been robustly analyzed for many areas of the economy, effects on long-term investment have been less well studied. For instance, construction has not been extensively studied. Construction labor productivity may be impacted by outdoor temperatures, but that is not the whole story. New construction may be needed to deal with climate-related natural disasters, and persistent climate change is likely to change the desired composition of construction activity across places.

Comprehensive Estimates Using Spatial Models. A key aim of the direct damages literature and associated integrated assessment models has been to work towards harmonized estimates of expected future climate damages, frequently presented in terms of end-of-century percentage of GDP losses. The spatial models we have surveyed suggest that the direct damages literature is missing important economic forces, but this spatial literature has not yet produced consensus estimates of how spatial spillovers and dynamic effects change end-of-century impacts. The initial papers report negligible climate damages (Desmet and Rossi-Hansberg, 2015, for instance), but some more recent papers suggest impacts in the range of 3-20% of welfare, relative to a counterfactual without climate change (Rudik et al., 2022; Bilal and Rossi-Hansberg, 2023). Cruz and Rossi-Hansberg (2024) estimate smaller damages, and both Bilal and Rossi-Hansberg (2023) and Cruz and Rossi-Hansberg (2024) emphasize the uncertainty in their estimates. With only a handful of spatial papers attempting to provide comprehensive end-of-century estimates, it is hard to know how much weight to put on these numbers or how to compare them to the direct damages literature.

Financial Markets as a Channel for Capital Reallocation. There is a large, and to date parallel, literature on the financial effects of climate change (Giglio, Kelly and Stroebel, 2021). We have discussed climate change consequences that are called "physical risks" in the climate finance literature (Carney, 2015). Within our conceptual framework in Section 2, financial markets could act as a channel for reallocating capital.

Tipping Points. Even over short periods of time, changes in the climate need not be small or smooth (Lenton et al., 2008; Armstrong McKay et al., 2022; Wang et al., 2023). Tipping points—such as the collapse of the Atlantic meridional overturning circulation (AMOC, related to the Gulf Stream)—raise the threat of rapid, large-magnitude changes or catastrophic impacts that could have especially severe consequences in a world with large adjustment costs. Recent work has made technical progress incorporating tipping points into climate IAMs (reviewed in Kopits, Marten and Wolverton, 2014; Li, Crépin and Lindahl, 2024; Jensen and Traeger, 2024). Existing work has used simplified models of tipping processes, impacts, and information, partly as a result of the state of scientific knowledge and partly as a result of limitations in economic models (Kopits, Marten and Wolverton, 2014). The new spatial models could be critical to estimating how various tipping points would change damage relationships, especially as many tipping points change the spatial pattern of climate change. And in the presence of adjustment costs, the ability of society to forecast and observe tipping points becomes critical. Further work on tipping points is of renewed importance because of recent natural science evidence showing larger probabilities of triggering important tipping points (Armstrong McKay et al., 2022; Wang et al., 2023; van Westen, Kliphuis and Dijkstra, 2024).

Natural Capital. Following the literature to date, we have emphasized market damages from climate change. However, the focus on market damages risks missing the forest for the timber. Come what may, the Earth will lose a substantial fraction of its natural heritage (Urban, 2015; IPCC, 2018). In time, new arrangements of species and ecosystems will emerge, but whereas the process of adjustment for human systems may take decades, the process of adjustment for natural systems may take millennia. Valuing projected changes in ecosystems and natural capital requires valuing changes in both their use values (as inputs to production) and their non-use values (as goods people care about directly) (see Krutilla, 1967; Hanley and Perrings, 2019; Bastien-Olvera and Moore, 2020). Prior work has formally explored discounting under damages to natural capital (Hoel and Sterner, 2007; Heal, 2009*b*; Gollier, 2010) and numerically assessed implications for the social cost of carbon (Tol, 1994; Sterner and Persson, 2008; Brooks and Newbold, 2014; Bastien-Olvera and Moore, 2020; Drupp and Hänsel, 2021). A key empirical question concerns the degree to which specific types of natural capital are essential in production and how that substitutability may change as the level of natural capital declines (see Cohen, Hepburn and Teytelboym, 2019). Future work could additionally consider the non-use costs of large-scale environmental change and how non-use preferences evolve as the environment changes. It is important to obtain a sense of the scale of non-use costs, as there is a chance that focusing on more readily measured market impacts misses the major part of the story.

Model Evaluation. It is important to probe whether the structure and calibration of models are sensible. Climate science relies heavily on structural models based on physical relationships, and there has long been an emphasis on evaluating these models through benchmark simulations (Tebaldi and Knutti, 2007; Taylor, Stouffer and Meehl, 2012). The AgMIP project (AgMIP, 2025) progresses in this direction for agricultural models of climate impacts. But climate economics more broadly lacks a set of benchmark simulations. For instance, perhaps well-calibrated economic models should be able to simulate economic responses to seasonal climate patterns such as El Niño or to major volcanic eruptions, without having used those same phenomena in calibration. Or perhaps models calibrated to microdata from some region or time period should be able to recreate aggregate data from other regions and time periods. Without established benchmarks, tests of external validity run the risk of cherry-picking and it becomes difficult to assess models' relative accuracy.

Using Multiple Approaches to Get a Richer Picture. We have emphasized that no one approach is likely to robustly and credibly estimate impacts that match those of widespread, persistent, anticipated climate change (see Section 3). A combination of approaches could provide a fruitful path toward improving our understanding of some issues we raise (see also Timmins and Schlenker, 2009; Todd and Wolpin, 2023). As Imbens (2010) discusses, there is a rich—if relatively recent—history in economics of using experiments and quasi-experiments to aid identification in structural models, an approach that could hold promise for the study of climate damages. There may also be room for new sources of quasi-experimental variation, taking advantage of the fact that climate change is here now. For instance, researchers may either find or create quasi-exogenous variation in information about future climate change and assess how information affects adaptation choices (see Haaland, Roth and Wohlfart, 2023). Or researchers may take advantage of quasi-exogenous variation in public adaptation projects to estimate their influence on climate impacts and individuals' choices (as in Kelly and Molina, 2023). We anticipate the emergence of creative quasi-experimental designs in the coming years.

6 Concluding Discussion

The path to paradise begins in hell.

– Dante Alighieri, *Inferno*

New science on climate change continues to emerge, and understanding of the economic implications continues to evolve. We have reviewed recent advances in this literature, emphasizing that we have learned a great deal over the last decade about direct damages, about the potential for adaptation, and about how direct damages can be mitigated or amplified by spatial linkages such as global trade.

There has been particularly substantial progress isolating the effects of one-off, potentially surprising, and localized weather shocks. A key remaining challenge is learning about substantive questions involving persistent, anticipated, and widespread changes in climate. A restored focus on matching the persistent, anticipated, and widespread nature of climate change can help in this endeavor, not by leaving the insights of the causal revolution behind, but by integrating causal identification into economic models of climate change impacts.

