Welcome to Hell:
A Guide to Climate Damages

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Abstract

Multiple lines of research aim to quantify the economic impacts of climate change, including through calibrated simulations, reduced-form estimation, and structural estimation. We formally decompose the effect of global climate change on output and welfare into several channels. These comprise the direct effects of changes in local weather, adaptation to changes in past weather, adaptation to expectations of future changes in weather, and general equilibrium effects of changes in weather around the world. Using this framework, we argue that estimation of climate impacts faces a trilemma: a methodology can have at most two of (i) robustness to model specification, (ii) quasi-experimental identification, and (iii) a valid interpretation in terms of climate change. We summarize the extensive empirical literature estimating the direct effects of climate change, which shows that climate affects many aspects of the economy. These damages point to the potential importance of adaptation and spatial spillovers, which emerging literatures investigate. We propose several directions for future work.

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

> *Our focus here is on climate solutions—and our task is urgent. Humanity has opened the gates of hell.*
>
> – UN Secretary General Guterres, *Climate Ambition Summit remarks* (2023)

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

The climate is rapidly changing. These changes already impact the economy, people's well-being, and the environment. Climate change destabilizes an important physical input to the economy, creates global systemic risks, and alters the geographic scope of human activity.[1] It thus has the potential to reshape markets, affecting economies across the world in profound ways. The many unknowns, complex interlinkages, and high stakes make climate change an economic "problem from hell" (Weitzman, 2015, p. 145). To tackle this problem, research on climate change is expanding across nearly every field of economics. We argue that methodological tensions may be irresolvable, so that progress in resolving unknowns will come from combining and comparing multiple approaches rather than from converging on one single method. Although we may be condemned to never know climate damages completely, we have made substantial progress towards understanding the scale, source, and geographic distribution of damages and can expect this progress to continue.

Estimates of damages determine both the stringency of actual climate policies and what policies economists recommend for implementation.[2] For instance, damage functions are a core component of Integrated Assessment Models (IAMs).[3] These models are used by academics and policymakers to calculate the social cost of carbon (SCC), which is an important input into economic and policy analyses and is a focal point for climate legislation and regulation around the world. The SCC is the present value of the stream of damages caused by the emission of one additional ton of carbon dioxide. Damage estimates are therefore the

[1] In the last decade, global surface temperatures reached 1.1°C (2°F) above 1850–1900 levels and have risen "faster since 1970 than in any other 50-year period over at least the last 2000 years" (IPCC, 2023, p. 4). Global average temperature set a new record in 2024 by exceeding 1.5°C (2.7°F) relative to 1850–1900 (Copernicus Climate Change Service, 2025). In addition to warming, climate change causes sea level rise, changes in precipitation patterns, extreme events like hurricanes and wildfires, ocean acidification, and more. For an overview of the physical science of climate change, see Hsiang and Kopp (2018), IPCC (2021), and IPCC (2023).

[2] Throughout, we use "damages" to refer to the impacts of climate change. Some regions may experience net benefits in the short-term, but there is now widespread consensus that aggregate global impacts in both the short- and long-term are negative. The translation from impacts to damages also involves important ethical questions, such as welfare aggregation, which are beyond the scope of this paper.

[3] Integrated assessment models mathematically represent the economy and the climate system, so that economic activity and the climate affect each other (Kelly and Kolstad, 1999; Nordhaus, 2013).

critical piece of the SCC: no damages, no SCC.[4] 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; Burke et al., 2023).

The large and growing literature on climate damages uses a variety of conceptual frameworks, modeling choices, and data. The original studies developed simulation models of agricultural impacts. Subsequent literature regressed outcomes on mean temperature within a cross-section of countries or counties. More recent literature uses panel data and a modern causal identification perspective. Some researchers use expert elicitation. Yet another strand builds on theoretical contributions from the trade and macro literatures, emphasizing dynamic spatial models.

Why are there so many different approaches? We aim to shed light on what different strands of the literature, and individual papers from those strands, can contribute and on the limitations they each face. We begin with a simplified model of climate change that is *widespread*, *persistent*, and *anticipated*. In particular, 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 instance, as heat waves hurt agricultural production). Others are more nuanced: current capital stocks depend on how agents responded to past changes in weather and respond to anticipated future changes in weather. And some of the terms involve cross-region spillovers: trade adjusts for direct effects of weather in each region and for the evolution of capital stocks in each region.

We next turn to a discussion of methods a researcher might use to study these effects. We discuss how cross-sectional, panel, and structural methods have been used in the literature. Our focus is not so much on the details of estimation (e.g., which fixed effects to include in a panel regression) but rather on conceptual questions regarding what each method might capture. We propose three desiderata: we want methods that are well-identified, informative about the climate change experiment, and robust to model specification. We argue that no single approach yet satisfies all three. Cross-sectional regression methods tend not to be clearly identified and correspond only to local changes in climate; panel regression methods capture weather changes that are localized, one-off, and surprising rather than

[4]We discuss SCC estimates, as they build on the damage estimates on which we center our review. We do not focus on SCC modeling, as it additionally involves questions like the choice of the discount rate, which are beyond the scope of this article. There have been many prior discussions of discounting in the context of climate change (e.g., Nordhaus, 2007; Weitzman, 2007; Dasgupta, 2008; Heal, 2009*a*; Gollier, 2013; Heal, 2017; Millner and Heal, 2023). Two recent papers that have built integrated assessment models of climate change to calculate the SCC are Rennert et al. (2022) and Barrage and Nordhaus (2024).

widespread, persistent, and anticipated; and structural methods require imposing a variety of particular model restrictions. The proliferation of papers using varying methods is a reasonable response to that tension and is likely to continue. It is imperative that these varied approaches speak to one another and ground-truth one another.

We review the recent literature in light of our model and our discussion of methodological approaches, beginning roughly where Dell, Jones and Olken (2014), in this journal, left off. We divide papers into three broad categories guided by the insights from our model: causal reduced-form estimates of direct damages, papers investigating the scope for adaptation, and spatial papers examining cross-region spillovers. In the direct damages strand, we note that data-driven efforts have led to tremendous advances in damage function estimates. These now take causal identification more seriously, offer more granularity across impact categories, and give a better sense of heterogeneity across space. Earlier IAMs were frequently criticized for outdated or unrealistic damage estimates, but recent IAMs have incorporated updated direct damage estimates.

Unfortunately, the recent causal estimates struggle to incorporate adaptation, trade, other general equilibrium effects, and endogenous economic growth. Adaptation—the set of actions people and society take to respond to climate change—determines the total damage from climate change both by affecting the damages people experience and by being costly in its own right (although little research has been done to date to quantify those costs). 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. And long-run determinants of growth determine the far-future projections that are central to climate damage estimates. Recent work on dynamic adjustment and on spatial spillovers aims to advance understanding of these topics by placing more structure on the problem.

The papers we cite are published in a wide variety of outlets: general interest journals in economics; field-specific economics journals encompassing not only energy and the environment but also international economics, macroeconomics, and more; and general interest scientific journals. As such, it may be difficult for individual researchers to keep up to date on the many recent intellectual innovations. We highlight the importance of different academic communities being in communication with one another, so that insights are not siloed.

The challenges we describe are not new.[5] Debates about the relative merits of various methods of estimating climate impacts are decades old (e.g., Cline, 1996; Tol, 2009; Dell, Jones and Olken, 2014; Massetti and Mendelsohn, 2018; Kolstad and Moore, 2020). We argue

[5] And although of special salience in climate change, these challenges are by no means particular to climate change (e.g., Heckman, 2000; Angrist and Pischke, 2010; Deaton, 2010; Einav and Levin, 2010; Mahoney, 2022).

that these debates recur because they are inherent to the enterprise. We formally show that the full set of climate change impacts contains channels that are beyond what a reduced-form analysis can plausibly capture. The search for experimental fit inevitably leads researchers to add structural restrictions. Structural methods inevitably raise questions of robustness to model specification. The search for robustness inevitably leads researchers back towards reduced-form methods, where they must choose between sacrificing causal identification for a type of experimental fit (in cross-sectional methods) versus ensuring causal identification while maintaining only the most limited experimental fit (in panel methods). Innovations hybridize and improve the methods, but the underlying tradeoffs are always present. As a result, we argue that there will always be room for multiple methodological approaches, and we propose that there may be gains from continuing the pursuit of hybrid methods and in using some methods to validate others.

In light of both the tremendous progress over the last few decades, and in light of the inherent conceptual challenges we show with our model and our trilemma, we conclude with a discussion of next steps. We offer some pragmatic, specific suggestions for future research. We discuss what the broad research agenda might look like in an environment of imperfect information. And we discuss ties to policy design when damages are imperfectly knowable.

This paper proceeds as follows. Section 2 lays out a stylized theoretical model, which decomposes the effect of a change in global climate into several channels. Section 3 discusses how various estimation approaches in the literature might be used to investigate these channels, emphasizing trade-offs between model robustness, causal identification, and experimental fit to anticipated global climate change. Section 4 summarizes and analyzes the existing literature on each of the channels. Section 5 proposes directions for future work, some extensions of existing analysis and some more conceptually distinct. Section 6 concludes with deeper challenges and bigger picture thoughts.

2 Stylized Model of Climate Change Impacts

E'en hell hath its peculiar laws.

– Johann Wolfgang von Goethe, *Faust*

To organize ideas, we develop a model of climate change damages that captures the essential challenges in estimating climate impacts. To capture the global, *widespread* nature of climate change, we model two regions; to capture the *persistent* nature of climate change, we model past periods in which the climate could have changed; and to capture the *anticipated* nature of climate change, we model future periods in which the climate is expected to remain

changed. The regions trade consumption goods. We model one factor that is fully flexible within a period and a second factor that is predetermined within a period. The former encompasses any easily adjustable inputs, and the latter encompasses less adjustable stocks of physical capital, resources, or knowledge. We refer to the first factor as "labor" and the second factor as "capital."[6]

Consider a world with two regions, denoted A and B, each comprised of small actors who take the other region's choices as given.[7] 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 $Y_t^j = q_{jt}^A + q_{jt}^B$.

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.

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 $\tilde{w}_t^k$ is independent and identically distributed over time and here independent of C. 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

[6]We keep the setting minimal, but it 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 climate or climate-exposed environmental stocks, climate affecting higher moments of the distribution of weather, or learning about climate change.

[7]Regions can also be interpreted as sectors within a given region.

following infinite-horizon problem:

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

where 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:

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

Define $V^j_t \triangleq V^j(K^j_t, K^k_t, w^j_t, w^k_t)$.

The appendix decomposes the effects of climate on variable, "labor" inputs ℓ^A_{Yt} into four terms:

$$\frac{\mathrm{d}\ell^A_{Yt}}{\mathrm{d}C} = \Gamma^{now}_{At} + \Gamma^{future}_{At} + \Gamma^{past}_{At} + \Gamma^{elsewhere}_{At}. \tag{2}$$

Each term reflects how climate alters weather in some region and time period.

A first term, Γ^{now}_{At}, captures how climate affects region A's time t labor allocation by altering weather w^A_t in that same region and same time period. The expression in the appendix has four components. First, the change in weather may directly alter the marginal product of labor, which affects the incentives to employ labor. Second, the change in weather may alter the value of labor's marginal product by directly affecting total output in region A. Third, the change in weather may alter prices, which also changes the value of labor's marginal product. Fourth, the change in weather may alter investment decisions in region B through channels described below, which in turn may affect investment in region A by changing expectations of prices in later periods. Together, these responses to contemporary, local changes in weather reflect *ex post adaptation to a short-run change in local climate.*

A second term, Γ^{future}_{At}, captures how climate affects time t expectations $E_t[w^A_{t+s}]$ of region A's weather in subsequent periods. These expectations affect region A's time t investment incentives when expected changes in weather alter the marginal product of capital in future

periods. In addition, these expectations can affect region A's time t investment when they affect region B's time t investment. These responses to expected, local changes in weather reflect *ex ante adaptation to an anticipated change in local climate*.

A third term, Γ_{At}^{past}, captures how climate change affects region A's time t labor allocation by altering region A's time t capital stock K_t^A. In other words, it is about how labor decisions are made in response to past weather given past capital investment decisions. These capital decisions are themselves determined in response climate change. 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 (2):

$$\frac{\mathrm{d}K_t^A}{\mathrm{d}C} = -\sum_{s=t_0}^{t-1}(1-\delta)^{t-1-s} f'(\ell_{Ks}^A)\left[\Gamma_{As}^{now} + \Gamma_{As}^{future} + \Gamma_{As}^{past} + \Gamma_{As}^{elsewhere}\right]. \tag{3}$$

The time t capital stock contains a memory of how all prior labor allocations were affected by climate change, whether due to the effect of climate on prior periods' weather (in Γ_{As}^{now}), on prior periods' expectations of subsequent weather (in Γ_{As}^{future}), on prior periods' capital stocks (in Γ_{As}^{past}), or on prior periods' weather and expectations in region B (in $\Gamma_{As}^{elsewhere}$, discussed below). The change in the time t capital stock therefore mixes ex post and ex ante adaptation that occurred prior to time t. The full expression in the appendix shows that the time t capital stock in turn may affect the time t marginal product of labor, the time t value of that marginal product at constant prices, time t prices, and the expected marginal product of capital in later periods, both directly and by affecting investment in region B. These responses to past changes in realized and expected weather terms reflect *adaptation to prior changes in global climate and to prior changes in expectations of global climate*.

A final term, $\Gamma_{At}^{elsewhere}$, captures how climate change also affects weather in region B. The full expression in the appendix shows that current changes in weather elsewhere on the planet affect prices in region A; anticipated changes in weather elsewhere on the planet affect investment incentives in region A; past changes in weather elsewhere around the planet affect capital stocks elsewhere around the planet and thereby affect both prices and investment incentives in region A; and all such changes can affect investment incentives in region B and thereby affect investment incentives in region A. These responses to present, projected, and past changes in other regions' weather reflect *adaptation to changes in other regions' climates*.

Now that we have examined how both variable and predetermined inputs respond to climate change, consider the effects of climate change on output and on welfare. First, the

effect of climate change on region A's output is

$$\frac{\mathrm{d}Y_t^A}{\mathrm{d}C} = \frac{\partial Y_t^A}{\partial w_t^A}\theta_A + \frac{\partial Y_t^A}{\partial \ell_{Yt}^A}\frac{\mathrm{d}\ell_{Yt}^A}{\mathrm{d}C} + \frac{\partial Y_t^A}{\partial K_t^A}\frac{\mathrm{d}K_t^A}{\mathrm{d}C}. \tag{4}$$

In order to recover this effect, we need to estimate the direct effect of altered weather on region A's production and we need to estimate the impacts of climate change on region A's inputs to production. Substituting from (2) and (3), this becomes:

$$\begin{aligned}\frac{\mathrm{d}Y_t^A}{\mathrm{d}C} =& \frac{\partial Y_t^A}{\partial w_t^A}\theta_A + \frac{\partial Y_t^A}{\partial \ell_{Yt}^A}\left[\Gamma_{At}^{now} + \Gamma_{At}^{future} + \Gamma_{At}^{past} + \Gamma_{At}^{elsewhere}\right] \\ & - \frac{\partial Y_t^A}{\partial K_t^A}\sum_{s=t_0}^{t-1}(1-\delta)^{t-1-s} f'(\ell_{Ks}^A)\left[\Gamma_{As}^{now} + \Gamma_{As}^{future} + \Gamma_{As}^{past} + \Gamma_{As}^{elsewhere}\right].\end{aligned}$$

The effects on any one region's output depends on current and past changes in weather in all regions and on current and past expectations of future changes in weather in all regions.[8]

Second, the appendix shows that the effect of climate change on period t welfare in region A is

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

We have the effect of climate change on own production and also the effect of climate change on the budget set, via its effect on prices. The effect on prices in turn depends on how climate change affects production in both regions. We saw above that the effect of climate change on production in any particular region depends on current and past changes in weather in all regions and on current and past expectations of future changes in weather in all regions.

Finally, the appendix shows that the effects of climate on intertemporal value in region A are:

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

[8]It would suffice to estimate the direct effects of altered weather if there were no trade, no durable capital stocks (i.e., as $\delta \to 1$), and no investment from period to period (i.e., as $f', f'' \to 0$). With the latter two conditions, $\mathrm{d}K_t^A/\,\mathrm{d}C = 0$ and the first-order condition for ℓ_{Yt}^A implies $\partial Y_t^A/\partial \ell_{Yt}^A = 0$. This one-region, static limit case corresponds to common analyses in the literature, which we discuss in Section 3.2.

The effects of $\ell_{Y_s}^A$ drop out by the envelope theorem, and therefore so too do adjustments to region A's capital stocks via current and future investment. However, we retain effects on two types of inputs. First, by altering weather and expectations of weather prior to time t, climate change alters the incoming time t capital stocks in both regions (see (3)) and thereby alters both regions' capital stocks in all later periods. Second, by altering weather and inputs in region B, climate change alters prices that affect intertemporal value in region A. Region B optimizes its inputs for their effects on intertemporal value in region B, but its inputs can have first-order impacts on intertemporal value in region A.[9]

In sum, recovering the effects of climate change on variables of economic interest within our stylized framework requires recovering the effects of climate change on (i) productivity; (ii) the value of that productivity, both directly and via prices; (iii) current capital stocks via past weather and past expectations of weather; (iv) current investment, via expectations of weather; and (v) trade, which transmits the effects of climate change on weather and expectations in other regions. The combination of all these effects encompasses ex post and ex ante adaptation, in the present period and in prior periods, and in the region of interest as well as in other regions connected to it by trade networks. The temporal and spatial structure of climate change could each be critical for impacts in any particular region at any particular time.

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 applications. 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.

3 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*

The empirical challenge is to project the impacts of climate change in some period T_1 using only data available up to some earlier period T_0, where $T_0 < T_1$. We discuss prominent

[9] If labor were freely mobile across regions or its services were tradeable across regions in competitive markets, then adjustments to $\ell_{Y_s}^B$ would drop out of $\mathrm{d}V_t^A/\mathrm{d}C$ and the only adjustments to K_s^B would be through changes in the predetermined stock K_t^B.

approaches through the lens of a trilemma: researchers desire methods that (A) are robust to model specification, (B) match the experiment of changing the climate, and (C) are econometrically well-identified. We argue that, as in many other areas of empirical economics, climate researchers can have at most two of the three. Researchers must accept the possibility of nonrobustness to formal structure, of experimental mismatch, or of econometric bias.