Beyond the concrete next steps from Section 5, deeper challenges remain. Projecting the damages from climate change is hard in part because it is fundamentally forward-looking: scientists anticipate future physical changes to the climate system that society can react to and that are out-of-sample from what we can observe in human history. But it is not only the forward-looking nature of climate change damage estimation that challenges economists. Isolating the effects of climate change is intrinsically hard.

Imagine that we are looking back from 2100, wondering how much climate change has cost to date. Even at that point, it would be challenging to robustly and credibly identify the effects of the climate change that occurred. We would still face econometric concerns when using cross-sectional variation, interpretation concerns when using panel variation, and model robustness concerns when specifying formal structure. Given this difficulty, we should not expect to obtain firm estimates of the cost of future climate change with the limited data we have in the 2020s. Several implications follow.

First, it is valuable to pursue diverse research methods, as no one approach will be the one to get it all right. We should not require any single paper to do everything, and we should encourage work on ways to combine methods. For instance, structural models can target moments that correspond to the identification strategies used in cross-sectional and panel methods. It is important to assess how large a role various model assumptions may play in qualitative conclusions and which types of effects are likely to be large or small in practice.

Second, it is critical to develop distributions of damages that contain a more complete accounting of uncertainty. Recent work has studied how uncertainty affects the social cost of carbon (Jensen and Traeger, 2024). And recent governmental updates to the social cost of carbon incorporate econometric uncertainty (as well as other sources of uncertainty, such as from socioeconomic and climatic projections), based on sampling variation in panel estimators (EPA, 2023). We have seen that each existing approach to estimating damages imposes model assumptions, some more explicitly than others and some more particularly than others. It is important to continue developing measures of damage uncertainty that account for uncertainty induced by model assumptions, by model misspecification, and by unmodeled channels for impacts and adaptation. These sources of uncertainty potentially swamp the econometric sources of uncertainty that economists are more comfortable presenting.

Third, economists should devote more effort to developing policy frameworks that do not rely on precise estimates of the marginal damage from carbon emissions. Indeed, policymakers are not waiting for economists to finally form a consensus around damage estimates. Some economists argue that pollution limits have special merit when marginal damages are so deeply uncertain (Baumol, 1972). Some economists explore carbon pricing under concerns about model uncertainty (Barnett, Brock and Hansen, 2020; Rudik, 2020). And other economists consider approaches to aggregating and revealing dispersed agents' information about climate change and climate damages (Aliakbari and McKitrick, 2018; Giglio, Kelly and Stroebel, 2021; Schlenker and Taylor, 2021; Lemoine, 2022). Taking the inherent limitations on knowledge seriously opens the door to analyzing the resilience of mitigation and adaptation policies to model error. Limited information is better than no information, and acting on limited information is better than waiting on complete information that will never arrive.

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Supplemental Appendix:
Navigating the 'Problem from Hell':
A Guide to Climate Damages

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Online Appendix

A Analysis for Section 2

Consider a world with two regions, denoted A and B, each comprised of small actors who take the other region's choices as given. In period t, region j produces quantity $Y_t^j \triangleq Y^j(\ell_{Yt}^j, K_t^j, w_t^j)$ of a nonstorable good using labor ℓ_{Yt}^j, capital K_t^j, and weather inputs w_t^j. Region j consumes quantities q_{At}^j and q_{Bt}^j of the goods produced by regions A and B, respectively. Its representative agent derives welfare $W_t^j \triangleq W^j(q_{At}^j, q_{Bt}^j)$ from that consumption bundle, with W^j increasing in each argument and concave. Using the price of region A's good as the numeraire, region A's time t budget constraint is $Y_t^A = q_{At}^A + p_t q_{Bt}^A$ and region B's time t budget constraint is $p_t Y_t^B = q_{At}^B + p_t q_{Bt}^B$. The market for the good produced by region j clears with $Y_t^j = q_{jt}^A + q_{jt}^B$. Each representative agent takes the terms of trade and the other region's capital stock as given, so that regions do not act strategically.

Region j is endowed with L^j units of labor. It allocates ℓ_{Yt}^j units of that labor to producing its good, and it allocates ℓ_{Kt}^j units of that labor to producing capital. The labor market clears with $\ell_{Yt}^j + \ell_{Kt}^j = L^j$. Region j's capital stock K_t^j depreciates at per-period rate $\delta \in (0,1)$ and increases as $f(\ell_{Kt}^j)$, with $f, f' > 0$ and $f'' < 0$. Capital and labor are here immobile across regions. All agents observe capital and weather in all regions.

The representative agent in region A at time t, with discount rate $r > 0$, solves the following

*ⓡ indicates that author order was randomized.

infinite-horizon problem, taking the path of p as given:

$$\begin{aligned}\max_{\ell^A_{Ys}(\cdot),\ell^A_{Ks}(\cdot),q^A_{As}(\cdot),q^A_{Bs}(\cdot)} \sum_{s=t}^{\infty} \frac{1}{(1+r)^{s-t}} E_t\left[W^A(q^A_{As}, q^A_{Bs})\right] \\ \text{s.t. } K^A_{s+1} =& f(\ell^A_{Ks}) + (1-\delta)K^A_s \\ Y^A(\ell^A_{Ys}, K^A_s, w^A_s) =& q^A_{As} + p_s q^A_{Bs} \\ L^A =& \ell^A_{Ys} + \ell^A_{Ks},\end{aligned}$$

where the policies $\ell^A_{Ys}(\cdot)$, $\ell^A_{Ks}(\cdot)$, $q^A_{As}(\cdot)$, and $q^A_{Bs}(\cdot)$ are functions of the time s state vector (comprising K^j_s, K^k_s, w^j_s, and w^k_s), and where E_t indicates expectations at the common time t information set. The representative agent in region B at time t solves an analogous problem, with the budget constraint adjusted appropriately. Optimal input and consumption choices in region j solve the following Bellman equation:

$$V^j(K^j_t, K^k_t, w^j_t, w^k_t) = \max_{\ell^j_{Yt},\ell^j_{Kt},q^j_{At},q^j_{Bt}} \left\{ W^j(q^j_{At}, q^j_{Bt}) + \frac{1}{1+r} E_t\left[V^j(K^j_{t+1}, K^k_{t+1}, w^j_{t+1}, w^k_{t+1})\right] \right\}, \tag{A-1}$$

with k indexing the other region. Define $V^j_t \triangleq V^j(K^j_t, K^k_t, w^j_t, w^k_t)$.