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 estimate $\mathrm{d}y_{iT_1} / \mathrm{d}C$.[10]

3.1 Cross-Sectional Methods

A first line of inquiry compares outcomes across locations with different climates (e.g., Mendelsohn, Nordhaus and Shaw, 1994; Nordhaus, 2006; Dell, Jones and Olken, 2009; Albouy et al., 2016).[11] Such a study may estimate a regression of the following form:

$$\bar{y}_i = \beta^{cs} \bar{w}_i + \gamma X_i + \varepsilon_i, \tag{5}$$

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. Assuming exogeneity of the error term, the estimated $\hat{\beta}^{cs}$ captures how changing average weather affects average output.[12]

This experiment changes historical weather in a given location, while holding climates in all other locations fixed. These cross-sectional methods permit counterfactuals that are clearly interpretable as changes in steady-state local climate,[13] and they are robust to different models of how a change in local climate affects outcomes. These methods therefore satisfy desiderata (A) and (B) when it comes to the experiment of a local change in climate.[14]

However, in order to interpret these counterfactuals as changes in global climate, one

[10] We here ignore challenges in projecting secular changes between times T_0 and T_1.

[11] The literature on the determinants of economic growth has undertaken similar analyses of the role of climate in growth (e.g., Masters and McMillan, 2001; Bloom, Canning and Sevilla, 2003), without explicit connection to climate change.

[12] Instead of estimating effects on output, "hedonic" or "Ricardian" studies estimate effects on land value or some comparable metric (e.g., Mendelsohn, Nordhaus and Shaw, 1994; Schlenker, Hanemann and Fisher, 2005; Severen, Costello and Deschênes, 2018). For reviews of Ricardian approaches, see **?**, **?**, and **?**. Using notation from Section 2, these applications regress V_t^i from some period t on $\theta_i C$. The discussion below applies to these types of cross-sectional studies as well.

[13] Cross-sectional comparisons modify expectations of future weather, but these expectations may not be formed only from the historical weather that the researcher observes. This makes cross-sectional methods potentially ill-suited to capturing the process of a repeatedly changing climate.

[14] However, timescales can be important: Dell, Jones and Olken (2014) argue that the estimated effects from a cross-sectional regression may be too long-run to be relevant to near-term climate change.

must assume away all of the trade terms ($\Gamma_{At}^{elsewhere}$) in equation (2) (see Gouel, 2025). These methods therefore require particular assumptions when it comes to the experiment of a global change in climate.

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 (e.g., Darwin, 1999; Hanemann, 2000; Schlenker, Hanemann and Fisher, 2005; Deschênes and Greenstone, 2007; Tol, 2009; Auffhammer and Schlenker, 2014; Dell, Jones and Olken, 2014; Blanc and Schlenker, 2017; Mendelsohn, 2019; Kolstad and Moore, 2020).

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 is not simply a question of interpretation but rather of bias: by treating the neighboring locations as "control" units, the impact on the "treated" location is estimated with bias. And as with bias from omitted variables, a SUTVA violation could generate bias that is either positive or negative.

Third, climate change is widely understood to already be happening. If measured in recent years, the outcome variable $\bar{y}_i$ already incorporates some effects of climate change. The problem is compounded when the dependent variable is the price of a forward-looking asset such as land (i.e., V_t^i), because it then also incorporates expectations of future climate change. Regressions of asset prices on climate would conflate anticipated changes in climate with the effects of the historical climate, which complicates interpreting the coefficients as capturing a change in climate (Severen, Costello and Deschênes, 2018).

In sum, cross-sectional methods target the effects of climate change in the absence of cross-border flows through trade or migration, and they do so without imposing further theoretical restrictions, but they suffer on the econometric identification front. If we could sign the econometric bias in a given application of cross-sectional methods and also sign the experimental bias from ignoring cross-border flows, 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

In part as a reaction 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; Dell, Jones and Olken, 2012; Fisher et al., 2012). Such a study may estimate a panel fixed effects regression of the following sort:

$$y_{it} = \beta^{panel} w_{it} + \delta_i + \nu_t + \varepsilon_{it}, \tag{6}$$

with δ_i a unit fixed effect to account for time-constant unobservables, ν_t a time effect to account for common shocks across space, and ε_{it} an error term.[15] 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, when including time fixed effects, for a time period.

Since this example regression does not control for how factor inputs respond to weather, the (probability limit of the) estimated $\hat{\beta}^{panel}$ captures, in the framework of Section 2,

$$\frac{\mathrm{d}Y_t^A}{\mathrm{d}w_t^A} = \frac{\partial Y_t^A}{\partial w_t^A} + \frac{\partial Y_t^A}{\partial \ell_{Yt}^A} \frac{\mathrm{d}\ell_{Yt}^A}{\mathrm{d}w_t^A}.$$

Comparing to equations (2) and (4), the estimated effect includes the direct effect of weather on output and also the effect on inputs through current weather (labeled Γ_{At}^{now} in equation (2)).

However, this panel method, by focusing on localized unusual weather, is unable to capture the other terms in equation (2), which reflect the effect of climate change on past weather, on expectations of weather, and on weather in other locations.[16] And it cannot be used to estimate how climate alters output via changes to the incoming capital stock in equation (4).[17] That is, this estimator reflects a localized, one-off, and surprising weather

[15] Some papers include time effects to control for common shocks across space; others include common linear or higher-order time trends; and some include location-specific time trends. Some papers estimate this regression in differences, again with varying combinations of time controls. It is well-known that measurement error can attenuate estimates more severely in the presence of fixed effects (e.g., Arellano, 2003). Researchers therefore face trade-offs in their choice of specification and controls. For instance, including additional time fixed effects or time trends may better control for unobservable confounders but risks increasing the fraction of residual variation comprised of measurement error (Auffhammer and Schlenker, 2014; Blanc and Schlenker, 2017).

[16] See Shrader (2023) and Lemoine (2023) on using weather forecast data to capture Γ_{At}^{future} in panel regressions.

[17] In addition, the evaluation point for the partial derivatives can be different from the evaluation point for

change rather than the widespread, persistent, and anticipated change in weather produced by climate change.[18]

The appeal of panel methods is that they are potentially well-identified, as high-frequency weather is typically exogenously assigned.[19] And they identify the effects of weather without imposing a particular model of how weather affects the economy. They therefore plausibly satisfy desiderata (A) and (C) when it comes to the effects of weather.

One often-discussed drawback of panel methods is that they leave out much adaptation (e.g., Deschênes and Greenstone, 2007; Dell, Jones and Olken, 2014; Massetti and Mendelsohn, 2018; Kolstad and Moore, 2020). To some, this omission is a virtue of the method: 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 (e.g., Hsiang, 2016).[20]

More generally, as shown in Section 2, the envelope theorem will not justify reducing the effect of climate change to Γ_{At}^{now} in a model with a future, a past, and regions interacting through trade. In that case, panel methods do not, by themselves, satisfy desideratum (B).

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the partial derivatives 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.

[18] A small number of papers has relied on time series variation, putting global temperature (or other aggregated temperature) on the right-hand side (Bansal and Ochoa, 2011; Bansal, Kiku and Ochoa, 2016; Bilal and Känzig, 2024). In this case, the effects are for a global, rather than localized, change in weather, sometimes motivated by a desire to capture $\Gamma_{At}^{elsewhere}$. The estimated effects still may not reflect the persistent and anticipated nature of climate change. One challenge for identification is isolating the component of global temperature changes that are true *shocks*: to do this, one must believe that the time series method (e.g., a filter) reflects how agents form expectations over future weather. If these methods successfully isolate shocks, then they do not attain desideratum (B) as they no longer match the experiment of persistent and anticipated global climate change. But if these methods do not successfully isolate shocks, then they do not attain desideratum (C) as they are not clearly identified in the econometric sense. Another challenge is that these regressions rely on limited variation in the data due to a small number of observations and strong global trends.

[19] With three important caveats. First, time-varying confounders may cause omitted variables bias (Fisher et al., 2012; Blanc and Schlenker, 2017). Second, 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. See Zappala (2024) for recent work focused on SUTVA and Rudik et al. (2022) for a demonstration of that bias. Third, weather shocks can be anticipatable, even conditional on fixed effects, given the wide availability of weather and climate forecasts (Shrader, 2023). And different shocks may not be equally anticipated. In particular, temperatures that turn out to be extreme tend to be, by construction, more extreme than their forecasts. Conventional panel specifications then identify the effects of relatively surprising extreme temperatures, which will often not be the effect of interest for projecting climate impacts (Bakkensen et al., 2025). Moreover, as discussed in footnote 21 below, there is a trade-off between using lower-frequency data to potentially identify more aspects of climate damage versus using higher-frequency data to make causal identification more plausible (Hsiang, 2016).

[20] It is important that the researcher 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 such as agricultural yields or an intermediate object such as revenue rather than an *optimized* object such as the present value of expected profits.

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 critical. To extrapolate panel estimates to climate change, we have to assume that all of these aspects of climate change are jointly small.[21]

In sum, panel methods focus on obtaining well-identified estimates of weather impacts without imposing theoretical restrictions, but to interpret their estimates in terms of climate change requires one to assume away capital and resource stocks and to assume away cross-border flows such as trade and migration. From these methods, we learn how large Γ_{At}^{now} may be and which types of weather variables are likely to be important channels for climate change.

3.3 Mixed Panel/Cross-Sectional Methods

Some work mixes panel and cross-sectional methods (e.g., Butler and Huybers, 2013; Auffhammer, 2022; Carleton et al., 2022). These papers may estimate a regression of the following form:[22]

$$y_{it} = \beta^{panel} w_{it} + \gamma^{cs,panel} \bar{w}_i w_{it} + \delta_i + \nu_t + \varepsilon_{it}. \tag{7}$$

This regression extends the benchmark panel regression (6) to include the interaction between a location's average weather and its weather shocks. This regression approach mitigates concerns about omitted variables bias relative to cross-sectional methods by considering only

[21] Following Dell, Jones and Olken (2012) and Burke and Emerick (2016), some work estimates models in "long differences," in which the timestep of a panel regression is on the order of a decade rather than on the order of a day or year. In some cases, the remaining variation is cross-sectional, and in others, the data retain panel variation. Either way, the hope is that the remaining variation reflects variation in climate trends. But this raises a dilemma. If the variation in weather over long timesteps indeed largely reflects climate trends, then because climate trends are not randomly assigned, any estimates may in fact reflect omitted variables that are correlated with climate trends rather than the climate trends themselves (Kolstad and Moore, 2020). In that case, we have lost desideratum (C). But if the variation in weather over long timesteps largely reflects sequences of weather shocks, then we are back to relying on the same weather shocks as panel methods. In this case, long differences will not capture any adaptation that could not be captured in a traditional panel regression and we have lost desideratum (B) (Lemoine, 2023). Some work finds that long difference estimates are similar to standard panel estimates and interprets this finding as evidence of a lack of adaptation (Dell, Jones and Olken, 2012; Burke and Emerick, 2016), but this similarity may instead reflect that the panel and long difference estimators are using the same underlying variation.

[22] Some work estimates this equation in two stages, by first estimating equation (6) unit by unit and then regressing the resulting $\hat{\beta}_i^{panel}$ on $\bar{w}_i$.

the cross-sectional component of panel variation, but it does not totally eliminate omitted variable concerns (Mendelsohn, 2019; Kolstad and Moore, 2020).[23]

The main question is whether we can mitigate the experimental limitations of panel methods by summing the estimated $\hat{\beta}^{panel}$ and the estimated $\hat{\gamma}^{cs,panel}$. To wit, the literature sometimes interprets the difference in the effects of weather between hotter and colder locations as evidence of adaptation. Phrased another way, then, the question is whether $\hat{\gamma}^{cs,panel}$ includes the Γ_{At}^{future} and Γ_{At}^{past} terms that are missing from $\hat{\beta}^{panel}$, 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 (7) is the cross-derivative of output with respect to weather and climate. $\hat{\gamma}^{cs,panel}$ therefore tells us how the marginal effect of a one-off, surprising, localized shock changes with background climate. However, this cross-derivative is not part of the Γ_{At}^{now} that appears in the marginal effect of climate change derived in Section 2. In addition, it still does not include the Γ_{At}^{future} and Γ_{At}^{past} terms that are not captured by panel regressions (nor does it include the $\Gamma_{At}^{elsewhere}$, though that has not been the focus of most applied research on adaptation to date). These past and future terms reflect how past responses to weather and current responses to anticipated weather affect labor, capital, and output today. The formal expressions for these terms (derived in the appendix) are not cross-derivatives of Γ_{At}^{now} with respect to C. Although $\hat{\gamma}^{cs,panel}$ does not capture the effects of weather at all time horizons, the information in the cross-derivative may be useful when projecting consequences of nonmarginal climate change (see Section 5).

Intuitively, the idea behind regression (7) 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 the effect of a shock conditional on that adaptation. The problem is that this method captures long-run adaptation only in as much as it is part of the response to shocks to current weather, but there are adaptation responses to climate change that impact output (or welfare) regardless of its mediating impact on current weather responses. For instance, imagine that climate change only mattered by affecting capital stocks. In that case, $\hat{\gamma}^{cs,panel}$ would 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 in equation (3) showing the effect of climate change on capital).

In sum, these mixed panel/cross-sectional methods complicate the clean identification of

[23]Specifically, heterogeneity along the average weather dimension might be due to differences in average climate or to any factor correlated with average climate (see Carleton et al., 2022, pg. 2040). See Schlenker, Roberts and Lobell (2013) for an example of this critique.

panel methods in the service of estimating terms that are relevant to nonmarginal changes in climate. As with panel methods, interpreting their estimates in terms of climate change requires a modeler to assume away capital and resource stocks and to assume away cross-border flows such as trade and migration. From these methods, we learn how stable Γ_{At}^{now} may be with climate change and we learn about heterogeneity in direct effects, even when this heterogeneity does not come with a causal interpretation.

3.4 Structural Methods

Many of the first attempts at estimating damages were structural models of agricultural production (e.g., **?**Rosenzweig and Iglesias, 1994). Some recent work attempts to capture the spatial structure of climate change by directly modeling trade and migration flows (see Section 4.3). Other recent work attempts to capture the temporal structure of climate change by directly modeling adaptation investments (e.g., 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 a response surface:

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

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 surface $f(\cdot, \cdot)$ that captures all of the channels derived in Section 2, including even the $\Gamma_{At}^{elsewhere}$ term missing from the other methods discussed so far.[24] Because the experiment is directly under the modeler's control, it can satisfy desideratum (B). And the estimation might be done in an econometrically sophisticated way that attempts to satisfy desideratum (C), although in practice many parameters are assumed or calibrated rather than estimated.

However, these methods suffer on desideratum (A). They are only as good as the functional form for $m(\cdot, \cdot)$. It is difficult to know when the functional form is even roughly correct, and the function $m(\cdot, \cdot)$ will not capture channels from Section 2 if the model $M(\cdot, \cdot)$ from which it emerges does not include those channels.

We saw above that we would have to make strong assumptions about cross-border flows and capital stocks to project climate impacts from cross-sectional or panel methods. Such

[24]Moreover, this method may go beyond the local analysis of Section 2 to model the process of transitioning from one climate to another.

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!). Structural methods have the advantage of making their model assumptions explicit. However, because cross-sectional and panel methods estimate the response surface directly, they are potentially robust to a broad set of underlying models, whereas structural models have to make many particular modeling choices and it can be difficult to evaluate the robustness of their conclusions to a broad class of alternate models.

In sum, structural methods can attempt counterfactuals beyond the reach of the other methods. The trade-off that comes with such methods is familiar within economics (Chetty, 2009; Acemoglu, 2010; Leamer, 2010; Nakamura and Steinsson, 2018): the natural experiments at hand (weather shocks) are not externally valid for the question of policy interest (about climate change). Imposing more structure can help bridge this gap but at the cost of stronger assumptions on functional form and potentially weaker identification of causal effects. As prior discussions across different economics fields also make clear, however, estimates from natural experiments and structural approaches can complement each. We anticipate progress in the coming years at using moments in empirical data to discriminate among models used to simulate climate impacts.

3.5 Structurally-Motivated Reduced-Form Methods

Some recent work attempts to combine the econometric identification and model robustness of panel methods with the experimental advantages of structural methods. 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 sufficient statistics approaches in the public economics literature (Chetty, 2009; Kleven, 2021).

In particular, 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 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.

As another example, Lemoine (2023) considers the effects of climate change on outcomes

that are not subject to the envelope theorem. This paper analytically derives the true effect of climate change within a dynamic environment, analytically derives the effects captured by coefficients from panel methods, and then shows how to bound the true effect of climate change from 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, as they are limited to experiments attainable with panel methods' coefficients, but gains a degree of model robustness and potentially improved identification. Relative to panel methods, the researcher gives up robustness to the whole class of models that all satisfy the same restrictions on cross-border flows and capital stocks but gains the ability to loosen some of those restrictions and thereby speak more directly to the effects of climate change. In the future, these hybrid methods may be used as a check on other methods: differences with panel methods may indicate when capital stocks or cross-border flows are important, and differences with structural methods may indicate when functional form assumptions are important.

4 Channels for Climate Damages

The conceptual model in Section 2 shows that the effects of climate change manifest through multiple channels: the direct effect of changes in local weather, agents' adaptation responses to these changes, and spillovers from other locations. Section 3 describes alternative methods used to identify some or all of these channels. We now discuss papers relating to these three channels. Many of these papers span multiple channels, so the goal is not to pigeonhole papers. Rather, we use individual papers to highlight where the frontier is and where it might still need to go.

4.1 Direct Effects

I heard many things in hell.

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

Much of the existing literature studies the immediate and direct effects of weather on economic outcomes. In the conceptual model, this is $\partial Y_t^A / \partial w_t^A$, as in the term on the right-hand side of equation (4).

Multiple excellent reviews have summarized the state of knowledge on these effects (Dell, Jones and Olken, 2014; Carleton and Hsiang, 2016; National Academies of Sciences, Engineering, and Medicine, 2017; Auffhammer, 2018; IPCC, 2023; Hogan and Schlenker, 2024).

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; we discuss how these estimates are used in integrated assessment modeling and in policymaking; and we discuss how, in some cases, identifying the direct effect is inextricably linked to identifying adaptation and spillovers.