Substituting in the budget constraint and the transition for capital in region A, and then substituting in region A's labor constraint, equation (A-1) for region A is equivalent to:

$$\begin{aligned}V^A(K^A_t, K^B_t, w^A_t, w^B_t) = \max_{\ell^A_{Yt},q^A_{Bt}} \Bigg\{ & W^A(Y^A(\ell^A_{Yt}, K^A_t, w^A_t) - p_t q^A_{Bt}, q^A_{Bt}) \\ & + \frac{1}{1+r} E_t\left[V^A\Big(f(L^A - \ell^A_{Yt}) + (1-\delta)K^A_t, K^B_{t+1}, w^A_{t+1}, w^B_{t+1}\Big)\right] \Bigg\}.\end{aligned} \tag{A-2}$$

The first-order condition for q^A_{Bt} yields:

$$p_t = \frac{\frac{\partial W^A(q^A_{At}, q^A_{Bt})}{\partial q^A_{Bt}}}{\frac{\partial W^A(q^A_{At}, q^A_{Bt})}{\partial q^A_{At}}}. \tag{A-3}$$

Substituting for q^A_{At} from the budget constraint, this equation implicitly defines q^A_{Bt} as a function of p_t and Y^A_t, and the analogous equation for region B implicitly defines q^B_{At} as a function of p_t and Y^B_t, from which the budget constraint yields q^B_{Bt}. Market-clearing for region B's production good becomes $Y^B_t = q^A_{Bt}(p_t, Y^A_t) + q^B_{Bt}(p_t, Y^B_t)$, which implicitly defines p_t as $p(Y^A_t, Y^B_t)$.

Because regions take the terms of trade as given, problem (A-2) becomes:

$$\begin{aligned}
&V^A(K_t^A, K_t^B, w_t^A, w_t^B) \\
&= \max_{\ell_{Yt}^A} \Bigg\{ W^A\Big(Y^A(\ell_{Yt}^A, K_t^A, w_t^A) - p_t q_B^A(p_t, Y^A(\ell_{Yt}^A, K_t^A, w_t^A)),\ q_B^A(p_t, Y^A(\ell_{Yt}^A, K_t^A, w_t^A))\Big) \\
&\qquad + \frac{1}{1+r} E_t \left[V^A\Big(f(L^A - \ell_{Yt}^A) + (1-\delta)K_t^A, K_{t+1}^B, w_{t+1}^A, w_{t+1}^B\Big)\right]\Bigg\}. \qquad \text{(A-4)}
\end{aligned}$$

The first-order condition for ℓ_{Yt}^A is

$$0 = \left[\frac{\partial W_t^A}{\partial q_{At}^A} + \frac{\partial q_{Bt}^A}{\partial Y_t^A}\left(\frac{\partial W_t^A}{\partial q_{Bt}^A} - p_t \frac{\partial W_t^A}{\partial q_{At}^A}\right)\right]\frac{\partial Y_t^A}{\partial \ell_{Yt}^A} - f'(\ell_{Kt}^A)\frac{1}{1+r}E_t\left[\frac{\partial V^A(K_{t+1}^A, K_{t+1}^B, w_{t+1}^A, w_{t+1}^B)}{\partial K_{t+1}^A}\right].$$

Substitute p_t from (A-3):

$$0 = \frac{\partial W_t^A}{\partial q_{At}^A}\frac{\partial Y_t^A}{\partial \ell_{Yt}^A} - f'(\ell_{Kt}^A)\frac{1}{1+r}E_t\left[\frac{\partial V^A(K_{t+1}^A, K_{t+1}^B, w_{t+1}^A, w_{t+1}^B)}{\partial K_{t+1}^A}\right]. \qquad \text{(A-5)}$$

The optimal choice of ℓ_{Yt}^A equates the marginal benefit in terms of today's production and the marginal cost in terms of forgone capital in the future.

Equation (A-5) implicitly defines ℓ_{Yt}^A as a function of ℓ_{Yt}^B, K_t^A, K_t^B, $\tilde{w}_t^A$, $\tilde{w}_t^B$, and C. The analogous equation for region B implicitly defines ℓ_{Yt}^B as a function of ℓ_{Yt}^A, K_t^A, K_t^B, $\tilde{w}_t^A$, $\tilde{w}_t^B$, and C. Recalling that $\tilde{w}_t^A$ and $\tilde{w}_t^B$ (mean-zero random variables reflecting stochasticity in weather) are independent of C,

$$\frac{\mathrm{d}\ell_{Yt}^A}{\mathrm{d}C} = \frac{\partial \ell_{Yt}^A}{\partial C} + \frac{\partial \ell_{Yt}^A}{\partial K_t^A}\frac{\mathrm{d}K_t^A}{\mathrm{d}C} + \frac{\partial \ell_{Yt}^A}{\partial K_t^B}\frac{\mathrm{d}K_t^B}{\mathrm{d}C} + \frac{\partial \ell_{Yt}^A}{\partial \ell_{Yt}^B}\frac{\mathrm{d}\ell_{Yt}^B}{\mathrm{d}C}. \qquad \text{(A-6)}$$

Substitute the analogous equation for region B and collect terms with $\mathrm{d}\ell_{Yt}^A/\mathrm{d}C$ on the left-hand side:

$$\begin{aligned}
\left[1 - \frac{\partial \ell_{Yt}^B}{\partial \ell_{Yt}^A}\frac{\partial \ell_{Yt}^A}{\partial \ell_{Yt}^B}\right]\frac{\mathrm{d}\ell_{Yt}^A}{\mathrm{d}C} &= \underbrace{\frac{\partial \ell_{Yt}^A}{\partial C} + \frac{\partial \ell_{Yt}^A}{\partial K_t^A}\frac{\mathrm{d}K_t^A}{\mathrm{d}C} + \frac{\partial \ell_{Yt}^A}{\partial K_t^B}\frac{\mathrm{d}K_t^B}{\mathrm{d}C}}_{\zeta_{At}} \\
&\qquad + \frac{\partial \ell_{Yt}^A}{\partial \ell_{Yt}^B}\Bigg[\underbrace{\frac{\partial \ell_{Yt}^B}{\partial C} + \frac{\partial \ell_{Yt}^B}{\partial K_t^A}\frac{\mathrm{d}K_t^A}{\mathrm{d}C} + \frac{\partial \ell_{Yt}^B}{\partial K_t^B}\frac{\mathrm{d}K_t^B}{\mathrm{d}C}}_{\zeta_{Bt}}\Bigg]. \qquad \text{(A-7)}
\end{aligned}$$

Applying the implicit function theorem to equation (A-5) and using the second-order condition for an optimum (which guarantees that the proportionality constant omitted below is positive), the term labeled ζ_{At} can be written as:

$$\zeta_{At} = \gamma_{At}^{now} + \gamma_{At}^{future} + \gamma_{At}^{past} + \gamma_{At}^{elsewhere},$$

where

$$\begin{aligned}
\gamma_{At}^{now} \propto & \frac{\partial W_t^A}{\partial q_{At}^A} \frac{\partial^2 Y_t^A}{\partial \ell_{Yt}^A \partial w_t^A} \theta^A + \left[\frac{\partial^2 W_t^A}{\partial [q_{At}^A]^2} + \frac{\partial q_{Bt}^A}{\partial Y_t^A} \left(\frac{\partial^2 W_t^A}{\partial q_{At}^A \partial q_{Bt}^A} - p_t \frac{\partial^2 W_t^A}{\partial [q_{At}^A]^2} \right) \right] \frac{\partial Y_t^A}{\partial \ell_{Yt}^A} \frac{\partial Y_t^A}{\partial w_t^A} \theta^A \\
& + \left[-\frac{\partial^2 W_t^A}{\partial [q_{At}^A]^2} \left(q_{Bt}^A + p_t \frac{\partial q_{Bt}^A}{\partial p_t} \right) + \frac{\partial^2 W_t^A}{\partial q_{At}^A \partial q_{Bt}^A} \frac{\partial q_{Bt}^A}{\partial p_t} \right] \frac{\partial Y_t^A}{\partial \ell_{Yt}^A} \frac{\partial p_t}{\partial Y_t^A} \frac{\partial Y_t^A}{\partial w_t^A} \theta^A, \\
\gamma_{At}^{future} \propto & - f'(\ell_{Kt}^A) \frac{1}{1+r} E_t \left[\frac{\partial^2 V^A(K_{t+1}^A, K_{t+1}^B, w_{t+1}^A, w_{t+1}^B)}{\partial K_{t+1}^A \partial w_{t+1}^A} \right] \theta^A, \\
\gamma_{At}^{past} \propto & \frac{\mathrm{d}K_t^A}{\mathrm{d}C} \Bigg\{ \frac{\partial W_t^A}{\partial q_{At}^A} \frac{\partial^2 Y_t^A}{\partial \ell_{Yt}^A \partial K_t^A} + \left[\frac{\partial^2 W_t^A}{\partial [q_{At}^A]^2} + \frac{\partial q_{Bt}^A}{\partial Y_t^A} \left(\frac{\partial^2 W_t^A}{\partial q_{At}^A \partial q_{Bt}^A} - p_t \frac{\partial^2 W_t^A}{\partial [q_{At}^A]^2} \right) \right] \frac{\partial Y_t^A}{\partial \ell_{Yt}^A} \frac{\partial Y_t^A}{\partial K_t^A} \\
& + \left[-\frac{\partial^2 W_t^A}{\partial [q_{At}^A]^2} \left(q_{Bt}^A + p_t \frac{\partial q_{Bt}^A}{\partial p_t} \right) + \frac{\partial^2 W_t^A}{\partial q_{At}^A \partial q_{Bt}^A} \frac{\partial q_{Bt}^A}{\partial p_t} \right] \frac{\partial Y_t^A}{\partial \ell_{Yt}^A} \frac{\partial p_t}{\partial Y_t^A} \frac{\partial Y_t^A}{\partial K_t^A} \\
& - (1-\delta) f'(\ell_{Kt}^A) \frac{1}{1+r} E_t \left[\frac{\partial^2 V^A(K_{t+1}^A, K_{t+1}^B, w_{t+1}^A, w_{t+1}^B)}{\partial [K_{t+1}^A]^2} \right] \Bigg\}, \\
\gamma_{At}^{elsewhere} \propto & \left[-\frac{\partial^2 W_t^A}{\partial [q_{At}^A]^2} \left(q_{Bt}^A + p_t \frac{\partial q_{Bt}^A}{\partial p_t} \right) + \frac{\partial^2 W_t^A}{\partial q_{At}^A \partial q_{Bt}^A} \frac{\partial q_{Bt}^A}{\partial p_t} \right] \frac{\partial Y_t^A}{\partial \ell_{Yt}^A} \frac{\partial p_t}{\partial Y_t^B} \frac{\partial Y_t^B}{\partial w_t^B} \theta^B \\
& - f'(\ell_{Kt}^A) \frac{1}{1+r} E_t \left[\frac{\partial^2 V^A(K_{t+1}^A, K_{t+1}^B, w_{t+1}^A, w_{t+1}^B)}{\partial K_{t+1}^A \partial w_{t+1}^B} \right] \theta^B \\
& + \left[-\frac{\partial^2 W_t^A}{\partial [q_{At}^A]^2} \left(q_{Bt}^A + p_t \frac{\partial q_{Bt}^A}{\partial p_t} \right) + \frac{\partial^2 W_t^A}{\partial q_{At}^A \partial q_{Bt}^A} \frac{\partial q_{Bt}^A}{\partial p_t} \right] \frac{\partial Y_t^A}{\partial \ell_{Yt}^A} \frac{\partial p_t}{\partial Y_t^B} \frac{\partial Y_t^B}{\partial K_t^B} \frac{\mathrm{d}K_t^B}{\mathrm{d}C} \\
& - (1-\delta) f'(\ell_{Kt}^A) \frac{1}{1+r} E_t \left[\frac{\partial^2 V^A(K_{t+1}^A, K_{t+1}^B, w_{t+1}^A, w_{t+1}^B)}{\partial K_{t+1}^A \partial K_{t+1}^B} \right] \frac{\mathrm{d}K_t^B}{\mathrm{d}C}.
\end{aligned}$$

ζ_{Bt} follows analogously. Substituting into equation (A-7), we find:

$$\begin{aligned}
\frac{\mathrm{d}\ell_{Yt}^A}{\mathrm{d}C} = & \frac{1}{1 - \frac{\partial \ell_{Yt}^B}{\partial \ell_{Yt}^A} \frac{\partial \ell_{Yt}^A}{\partial \ell_{Yt}^B}} \left[\gamma_{At}^{now} + \gamma_{At}^{future} + \gamma_{At}^{past} + \gamma_{At}^{elsewhere} \right] \\
& + \frac{1}{1 - \frac{\partial \ell_{Yt}^B}{\partial \ell_{Yt}^A} \frac{\partial \ell_{Yt}^A}{\partial \ell_{Yt}^B}} \frac{\partial \ell_{Yt}^A}{\partial \ell_{Yt}^B} \left[\gamma_{Bt}^{now} + \gamma_{Bt}^{future} + \gamma_{Bt}^{past} + \gamma_{Bt}^{elsewhere} \right]. \qquad \text{(A-8)}
\end{aligned}$$