Damage functions in early, influential IAMs like DICE, PAGE, and FUND assumed that climate impacts would be a smooth function of average temperature (Nordhaus, 1993; Hope, Anderson and Wenman, 1993; Tol, 1997). The damage function's parameters were based on a small number of studies—largely of impacts on agriculture and from sea level rise—and typically conducted using data only from the U.S. or Europe (Howard and Sterner, 2017). These shortcomings have received criticism (Sterner and Persson, 2008; Stern, 2013; Pindyck, 2013*a*; National Academies of Sciences, Engineering, and Medicine, 2017). In response, researchers have focused considerable attention on increasing the coverage of climate effects on different aspects of the economy and regions of the world.

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 effects of weather on output using causal methods.[25] This literature has applied methods and frameworks from the causal identification revolution that swept through applied microeconomics (Angrist and Pischke, 2010), here 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 effects on output is the one on climate impacts on the agricultural sector. We begin our review with that sector both because of the importance of climate impacts on the agricultural sector and because of the way it exemplifies many important issues. We then proceed with other outcomes, including energy use, mortality, productivity, and more.

One influential paper that typifies the current approach is Schlenker and Roberts (2009), which leverages weather shocks in a fixed effects framework to estimate the impact of annual temperature variation on U.S. agricultural yields. This paper analyzes effects on corn, soybean, and cotton yields. A key insight—and a running theme through much of the literature that has followed—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

[25] In the conceptual model, we describe the economic outcome Y_t^A as production, but our analysis of $\mathrm{d}Y_t^A/\,\mathrm{d}C$ in equation (4) applies to many outcomes that are functions of weather, variable inputs, and fixed inputs.

decline steeply. The paper projects the effects of climate change by predicting changes in yield based on those estimates under warmer, potential, future weather distributions. It projects severe crop yield declines under global warming because the relatively large, negative effect of more frequent hot temperatures outweighs the modest gain in yield from less frequent cold temperatures. In addition to these central findings, the paper also presaged many of the debates that would follow: it qualitatively discussed—but did not estimate—the effect of adaptation, of other dimensions of climate like precipitation, of slow-moving climate changes like CO_2 fertilization, and of price changes and other spillovers as well as related consequences for food security.

Schlenker and Roberts (2009) has spurred a number of papers on other crops, other regions, and other time periods. Examples include Schlenker and Lobell (2010), which investigates yield impacts for five staple crops in Africa, again finding qualitatively important negative effects of heat shocks. Ortiz-Bobea et al. (2021) examine aggregate food production—for both crops and livestock—globally. One innovation in this paper's approach is modeling the impact on the growth rate of agricultural productivity. The authors attribute a slowdown in agricultural productivity growth over the last several decades to the impact of global warming. They estimate the greatest impacts in Africa, the Near East and North Africa, and Latin American and the Caribbean.

As an illustration of how these causal estimates can be used to gain a better understanding of climate impacts, Moore et al. (2017) place causally-identified weather impacts on agriculture into an integrated assessment framework. In line with a general theme throughout this literature, in doing so they find that climate damages are larger than previously thought, with substantial losses for global welfare coming from the agricultural sector. Other papers that incorporate causally-identified agriculture estimates into a comprehensive, multi-sector damage estimate are Hsiang et al. (2017) and Rennert et al. (2022). In both papers, agricultural damages make up a substantial portion of aggregate damages, although both note the uncertainties that stem from non-heat effects (some of which are positive) such as precipitation and CO_2 fertilization. For a review of related papers, we refer the reader to Dell, Jones and Olken (2014) and Ortiz-Bobea (2021). Bezner Kerr et al. (2022) reviews the broad literature across disciplines on the effects of climate change on agriculture, forestry, fisheries, and aquaculture.

Agricultural outputs and yields are of course not the only area of the economy impacted by climate change. A robust literature attempts to generate estimates of other impacts. The primary outcomes considered in this literature are energy use, morbidity and mortality, conflict, and labor productivity. These outcomes do not correspond directly to output effects ($\partial Y_t^A / \partial w_t^A$)—in fact, changes to energy use are an adaptation effect—but they do illuminate

mechanisms by which sectoral or aggregate output could be impacted in direct and immediate ways.

Estimates for energy use or expenditures were, along with agricultural impacts, some of the earliest causally-identified impact estimates. Papers such as Davis and Gertler (2015), Auffhammer, Baylis and Hausman (2017), and Li, Pizer and Wu (2019) show that in countries as varied as China, Mexico, and the U.S., electricity expenditures are expected to rise with global warming because of increased air conditioning needs. 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—varying 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. For instance, Wenz, Levermann and Auffhammer (2017) project decreases in electricity demand in Northern Europe. And Rode et al. (2021), in providing the first global estimates, project energy expenditures to fall over the next century under either moderate- or high-emission scenarios. They project that electricity use will increase in most countries but will be outweighed by reduced consumption of other fuels (and by reduced electricity use in a few northern countries).

4.1.2 Estimated Mortality Effects are Large

The U-shaped impact of temperature also appears for mortality estimates.[26] However in this case, the increase in mortality around most of the world is projected to outweigh the decreases in mortality expected in cold climates, leading to an overall increase in 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. The authors project a large impact of climate change on mortality by end of century: amounting to three percent of GDP in 2100, substantially larger than previous estimates. The authors also document spatial heterogeneity, as they project warming to lead to many more deaths in some countries than in others. This heterogeneity results from both differences in baseline temperature (combined with the U-shaped mortality effects) and differential slopes: the relationship between temperature and mortality is steeper in some places than in others in a way that is correlated with both

[26]Deschenes (2014) and Graff Zivin and Shrader (2016) review estimates of direct effects on mortality and other aspects of health.

income levels and historical exposure to heat. 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, which 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. (Mechanisms for offsetting those effects are discussed below when we review the adaptation literature.) Hsiang, Burke and Miguel (2013) and Burke, Hsiang and Miguel (2015*a*) summarize the existing 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. In a related strand, Carleton (2017) and Burke et al. (2018) estimate heat effects on suicides. Carleton (2017) notes that effects in India are driven by heat shocks during the growing season, thereby associated with weather-related shocks to agricultural income. There are fewer papers on morbidity than on mortality, although two recent papers include Carlson et al. (2023) and Gould et al. (2024). As with mortality, warming in some cases is projected to reduce morbidity. For instance, cold weather-induced illnesses may decrease, or temperatures may move away from the ideal temperature for malaria-carrying mosquitoes (while potentially becoming more suitable in other locations).

4.1.3 Parallels in Other Outcomes: Labor, Climate Amenities, and Aggregate GDP

A number of papers estimate labor market effects. This work originates with Graff Zivin and Neidell (2014), which estimates the effect of temperature on labor supply. Additional literatures 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). These papers generally find that heat stress lowers labor supply, labor productivity, and exam performance.[27] Like the agricultural, energy, and mortality outcomes, labor productivity and learning frequently exhibit nonlinear effects, with damages sharply 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 suggest inequality in the ability to adapt to heat and potentially in the ability to adapt to climate change, topics we return to below.

[27] Thus far, we have discussed outcomes that are functions of both weather and choices. These outcomes correspond to effects such as those in equation (4). In contrast, the effect of weather shocks on labor productivity is the first component of Γ_{At}^{now} (see appendix), which in turn controls the choice of variable inputs in equation (2).

Many additional outcomes are more closely related to the adaptation terms in the conceptual model. One example is migration, which we discuss in Section 4.2 below. Some outcomes are more closely related to welfare effects ($\mathrm{d}V_t^A/\,\mathrm{d}C$ in the model), such as pleasure associated with climate amenities. Albouy et al. (2016) use 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. **?** 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. **?** compare the hedonic and discrete choice approaches.

Here we have focused on the direct effects of weather on individual sectors, reflecting the focus of 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 (e.g., Dell, Jones and Olken, 2012; Burke, Hsiang and Miguel, 2015*b*; Newell, Prest and Sexton, 2021) or regional output and income (e.g., Colacito, Hoffmann and Phan, 2019; Kalkuhl and Wenz, 2020; Lemoine, 2023).[28] As with sectoral-level impacts,[29] these tend to find 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 sector-specific impacts, they may not be robust to empirical choices (Newell, Prest and Sexton, 2021; Barker, 2024), and there are fundamental questions about whether effects on the level of GDP or on the growth rate of GDP are more plausible (Pindyck, 2013*a*; Newell, Prest and Sexton, 2021). The answer to this last question is crucial: projecting impacts over the next 100 years can yield very different damage estimates if the effects of a level change in temperature accumulate via lowered growth rates. It is important to develop formal models that can distinguish between a series of level impacts and a true growth impact, based on an analysis of mechanisms through which temperature affects the economy. Further refinements in empirical strategy might also help to distinguish these two alternatives.[30]

[28]Different papers in this literature use different measures of temperature, including some that use global average temperature (Bansal and Ochoa, 2011; Bilal and Känzig, 2024).

[29]We refer to these impacts as occurring within "sectors" as is common in the literature but note that not all impacts occur within traditional economic sectors. For example, one of the most important consequences of climate change is direct temperature-related mortality, which is partly a nonmarket impact.

[30]For instance, Kahn et al. (2021) uses a stochastic growth model to derive an estimating equation that nests level and growth effects. Nath, Ramey and Klenow (2024) estimate a model where climate impacts can be temporary or persistent and find that while effects of warming are not permanent, they are persistent. Ultimately, it may be impossible to firmly distinguish growth impacts from a series of level impacts in the finite data available (see Temple, 2003).