Observe that:

$$
\begin{aligned}
\gamma_{Bt}^{elsewhere} \propto & \left[-\frac{\partial^2 W_t^B}{\partial q_{Bt}^B \partial q_{At}^B}\left(q_{Bt}^B - Y_t^B + p_t \frac{\partial q_{Bt}^B}{\partial p_t}\right) + \frac{\partial^2 W_t^B}{\partial [q_{Bt}^B]^2}\frac{\partial q_{Bt}^B}{\partial p_t}\right] \frac{\partial Y_t^B}{\partial \ell_{Yt}^B}\frac{\partial p_t}{\partial Y_t^A}\frac{\partial Y_t^A}{\partial w_t^A}\theta^A \\
& - f'(\ell_{Kt}^B)\frac{1}{1+r}E_t\left[\frac{\partial^2 V^B(K_{t+1}^B, K_{t+1}^A, w_{t+1}^B, w_{t+1}^A)}{\partial K_{t+1}^B \partial w_{t+1}^A}\right]\theta^A \\
& + \left[-\frac{\partial^2 W_t^B}{\partial q_{Bt}^B \partial q_{At}^B}\left(q_{Bt}^B - Y_t^B + p_t \frac{\partial q_{Bt}^B}{\partial p_t}\right) + \frac{\partial^2 W_t^B}{\partial [q_{Bt}^B]^2}\frac{\partial q_{Bt}^B}{\partial p_t}\right] \frac{\partial Y_t^B}{\partial \ell_{Yt}^B}\frac{\partial p_t}{\partial Y_t^A}\frac{\partial Y_t^A}{\partial K_t^A}\frac{\mathrm{d}K_t^A}{\mathrm{d}C} \\
& - (1-\delta)f'(\ell_{Kt}^B)\frac{1}{1+r}E_t\left[\frac{\partial^2 V^B(K_{t+1}^B, K_{t+1}^A, w_{t+1}^B, w_{t+1}^A)}{\partial K_{t+1}^B \partial K_{t+1}^A}\right]\frac{\mathrm{d}K_t^A}{\mathrm{d}C}.
\end{aligned}
$$

Substituting for $\gamma_{Bt}^{elsewhere}$ in (A-8), using the implicit function theorem with equation (A-5) to obtain $\partial \ell_{Yt}^A / \partial \ell_{Yt}^B$, and collecting terms, we have:

$$
\frac{\mathrm{d}\ell_{Yt}^A}{\mathrm{d}C} = \Gamma_{At}^{now} + \Gamma_{At}^{future} + \Gamma_{At}^{past} + \Gamma_{At}^{elsewhere}, \tag{A-9}
$$

where:

$$
\begin{aligned}
\Gamma_{At}^{now} \triangleq & \frac{1}{1 - \frac{\partial \ell_{Yt}^B}{\partial \ell_{Yt}^A}\frac{\partial \ell_{Yt}^A}{\partial \ell_{Yt}^B}}\Bigg\{\gamma_{At}^{now} \\
& + \chi_{At}\left[-\frac{\partial^2 W_t^B}{\partial q_{Bt}^B \partial q_{At}^B}\left(q_{Bt}^B - Y_t^B + p_t \frac{\partial q_{Bt}^B}{\partial p_t}\right) + \frac{\partial^2 W_t^B}{\partial [q_{Bt}^B]^2}\frac{\partial q_{Bt}^B}{\partial p_t}\right] \frac{\partial Y_t^B}{\partial \ell_{Yt}^B}\frac{\partial p_t}{\partial Y_t^A}\frac{\partial Y_t^A}{\partial w_t^A}\theta^A\Bigg\}, \\
\Gamma_{At}^{future} \triangleq & \frac{1}{1 - \frac{\partial \ell_{Yt}^B}{\partial \ell_{Yt}^A}\frac{\partial \ell_{Yt}^A}{\partial \ell_{Yt}^B}}\left\{\gamma_{At}^{future} - \chi_{At} f'(\ell_{Kt}^B)\frac{1}{1+r}E_t\left[\frac{\partial^2 V^B(K_{t+1}^B, K_{t+1}^A, w_{t+1}^B, w_{t+1}^A)}{\partial K_{t+1}^B \partial w_{t+1}^A}\right]\theta^A\right\}, \\
\Gamma_{At}^{past} \triangleq & \frac{1}{1 - \frac{\partial \ell_{Yt}^B}{\partial \ell_{Yt}^A}\frac{\partial \ell_{Yt}^A}{\partial \ell_{Yt}^B}}\Bigg\{\gamma_{At}^{past} \\
& + \chi_{At}\left[-\frac{\partial^2 W_t^B}{\partial q_{Bt}^B \partial q_{Bt}^A}\left(q_{Bt}^B - Y_t^B + p_t \frac{\partial q_{Bt}^B}{\partial p_t}\right) + \frac{\partial^2 W_t^B}{\partial [q_{Bt}^B]^2}\frac{\partial q_{Bt}^B}{\partial p_t}\right] \frac{\partial Y_t^B}{\partial \ell_{Yt}^B}\frac{\partial p_t}{\partial Y_t^A}\frac{\partial Y_t^A}{\partial K_t^A}\frac{\mathrm{d}K_t^A}{\mathrm{d}C} \\
& - \chi_{At}(1-\delta)f'(\ell_{Kt}^B)\frac{1}{1+r}E_t\left[\frac{\partial^2 V^B(K_{t+1}^B, K_{t+1}^A, w_{t+1}^B, w_{t+1}^A)}{\partial K_{t+1}^B \partial K_{t+1}^A}\right]\frac{\mathrm{d}K_t^A}{\mathrm{d}C}\Bigg\}, \\
\Gamma_{At}^{elsewhere} \triangleq & \frac{1}{1 - \frac{\partial \ell_{Yt}^B}{\partial \ell_{Yt}^A}\frac{\partial \ell_{Yt}^A}{\partial \ell_{Yt}^B}}\left\{\gamma_{At}^{elsewhere} + \chi_{At}\left[\gamma_{Bt}^{now} + \gamma_{Bt}^{future} + \gamma_{Bt}^{past}\right]\right\}, \\
\chi_{At} \propto & f'(\ell_{Kt}^B) f'(\ell_{Kt}^A)\frac{1}{1+r}E_t\left[\frac{\partial^2 V^A(K_{t+1}^A, K_{t+1}^B, w_{t+1}^A, w_{t+1}^B)}{\partial K_{t+1}^A \partial K_{t+1}^B}\right].
\end{aligned}
$$

The leading fraction in each of the four Γ terms is strictly positive in the regular case, in which investment in one region moves less than one for one with investment in the other. χ_{At} measures the spillover from region B's investment choice into region A's investment choice, operating through how region B's investment changes the subsequent prices p_{t+s} of its good. It scales the impact of climate-induced changes in region B's investment on region A's labor allocated to investment.

Now relate the channels within each Γ that are informally described in Section 2 to the formal expressions. Γ^{now}_{At} has four components. The first three are from γ^{now}_{At}: weather may directly alter the marginal product of labor (first term on first line in γ^{now}_{At}), weather may alter the value of labor's marginal product by directly affecting total output in region A (second term on first line in γ^{now}_{At}), and weather may alter prices (second line in γ^{now}_{At}). The fourth component reflects how weather may alter investment decisions in region B (terms with χ_{At} in Γ^{now}_{At}).

Γ^{future}_{At} has two components: how expected weather directly alters the marginal product of region A's capital in future periods (in γ^{future}_{At}), and how these expectations can affect region A's time t investment via region B's time t investment (term with χ_{At} in Γ^{future}_{At}).

In Γ^{past}_{At}, the time t capital stock may affect the time t marginal product of labor (first term on the first line in γ^{past}_{At}), the time t value of that marginal product at constant prices (second term on the first line in γ^{past}_{At}), time t prices (second line in γ^{past}_{At}), or the expected marginal product of capital in later periods, whether directly (third line in γ^{past}_{At}) or by affecting investment in region B (terms with χ_{At} in Γ^{past}_{At}). Let t_0 indicate some time prior to which C had been constant and prior to which there was no knowledge that C would ever change. Then, from the capital transition equation, labor market-clearing, and equation (A-9):

$$\frac{\mathrm{d}K^A_t}{\mathrm{d}C} = -\sum_{s=t_0}^{t-1} (1-\delta)^{t-1-s} f'(\ell^A_{Ks}) \left[\Gamma^{now}_{As} + \Gamma^{future}_{As} + \Gamma^{past}_{As} + \Gamma^{elsewhere}_{As} \right]. \tag{A-10}$$

The capital stock contains a memory of all past effects of climate change, which encompass how climate change affected weather in all earlier periods and how climate change affected expectations of subsequent weather held by agents in earlier periods.[1]

In $\Gamma^{elsewhere}_{At}$, current weather elsewhere on the planet affects prices in region A (first line in $\gamma^{elsewhere}_{At}$); anticipated weather elsewhere on the planet affects investment incentives in region A (second line in $\gamma^{elsewhere}_{At}$); past weather elsewhere around the planet affects capital stocks elsewhere around the planet and thereby affects both prices (third line in $\gamma^{elsewhere}_{At}$) and investment incentives (fourth line in $\gamma^{elsewhere}_{At}$) in region A; and all such weather can affect investment incentives in region B and thereby affect investment incentives in region A (terms with χ_{At} in $\Gamma^{elsewhere}_{At}$).

[1] The evaluation point for the partial derivatives in equation (4) in Section 3.2 can be different from the evaluation point for the partial derivatives in this appendix and in Section 2 because climate change alters the incoming capital stock. The evaluation points are the same only for the very first increment of surprising climate change.

To derive the effect of climate on period welfare in region A, observe from (A-4) that

$$\frac{\mathrm{d}W_t^A}{\mathrm{d}C} = \left[\frac{\partial W_t^A}{\partial q_{At}^A} + \frac{\partial q_{Bt}^A}{\partial Y_t^A}\left(\frac{\partial W_t^A}{\partial q_{Bt}^A} - p_t \frac{\partial W_t^A}{\partial q_{At}^A}\right)\right]\frac{\mathrm{d}Y_t^A}{\mathrm{d}C} + \left[-\frac{\partial W_t^A}{\partial q_{At}^A} q_{Bt}^A + \frac{\partial q_{Bt}^A}{\partial p_t}\left(\frac{\partial W_t^A}{\partial q_{Bt}^A} - p_t \frac{\partial W_t^A}{\partial q_{At}^A}\right)\right]\frac{\mathrm{d}p_t}{\mathrm{d}C}.$$

Using the equilibrium price from (A-3), we find:

$$\frac{\mathrm{d}W_t^A}{\mathrm{d}C} = \frac{\partial W_t^A}{\partial q_{At}^A}\left[\frac{\mathrm{d}Y_t^A}{\mathrm{d}C} - \underbrace{\left(\frac{\partial p_t}{\partial Y_t^A}\frac{\mathrm{d}Y_t^A}{\mathrm{d}C} + \frac{\partial p_t}{\partial Y_t^B}\frac{\mathrm{d}Y_t^B}{\mathrm{d}C}\right)}_{\mathrm{d}p_t/\,\mathrm{d}C} q_{Bt}^A\right].$$

We have the effect of climate change on local production (as in equation (1)) and also the effect of climate change on prices, which in turn depends on how climate change affects production everywhere around the world. As a result, effects on period welfare depend on all of the effects discussed following equation (1), for all regions at once. The value of these effects depends on the marginal value of consumption in welfare.

To derive the effect of climate change on intertemporal welfare in region A, differentiate the maximized value function from equation (A-4), and substitute for p_t from equation (A-3):

$$\frac{\mathrm{d}V_t^A}{\mathrm{d}C} = \frac{\partial W_t^A}{\partial q_{At}^A}\left(1 - \frac{\partial p_t}{\partial Y_t^A} q_{Bt}^A\right)\left(\frac{\partial Y_t^A}{\partial w_t^A}\theta^A + \frac{\partial Y_t^A}{\partial \ell_{Yt}^A}\frac{\mathrm{d}\ell_{Yt}^A}{\mathrm{d}C} + \frac{\partial Y_t^A}{\partial K_t^A}\frac{\mathrm{d}K_t^A}{\mathrm{d}C}\right) - \frac{\partial W_t^A}{\partial q_{At}^A}\frac{\partial p_t}{\partial Y_t^B} q_{Bt}^A\left(\frac{\partial Y_t^B}{\partial w_t^B}\theta^B + \frac{\partial Y_t^B}{\partial \ell_{Yt}^B}\frac{\mathrm{d}\ell_{Yt}^B}{\mathrm{d}C} + \frac{\partial Y_t^B}{\partial K_t^B}\frac{\mathrm{d}K_t^B}{\mathrm{d}C}\right) + \frac{1}{1+r}E_t\left[\frac{\mathrm{d}V_{t+1}^A}{\mathrm{d}C}\right].$$