4.1.4 Direct Effects, the Social Cost of Carbon, and Policy Updates

The proliferation of new estimates of direct effects of climate change has affected policy evaluation. The SCC monetizes the reduction in welfare from emitting one more unit of carbon dioxide along a predefined emission pathway (Nordhaus, 2014, 2019).[31] It 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), 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), and the parameter proved useful for coordinating the academic literature around improving the number.

Over the subsequent decade, there were widespread calls for methodological and conceptual updates to the federal government's SCC estimate (Burke et al., 2016; Carleton and Hsiang, 2016; Diaz and Moore, 2017). 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 four modules—"socioeconomic and emissions projections, climate modeling, estimation of climate impacts and damages, and discounting net monetary damages" (p. 6)—so that each individual component could be modernized by experts in each subject area (and updated every five years thereafter).

Two teams of researchers—the Climate Impact Lab (CIL) and Rennert et al. (2022)—undertook implementation of the NASEM recommendations. The latter team released an open-source model, GIVE (Greenhouse gas Impact Value Estimator), to address both NASEM's modularization recommendation and its recommendation for greater transparency. The paper reports a central estimate of the SCC of \$185 per ton (2020 dollars), with a range of alternative values to account for uncertainty and alternative discount rates. This estimate was nearly four times higher than the federal government's SCC at the time, a result both of using lower discount rates and of updating direct effect damage estimates.

Policymakers have paid close attention to these empirical and conceptual updates. In particular, in 2023 under the Biden administration, the U.S. Environmental Protection Agency released new estimates of the SCC based on adapting the frameworks from Howard and Sterner (2017), Carleton and Greenstone (2022), and Rennert et al. (2022). These new es-

[31] In the absence of other externalities or fiscal considerations, the optimal carbon tax equals the social cost of carbon along the optimal emission pathway.

timates place the SCC at $190 per ton of CO_2 for emissions in 2020 (2020 dollars), using a near-term discount rate of 2% (alternative estimates are also provided for later years, and for both higher and lower discount rates) (EPA, 2023). The new SCC is based on estimates of the effect of temperature, sea level rise, and CO_2 fertilization on mortality, agricultural output, energy use, labor supply, and coastal land use (for a summary, see EPA, 2023, Table 3.2.1).

In summary, much progress has been made on estimating the direct effects of climate change on many important outcomes: output and productivity in key sectors like agriculture; health and mortality effects; and numerous other economic and social outcomes. Weather clearly matters for a range of economic outcomes. The bulk of these papers have implied much higher damages than was previously believed. And policymakers are taking these estimates seriously. A missing component, though, is that these papers are generally unable to address comprehensively and with nuance the potential importance of adaptation effects and general equilibrium effects. We next turn to emerging literatures in these areas.

4.2 Adaptation

But in hell the torments cannot be overcome by habit.

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

Adaptation—actions that individuals or groups take to prepare for or adjust to climate change—affects the amount of damage that climate change will ultimately cause. Given that climate change is already well underway and that we expect substantial further changes to come, adaptation is an increasingly relevant area of study, policy focus, and practical interest for people all around the world. And because adaptation involves endogenous responses by agents, insights from economics are particularly helpful. Adaptation is contingent on all of the things that affect an agent's ability and willingness to act, including the costs and benefits of that 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 due to the challenge of studying economically contingent behavior, the wide range of possible adaptation actions, the time scales involved in climate adaptation, and the need for estimates of "macro" adaptation that can inform aggregate damage functions for use in IAMs.[32]

[32]There have also been calls for research into incentives for adaptation (e.g., Smith, 2010). Although adaptation policy is a potentially important determinant of climate damages, we will touch on that literature

One of the challenges in studying adaptation is the multiplicity of definitions of "adaptation" that can 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 short-run responses, as denoted by the $\mathrm{d}\ell_{Yt}^{A}/\,\mathrm{d}C$ term from equation (2), or long-run investments, captured by the $\mathrm{d}K_{t}^{A}/\,\mathrm{d}C$ term from equation (3). This definition is broad in the sense that it captures *anything* an agent does to adjust to a changing climate. For example, a farmer might adapt to a hotter climate through adoption of heat-resistant seed varieties but also through changes in more routine practices that help with heat resilience, such as more intensive watering, pest control, or weeding.[33]

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, which could make climate change far less of a problem as it unfolds over the coming centuries (e.g., Ausubel, 1991; Schelling, 1992). For example, households in developing countries are likely to adopt air conditioning as they face hotter temperatures and also as they grow richer (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 a secular trend in damages and consider it part of the background we must project when analyzing climate change. Some studies look at how the sensitivity of economic outcomes to temperature changes over time or space (e.g., Turner et al., 2012; Bleakley and Hong, 2017; Burke et al., 2024). These studies can be important for determining that there is scope for adaptation. However, the detected changes need not themselves reflect adaptation, as they could be due to variation in other (non-climate) factors.

Studying adaptation sheds light on three important questions related to climate change damages. First, it helps us better understand empirical damage estimates derived from historical data. Examining adaptation mechanisms can help corroborate findings of high or low damages across people or places. For example, two recent reduced-form analyses of temperature-related mortality have concluded that hot days are less harmful in hot locations (Carleton et al., 2022) or even beneficial in hot locations (Heutel, Miller and Molitor, 2021). If this heterogeneity is causal in the sense that sensitivity to heat within a location will fall as climate change makes it hotter, then accounting for this effect reduces projected mortality from climate change substantially.[34] A better understanding of the mechanisms by which

only indirectly.

[33]One of the major goals of economic studies of adaptation is to move beyond studies of single adaptation actions and instead be able to say something about the overall benefits and costs of the suite of adaptation behaviors that agents can engage in. Care must be taken, however, that valid projections of future adaptation benefits and costs can still be estimated when abstracting from individual behavior.

[34]In this case, U.S. mortality would actually be *lower* with climate change (Heutel, Miller and Molitor, 2021) but global mortality would still be higher with climate change (Carleton et al., 2022).

people avoid heat-related health shocks would help determine to what degree estimated heterogeneity in temperature sensitivity reflects adaptation that should arise under future climate change.

Second, understanding adaptation improves our ability to project future climate damages, a crucial step in calculating the SCC and setting the stringency of mitigation policy. Understanding adaptation, and in particular the relationship between adaptation and the direct effects discussed above, is central to producing accurate projections because expected future damages should alter the incentive of agents to adapt. This has been characterized as a form of the Lucas critique as applied to climate damage projections (Kahn, 2015). Because many important questions about adaptation remain unanswered, climate change damage projections in the literature often do not explicitly represent adaptation (Nordhaus, 1993; Schlenker and Roberts, 2009).

Third, public policy can affect adaptation, making it important to understand the effectiveness of adaptation in different contexts and the opportunities for policy to encourage adaptation as well as the ways in which policy might inadvertently stymie adaptation. Adaptation has received substantially less policy focus than mitigation, but as climate change continues, this balance is likely to shift. Policy can impede adaptation or even induce apparent maladaptation. Scholars have long discussed how agricultural policies, in particular, may impede adaptation (**?**). This effect has 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).[35]

4.2.1 The High Dimensionality of Adaptation Actions

Much of the existing work on adaptation has studied specific adaptation actions such as migration (Missirian and Schlenker, 2017), time use (Graff Zivin and Neidell, 2014), employment (Downey, Lind and Shrader, 2023), crop switching (Rising and Devineni, 2020), farm relocation (Sloat et al., 2020), or adoption of air conditioning (Barreca et al., 2016). In some cases, the papers also estimate the benefits of adaptation (the second and third terms in equation (4)).

A challenge when estimating adaptation benefits comes from the potentially high dimen-

[35]Maladaptation refers to actions that make agents more sensitive 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 the agent even as it increases climate damage.

sionality of different adaptation actions. If one wants a comprehensive estimate, for instance, of the benefits of adaptation (the $(\partial Y_t^A/\partial \ell_{Yt}^A)(\,\mathrm{d}\ell_{Yt}^A/\,\mathrm{d}C)$ term that appears in equation (4)), it is not sufficient to estimate the effect of any single adaptation action. Shrader (2023) proposes using forecasts of upcoming weather shocks to identify the benefits of ex ante adaptation actions. Carleton et al. (2022) estimates interactions between temperature shocks and average temperature, allowing for reduced-form heterogeneity in climate damages that might reflect ex interim adaptation. We discuss challenges with interpretation of these estimates in Section 3.3.

Our model makes clear that both short- and long-run actions are potentially important for adaptation. Much of the research cited above has focused on either short-run adaptation behavior (e.g., changing time use on a day with hot temperatures) or responses that might have durable effects but which occur in response to short-run changes in weather (e.g., migration in response to a severe but temporary drought). This focus is for econometric identification reasons that are discussed in Section 3. And short-run adaptation actions can have important effects on climate damage. For instance, actions in response to even 1-day-ahead weather forecasts substantially reduce mortality from hot temperatures (Shrader, Bakkensen and Lemoine, 2023).