Advancing by one period yields $\mathrm{d}V_{t+1}^A/\,\mathrm{d}C$. We can then substitute $\mathrm{d}V_{t+1}^A/\,\mathrm{d}C$ into the right-hand side. Repeating this process yields:

$$\frac{\mathrm{d}V_t^A}{\mathrm{d}C} = \sum_{s=t}^{\infty}\frac{1}{(1+r)^{s-t}}E_t\left[\frac{\partial W_s^A}{\partial q_{As}^A}\left(1 - \frac{\partial p_s}{\partial Y_s^A} q_{Bs}^A\right)\left(\frac{\partial Y_s^A}{\partial w_s^A}\theta^A + \frac{\partial Y_s^A}{\partial \ell_{Ys}^A}\frac{\mathrm{d}\ell_{Ys}^A}{\mathrm{d}C} + \frac{\partial Y_s^A}{\partial K_s^A}\frac{\mathrm{d}K_s^A}{\mathrm{d}C}\right)\right] - \sum_{s=t}^{\infty}\frac{1}{(1+r)^{s-t}}E_t\left[\frac{\partial W_s^A}{\partial q_{As}^A}\frac{\partial p_s}{\partial Y_s^B} q_{Bs}^A\left(\frac{\partial Y_s^B}{\partial w_s^B}\theta^B + \frac{\partial Y_s^B}{\partial \ell_{Ys}^B}\frac{\mathrm{d}\ell_{Ys}^B}{\mathrm{d}C} + \frac{\partial Y_s^B}{\partial K_s^B}\frac{\mathrm{d}K_s^B}{\mathrm{d}C}\right)\right].$$

Using (A-5), this becomes:

$$\frac{\mathrm{d}V_t^A}{\mathrm{d}C} = \sum_{s=t}^{\infty}\frac{1}{(1+r)^{s-t}}E_t\left[\frac{\partial W_s^A}{\partial q_{As}^A}\left(1 - \frac{\partial p_s}{\partial Y_s^A} q_{Bs}^A\right)\left(\frac{\partial Y_s^A}{\partial w_s^A}\theta^A + (1-\delta)^{s-t}\frac{\partial Y_s^A}{\partial K_s^A}\frac{\mathrm{d}K_t^A}{\mathrm{d}C}\right)\right] - \sum_{s=t}^{\infty}\frac{1}{(1+r)^{s-t}}E_t\left[\frac{\partial W_s^A}{\partial q_{As}^A}\frac{\partial p_s}{\partial Y_s^B} q_{Bs}^A\left(\frac{\partial Y_s^B}{\partial w_s^B}\theta^B + \frac{\partial Y_s^B}{\partial \ell_{Ys}^B}\frac{\mathrm{d}\ell_{Ys}^B}{\mathrm{d}C} + \frac{\partial Y_s^B}{\partial K_s^B}\frac{\mathrm{d}K_s^B}{\mathrm{d}C}\right)\right].$$

The local component to the transitory adaptation channel (i.e., effect of ℓ_{Ys}^A) from equation (1) drops out, as current and future allocations to production and investment are optimized for local intertemporal value (i.e., the envelope theorem applies). However, effects on two types of inputs remain. First, climate effects are history dependent. Time t capital stocks are predetermined as of time t, so the effects of climate change on those capital stocks do not drop out of intertemporal value as of time t. Second, other regions optimize their inputs for their own intertemporal value, so effects on inputs elsewhere around the world can have first-order effects on local intertemporal value, via trade.

The first-order change in the welfare of all agents, in both locations and in both the present and future, can be even simpler. If global markets are competitive and fully integrated, then the equilibrium allocation maximizes a global intertemporal welfare function with particular weights on each region and time period. If the global social welfare function has these same weights, then, by the envelope theorem, the adaptation channel from equation (1) in every region of the world drops out of the marginal effect of climate change on global social welfare. However, the capital response does remain, because capital stocks are predetermined as of time t rather than optimized at time t. So past adaptation does affect intertemporal welfare.[2] Moreover, if either the social welfare function uses different weights or global markets have imperfections, then the envelope theorem does not apply and the adaptation channels from equation (1) are part of the effect of climate change on social welfare.

B Papers Included in Trilemma Figure

Adams et al. (1988)

This paper *does not satisfy* desideratum (A) because the analysis is based on calibrating a specific structural model.

This paper *moderately satisfies* desideratum (B). There is adaptation through spatial equilibrium and there is a nuanced representation of hydrologic resource constraints, but there is little representation of agents responding to past or future climate change in ways that would alter yield responses from crop simulation models.

This paper *partially satisfies* desideratum (C). Nothing is estimated directly, but yield responses are based on simulation models based on agronomic understanding of crop growth.

[2] One might wonder why optimization in earlier periods does not mean that marginal changes in the time t capital stock have no effect on time t intertemporal welfare. The reason is that, by standard dynamic analysis, the shadow value of a state variable such as capital obeys a costate equation that does not generally set it to zero.

Mendelsohn, Nordhaus and Shaw (1994)

This paper *largely satisfies* desideratum (A) because the empirical analysis is based on an envelope condition which, although relying on optimizing behavior, is not predicated on a single, specific structural model.

This paper *moderately satisfies* desideratum (B). It uses long-run average temperature as the primary explanatory variable and thereby plausibly captures the persistent nature of climate change. It goes some way towards capturing the anticipated nature of climate change (because anticipation is wrapped up in long-run weather), but anticipation may be very different when applied to the process of future climate change. And it does not capture the widespread nature of climate change because it treats units and their climates as independent of each other.

The paper *does not satisfy* desideratum (C). A primary criticism leveled against cross-sectional analyses like the one in this paper is that they are vulnerable to omitted variable bias. Indeed, Schlenker, Hanemann and Fisher (2005) demonstrate omitted variables bias in the context of this paper.

Schlenker and Roberts (2009)

This paper *fully satisfies* desideratum (A) because the authors leverage the reduced-form empirical approach to implement multiple semiparametric analyses, aiming to achieve robustness to a broader set of potential underlying models.

This paper *does not satisfy* desideratum (B). It uses short-run (growing season) variation in local weather that does not capture persistent, anticipated, or widespread aspects of climate change.

The paper *largely or completely satisfies* desideratum (C). It uses variation in a location's growing season weather across years in order to find variation in weather that is relevant to agricultural production but also quasi-randomly assigned.

Carleton et al. (2022)

This paper *fully satisfies* desideratum (A) because the authors leverage the reduced-form empirical approach to implement multiple semiparametric analyses, aiming to achieve robustness to a broader set of potential underlying models. The analysis is based on a sufficient statistics approach.

This paper *partially satisfies* desideratum (B). The main variation is short-run, local weather that does not capture persistent, anticipated, or widespread aspects of climate change. The analysis includes interactions with longer-run weather, but this interaction only influences outcomes by modifying the estimated effect of short-run weather.

This paper *moderately satisfies* desideratum (C). It uses variation in a location's annual weather across years to identify the effect of abnormal weather on mortality. However, the cross-sectional interactions are not causally identified.

Cruz and Rossi-Hansberg (2024)

This paper *does not satisfy* desideratum (A). The estimates are based on a specific structural model of the economy.

This paper *largely satisfies* desideratum (B). The model includes the effects of spillovers in climate damages, capturing aspects of the widespread nature of climate change. The model rules out some effects of persistent climate change due to the way it models economic behavior.