Long-run adaptation is also likely to be important for future climate change damages. However, estimates based on short-run weather shocks might not be a good guide to long-run effects (see Lemoine (2023) for formalization). A classic example is irrigation for agriculture (Auffhammer and Schlenker, 2014; Blanc and Schlenker, 2017; Auffhammer, 2018). 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 case of depletable resources, 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. In the irrigation example, agents may install new irrigation systems or drill deeper wells when they anticipate or experience regularly hot, dry conditions. One of the distinguishing characteristics of climate change as an economics problem is the wide range of relevant temporal scales. Determining how much adaptation is of the depletable resource type versus the adjustment cost type is important for projecting future climate damages.[36]

Technical change and the development of new production practices can also be thought of as long-run adaptation. For projections of climate change damage over hundreds of years,

[36]Hornbeck and Keskin (2014) and Hagerty (2022) empirically estimate long-run adaptation to water scarcity in agriculture.

such adaptation is likely to be especially important but also especially hard to investigate using any single empirical approach. Historical evidence suggests that plant breeders and farmers have been able to adapt to substantially different geographic climates but that 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, and 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 (**?**).

For extreme events made more likely by climate change, adaptation can include investing in resilience against these weather outcomes. Fried (2022) and Bakkensen and Barrage (2024) 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 demonstrates that greater storm risk increases precautionary savings and, potentially, growth 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 (Castro-Vincenzi et al., 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).

Finally, adaptation can also mitigate exposure to uncertain climate change rather than to effects known with certainty. 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). For instance, firms that learn about climate risks may choose different suppliers (Pankratz and Schiller, 2024), and farmers who are uncertain about monsoon dynamics may choose planting times with an eye towards robustness (Kala, 2019). Financial markets can also be important tools through which agents achieve financial resilience. For instance, investors may choose their portfolios so as to financially hedge climate risks (Engle et al., 2020), and homeowners may choose mortgages that implicitly insure them against sea level risks (Bakkensen, Phan and Wong, 2025).

4.2.2 The Continuous Need for Adaptation Actions

Climate change is not a one-time event. Nonstationarity in the climate continuously causes changes in the climate state, necessitating repeated—and potentially costly—adjustment by economic agents. Some original economic analyses of climate change emphasize that adjustment costs could be an important source of climate damage.[37] And critiques of early studies on agricultural damage highlight that such estimates did not include adjustment costs (Quiggin and Horowitz, 1999; Kelly, Kolstad and Mitchell, 2005). Within a dynamic model of timber markets, **?** show how dynamic adjustment reduces the relevance of steady-state comparisons. Beyond capital adjustment costs, Ostrom (1990) (writing more broadly about commons problems) notes that costly adjustment is an important determinant of the response of social systems to changing conditions, saying that "there is the possibility that external changes may sweep rapidly over a group, giving them insufficient time to adjust their internal structures to avoid the suboptimal outcomes." Work combining micro and macro evidence would help inform these costs of adjustment.

In addition to changes in average temperature, climate change also has the potential to change the volatility of weather systems.[38] Over and above the costs paid for adjusting between equilibria discussed above, increased volatility also causes damage as agents pay costs to adjust to more frequent shocks or find themselves more routinely misallocated. Downey, Lind and Shrader (2023) estimates this form of climate volatility-driven adjustment cost for the construction sector in the U.S.

In both of these cases, adaptation plays a dual role. On one hand, costly adjustment to changes in the climate leads to damage. On the other hand, some types of adaptation can help ease this source of damage. 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.

4.2.3 Adaptation Costs and Constraints

Beyond adjustment costs, adaptation costs and constraints more generally are important determinants of past and future adaptation. Early work on climate damages did account for adaptation costs within simulation models, but the level of adaptation was fixed exogenously

[37] Fisher and Hanemann (1993, p. 151) write, "we would urge that more of the economic research be focused on the potentially very large costs of adjustment affecting stocks of physical, human, and natural capital," as "virtually all" climate economics research to date was more of a comparative static analysis.

[38] Increased volatility is especially likely for precipitation (IPCC, 2021).

rather than emerging from incentives and calculations within the model (Fankhauser and Tol, 1996). In more recent literature, costs of adaptation have not received as much empirical attention as the benefits of adaptation, in part because accurate estimation of adaptation benefits helps improve estimates of the direct effect of climate change that have been central inputs into climate mitigation policy. However, because successful mitigation would allow agents to avoid paying adaptation costs, these savings should be factored into the benefits of limiting climate change.

Costs are also challenging to observe in relevant datasets, and more work to measure adaptation costs would be valuable. Two of the most-studied climate impacts—agricultural losses and mortality—illustrate this challenge. In both cases, the economic outcome (yield and mortality, respectively) is relatively well-measured across many countries around the world, permitting estimates of direct effects and adaptation benefits.[39] 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 even well-established, much less the costs of those actions.[40]

In response to this challenge, Carleton et al. (2022) back out adaptation costs from their estimated marginal benefits. They assume 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 an instant.[41] In that case, they show that we 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 formalize their result in 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 (7).

[39] Ortiz-Bobea (2021) summarize the agricultural literature. For mortality, see Barreca et al. (2016) and Shrader, Bakkensen and Lemoine (2023).

[40] 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. But standard approaches to the valuation of time based on wage rates would say that such time shifting has no net cost.

[41] More precisely, they assume that: (i) adaptation is an optimized 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) 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 and (2) marginal benefits at any point along that trajectory must equal marginal costs at that same point. (See the appendix for a formal derivation.) Nonetheless, Carleton et al. (2022) do estimate positive net benefits to adaptation. They informally argue that adaptation becomes inframarginal at later points in time. However, if adaptation is a stock that accumulates, then forward-looking agents should choose adaptation in awareness of the trajectory of climate change and the derivation no longer holds.

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 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 rise over subsequent years. This finding highlights the intertemporal tradeoffs involved in adaptation decisions. Data on additional sectors and locations would helpfully allow for further estimates along these lines.

4.2.4 Inequality in Access to Adaptation

Adaptation, like direct damages from climate change, also raises important questions about inequality. As a next step for the literature, dynamic and spatial costs of adjustment should be analyzed jointly to understand how heterogeneity in costs of adjustment affect how different regions or individuals will respond to the climate shocks that they will face. For example, New York and Miami will both be affected by sea level rise, but Miami faces unique costs in constructing defensive infrastructure due to factors such as the porous geology of the area. There are also important open questions about how adaptation and mitigation interact. Differences in access to or willingness to pay for adaptation could affect how different groups perceive the urgency of climate mitigation.

4.3 Spillovers: Trade, Migration, and More

Hell is—other people!

– Jean-Paul Sartre, *No Exit*

The literatures on direct effects and on adaptation effects 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. 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 (2)) depends, via trade, on how weather changes in region B: the $\Gamma^{elsewhere}_{At}$ term in equation (2) comprises climate change's impacts on current, past, and future weather in other locations. 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.[42] For a recent review dedicated to the new spatial-climate literature, see Desmet and Rossi-Hansberg (2024), 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 Effects Literature

As early as Cline (1996), it has been argued that the direct effects papers described in Section 4.1 assume constant prices and thus miss welfare impacts that could come from equilibrium effects on relative prices. In the simplest model with one country and one commodity, ignoring these price effects causes common estimators of the impact of climate change on supply to miss changes in consumer welfare. Mendelsohn and Nordhaus (1996) argued that these missed welfare effects are likely to be small and lead to underestimation of climate damages.[43] The recent paper Gouel (2025) provides a history of this debate, an extension to open economies and multiple commodities, and estimates—for the agricultural sector—of the size of the gap between supply-side estimates of climate damage (coming from Ricardian or panel approaches) and overall welfare impacts based on incorporating climate shocks on multiple crops into a global trade model. The spatial papers that we next review naturally incorporate price effects, as they model 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 on trade. They explore the implications of a coarse border between the global North and global South that hinders trade and migration. The authors specifically contrast their paper with the direct effects literature, arguing that existing work which does not allow migration or trade overestimates climate damages. They also contrast their paper with integrated assessment models that do not have linkages across regions, writing "It is impossible to use them to understand changes in geographic specialization and trade patterns, as well as the geography of innovation and migration" (Desmet and Rossi-Hansberg, 2015, p. 17).

The authors argue that trade in goods directly protects against climate damages and also that trade responds as climate change impacts comparative advantage around the world. Be-

[42] A distinct literature studies how the spatial distribution of climate change impacts affects optimal and feasible mitigation policies (e.g., Nordhaus and Yang, 1996; Tol, 2002; 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. In contrast, the papers we discuss below explicitly represent migrants' decision problems.

[43] Though, in addition to the assumptions of a closed economy and one output, this conclusion also relies on the climate damages affecting supply rather than demand.

cause these adjustments work to maintain aggregate production, the authors expect climate damages to be small. Within a 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.[44] 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 counterfactuals 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 these already large costs, which makes the effect of trade relatively small.[45] An idealized comparison of frictionless trade with a no-trade-adjustment scenario would be more in keeping with their idealized adaptation experiment.

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. As discussed below, model assumptions make innovation and migration choices optimally myopic, so that neither choice anticipates future climate change. Having more labor in a location creates two types

[44] Gouel and Laborde (2021) extend this model to include more crops and countries. They argue that including more crops makes all land valuable in the current climate, which limits the scope for low-cost adjustments via conversion of unused land.

[45] 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. The fact that their no-trade-adjustment scenario does include some trade adjustment in level terms again favors finding a small role for trade when comparing their reference scenario to their no-trade-adjustment scenario. Gouel and Laborde (2021) show that turning off trade adjustment is much more costly when the counterfactual instead fixes bilateral import shares, so that countries can adjust their export share but cannot adjust their import mix.

of agglomeration economies: having more people around reduces the cost of hiring factors to innovate, and population is a source of new ideas.