This paper *partially satisfies* desideratum (C). It regresses productivities and amenities on temperature in a panel environment. However, productivities and amenities are themselves residuals that depend on a particular model, and trade and migration costs are set to make the model perfectly fit observed trade and migration data, so that their identification is ultimately from the model's structure.

Bilal and Känzig (2024)

This paper *largely satisfies* desideratum (A). It estimates a reduced-form relationship between global temperature variation and global production using frontier time series econometrics. It does not do a perfect job because the estimated model is linear rather than semiparametric, in part due to data limitations.

This paper *moderately satisfies* desideratum (B). The use of global variation in principle could capture the widespread effects of climate change, although there is little data to identify this effect. But if successful, the filtration procedure means that the estimates do not capture the effect of anticipated or persistent climate change. The paper includes estimates of dynamics in economic outcomes (output and capital) but in response to global weather shocks rather than permanent climate change.

This paper *partially satisfies* desideratum (C). It is the mirror image of Mendelsohn, Nordhaus and Shaw (1994) in that it relies purely on time series variation whereas the earlier paper relies purely on cross-sectional variation. In principle, this time-series approach might provide as good or better identification than a cross-sectional approach, but in practice it is hampered by limited data (short time series) and retains potential for omitted variables bias.

C An Alternative Formalization for the Adaptation Cost Recovery of Carleton et al. (2022)

Let $C_i(t)$ be the climate in location i at time t, $A(C_i(t))$ be an action that can be used for adaptation at time t, $c(A)$ be adaptation costs at time t, and $y(w_i(t), A(C_i(t)))$ be an outcome at time t, in terms of value. Weather $w_i(t)$ has mean $C_i(t)$ and a stochastic component that is independently and identically distributed over time. Let all functions be continuous and differentiable, ruling out the types of extensive margin adaptation studied by Guo and Costello (2013).

Agents choose time t actions with knowledge of $C_i(t)$ but before $w_i(t)$ is realized. They choose actions to maximize expected net benefits:

$$\max_{A(\cdot)} \int_{t_0}^{\infty} e^{-rt} E\Big[y(w_i(t), A(C_i(t))) - c(A(C_i(t)))\Big] \text{ d}t. \tag{A-11}$$

where the discount rate is $r > 0$. Because there are no intertemporal linkages (for instance, adaptation is assumed completely transitory), this integral can be maximized pointwise, so that optimal actions in time t satisfy:

$$\max_{A(C_i(t))} E\Big[y(w_i(t), A(C_i(t))) - c(A(C_i(t)))\Big]. \tag{A-12}$$

Consider climate change from time t_0 to time T. Carleton et al. (2022) are interested in adaptation costs incurred at time T: $c(A^*(C_i(T))) - c(A^*(C_i(t_0)))$, where a star indicates an optimized outcome. By the second fundamental theorem of calculus,[3]

$$c(A^*(C_i(T))) - c(A^*(C_i(t_0))) = \int_{t_0}^{T} c'(A^*(C_i(s)))\, A^{*\prime}(C_i(s))\, C_i'(s) \text{ d}s.$$

From (A-12), optimal adaptation in each instant t solves the first-order condition:

$$E\left[\frac{\partial y(w_i(t), A^*(C_i(t)))}{\partial A}\right] = c'(A^*(C_i(t))).$$

[3] We could avoid confusion about the time dimension of climate change by instead expressing this difference as:

$$c(A^*(C_i(T))) - c(A^*(C_i(t_0))) = \int_{C_i(t_0)}^{C_i(T)} c'(A^*(C))\, A^{*\prime}(C) \text{ d}C.$$

We maintain the form in the text in order to end up at the equation used in Carleton et al. (2022).

Substituting in pointwise, adaptation costs are

$$c(A^*(C_i(T))) - c(A^*(C_i(t_0))) = \int_{t_0}^{T} E\left[\frac{\partial y(w_i(s), A^*(C_i(s)))}{\partial A}\right] A^{*\prime}(C_i(s))\, C_i'(s)\ \mathrm{d}s.$$

Move the derivative of A^* inside the expectation operator:

$$c(A^*(C_i(T))) - c(A^*(C_i(t_0))) = \int_{t_0}^{T} E\left[\frac{\partial y(w_i(s), A^*(C_i(s)))}{\partial A} A^{*\prime}(C_i(s))\right] C_i'(s)\ \mathrm{d}s. \quad \text{(A-13)}$$

To recover the integrand in (A-13), recall regression (5):

$$y_{it} = \beta^{panel} w_{it} + \gamma^{cs,panel} \bar{w}_i w_{it} + \delta_i + \nu_t + \varepsilon_{it}.$$

Carleton et al. (2022) assume

$$E\left[\frac{\partial\, y(w_i, A(C_i))}{\partial A} A'(C_i)\right] = E\left[\frac{\partial y_{it}}{\partial \bar{w}_i}\right], \quad \text{(A-14)}$$

so that, for purposes of adaptation, cross-sectional variation in $\bar{w}_i$ is equivalent to variation in C_i over time. This assumption suits their timeless setting in which the history and future of climate change are irrelevant.

Substituting from regression (5) into (A-14),

$$E\left[\frac{\partial\, y(w_i, A(C_i))}{\partial A} A'(C_i)\right] = \hat{\gamma}^{cs,panel} E[w_{it}].$$

Using that equivalence, adaptation costs in (A-13) become

$$c(A^*(C_i(T))) - c(A^*(C_i(t_0))) = \int_{t_0}^{T} \hat{\gamma}^{cs,panel} E[w_{is}]\, C_i'(s)\ \mathrm{d}s.$$

Using $E[w_{is}] = C_i(s)$, this becomes:

$$c(A^*(C_i(T))) - c(A^*(C_i(t_0))) = \int_{t_0}^{T} \hat{\gamma}^{cs,panel} C_i(s)\, C_i'(s)\ \mathrm{d}s,$$

which we can discretize as

$$c(A^*(C_i(T))) - c(A^*(C_i(t_0))) \approx \hat{\gamma}^{cs,panel} \sum_{t=t_0+1}^{T} C_i(t) \Big[C_i(t) - C_i(t-1)\Big].$$

Within this economic environment, a regression that shows how the marginal effects of weather vary cross-sectionally with climate thereby yields how the total costs of adaptation accrue over time as a location's climate changes.

The key assumption is the timeless nature of the decision-making environment. It has two implications. First, optimizing agents equate the flow of marginal costs to the flow of marginal benefits at every instant, so that instantaneous marginal costs can be substituted pointwise for instantaneous marginal benefits (equation (A-12)). Second, adaptation to different climates over time is equivalent to observed cross-sectional adaptation to different climates over space (equation (A-14)). If adaptation were instead not completely transitory, optimization would not permit problem (A-11) to be solved via (A-12) and there is little reason to expect (A-14) to hold.

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