The authors show that innovation and migration responses greatly reduce aggregate losses from coastal 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.[46] They 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 factors such as frictions in housing markets and political economy considerations that may hinder efficient movements. Others have found such factors to be important in studying sea level rise (Hsiao, 2023; Balboni, 2025).

4.3.3 The Role of Spatial Linkages in Global Inequality

Costinot, Donaldson and Smith (2016) and Desmet et al. (2021) emphasize spatial heterogeneity of impacts. Both papers find regions with gains from climate change, regions with moderate losses, and regions with substantial losses (for instance, Malawi in the case of Costinot, Donaldson and Smith (2016), and Bangkok and Shanghai in the case of Desmet et al. (2021)). Spatial heterogeneity is not a new finding—we describe above how many direct effects 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 instead also depend on how changes in climate around the world change comparative advantage and factor distribution. For instance, 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.

[46] These dynamics were missing from earlier studies of sea level rise with static computable general equilibrium models (e.g., Bosello, Roson and Tol, 2007).

4.3.4 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 (e.g., 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). To capture these linkages, a model must combine trade in agricultural goods with preferences that respect subsistence needs among consumers.

The direct effects literature summarized in Section 4.1 has made much progress on 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 (e.g., Kane, Reilly and Tobey, 1992; Tobey, Reilly and Kane, 1992; Reilly and Hohmann, 1993; **?**). Earlier 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. Building on longstanding insights (e.g., Adams et al., 1998), Moore et al. (2017) show that the price changes induced by widespread climate change are critical for its incidence.[47] When crop productivity decreases, the corresponding increase in crop prices tends to benefit agricultural exporters (and, in a micro setting, tends to benefit farmers).[48] An analysis that treated climate change as only a localized shock would miss this effect on prices (see also Cline, 1996).

There is a widespread belief among scientists that it is technically possible (albeit potentially costly) to adapt enough to fully offset global food losses from climate change (Vermeulen, Campbell and Ingram, 2012, p. 210). 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 track changes in comparative advantage, which depends on how agricultural productivity changes in comparison to productivity in manufacturing and services.

[47] Gouel (2025) formalizes these terms of trade effects.

[48] Baldos, Hertel and Moore (2019) and Gouel and Laborde (2021) study similar terms-of-trade mechanisms.

Nath (2025) shows that the combination of high trade barriers and nonhomothetic preferences in the developing world can change this story. 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 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.[49] Trade barriers thereby become especially costly to these countries.

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. Many papers conduct experiments with migration and trade barriers. To better ground the experiment in observed policy, 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 (**??**). 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.[50] 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. Their 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

[49] 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.

[50] 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.

stylized fashion. Another strand of recent literature is more closely related to Desmet et al. (2021). It is more thoroughly structural and aims to be more comprehensive. We turn to it next.

4.3.5 Broadening the Analysis of Spatial Linkages

The early papers in Sections 4.3.1-4.3.3 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, building on Desmet, Nagy and Rossi-Hansberg (2018), 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.[51]

Rudik et al. (2022) abstract from innovation and investment in order to introduce production networks and households who account for future climate change when migrating. They find that global losses from warming are mostly driven by hits to amenities rather than hits to productivity. Within their model, accounting for production networks (i.e., input-output linkages among sectors and locations) tends to mitigate the effects of climate change on productivity. Permitting households to anticipate future climate change has smaller effects on welfare. Accounting for temperature extremes within a year substantially increases welfare losses from climate change.

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, including indirectly 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

[51] 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. Moreover, migration policies do little to help people driven to extreme poverty by climate change, as opening borders primarily incudes international migration from people who would have migrated internally and closing borders reduces brain drain without directly fighting climate poverty.

regress these parameters on temperature within a panel environment in order to estimate damage functions.[52] Rudik et al. (2022) express their model's equilibrium conditions on trade and migration in a form amenable to panel estimation of the effects of temperature on, respectively, productivity and amenities.[53] 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, 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.[54]

Importantly, these three papers imply very different magnitudes of climate damages overall, with Cruz and Rossi-Hansberg (2024) finding relatively small damages (albeit with uncertainty) and Rudik et al. (2022) finding quite large damages globally. Clearly more work is needed to yield a consensus on how various adaptation mechanisms and spatial spillovers interact and to be able to quantify expected overall damages under different emission pathways.

4.3.6 Limitations and Potential Progress

The papers discussed in Sections 4.3.1-4.3.3 each introduce new spatial considerations to adaptation and impacts. To do so, they dramatically simplify the time dimension of adaptation, with Γ_{At}^{future} and, often, Γ_{At}^{past} assumed to be zero. Costinot, Donaldson and Smith (2016) use cross-sectional data on trade flows to discipline trade costs, but their data lack the time dimension necessary to discipline adjustment costs in adaptation. As a result, they assume no adaptation costs in their reference scenario: crops' productivities after climate change are calibrated to an agronomic model with optimized inputs, and farmers can choose crops without considering what crops they planted in the past.[55] In their no-adaptation

[52]Their temperature variable 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.

[53]Rudik et al. (2022) also show that estimates of amenity values can be biased when estimating equations do not account for the forward-looking nature of migration decisions.

[54]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.

[55]Discussing an early analysis of agricultural damages with a "static, spatial-equilibrium model", Fisher and Hanemann (1993, p. 142) observe that it "assumes malleable capital that can be shifted costlessly in response to perfectly anticipated economic changes." It lacks any adjustment costs and therefore captures a steady-state, equilibrium response to climate change rather than the trajectory of climate change that must be lived through. But, they 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

scenario, Costinot, Donaldson and Smith (2016) increase the cost of adjusting crop choices to infinity, so that crop shares are fixed while farming inputs are implicitly 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.[56] And migration is costless when feasible, so workers can choose where to locate in a static fashion. As a consequence, no actors in the model make forward-looking decisions that account for the trajectory of warming.[57] Desmet et al. (2021) introduce costly migration, but all migration and innovation decisions remain static decisions: people pay a moving cost only as long as they stay in a location away from their original home and their costs of moving again are independent of any prior moves, 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.[58] 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.[59]

The more recent papers generalize some of these assumptions. In doing so, some qualitatively different results emerge. For instance, Bilal and Rossi-Hansberg (2023) find a smaller value of migration than in prior work with optimally myopic households. Part of this is because people will not move as much in models that do not assume moving costs will be refunded upon a subsequent move, and part of this is because the net benefits from adjusting migration are smaller once migration patterns are intertemporally optimized.[60]

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cycle of the affected capital."

[56]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 (e.g., **?**).

[57]Decisions are dynamic in the sense that they do evolve with warming. Decision-making is not dynamic in the sense that decisions do not depend on beliefs about how variables such as temperature will evolve in subsequent periods.

[58]The migration cost structure has another effect as well: agents always have an incentive to, all else equal, return to their original home so that they no longer pay any flow costs of having migrated. An agent who moves away because of a preference shock is decently likely to move back in the future, but an agent who moves away due to a persistent factor such as climate change is more likely to stay away from home.

[59]Discussing an early analysis of sea level damages, Fisher and Hanemann (1993, p. 139) observe that it "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."

[60]In an alternative approach to paramterization, Baluja (2024) combines a structural model of migration and wages, microdata on households, and climate modeling data (for variation in expected weather) study the role of beliefs about climate change in driving climate migration within Mexico. He finds that damages would be much higher if people could not migrate. The use of microdata allows for estimation of heterogeneity within the population, particularly in the costs of migrating (see also **?**).

The results from the more recent papers discussed in Section 4.3.5 nonetheless leave room for future work. First, on the model side, each paper still does 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, 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. Future work should seek to compare channels and calibrations within a single framework.[61]

Second, recent papers are limited by the data available. Papers that seek to undertake gridded global analyses typically use the G-Econ database, which contains economic output estimates 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 (e.g., 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 global data could propagate into estimated model parameters. In other cases, model equations require data on variables such as population flows that restrict the geographic scope of the application (e.g., Rudik et al., 2022). And data at the resolution of individuals or properties will have restricted geographic coverage (e.g., Hsiao, 2023; Baluja, 2024). In contrast, many weather variables are fairly well-measured on fine grids with comprehensive geographical coverage (for more details, see Auffhammer et al., 2013). Future work could prioritize the development of analogous economic datasets (such as the recently released dataset reported in Rossi-Hansberg and Zhang (2025)).

Third, the papers in the spatial spillovers literature tend to emphasize the dynamic aspects of spatial variables such as migration over the dynamic aspects of traditional forms of adaptation. Yet not only are the Γ_{At}^{future} and Γ_{At}^{past} terms in equation (2) potentially relevant in their own right, the $\Gamma_{At}^{elsewhere}$ term of interest to this literature does comprise dynamic adaptation in other locations. Future work could seek to integrate the new spatial spillovers literature with the dynamic adaptation literature described in Section 4.2.1.

Fourth, these papers tend to treat spatial linkages as reflecting first-order concerns about comparative advantage. However, spatial linkages may also reflect second-order, insurance

[61] Krusell and Smith (2022) consider a distinct spillover from those described above, in the form of capital mobility via a global bond market. This market enables agents around the world to adapt to climate change by adjusting savings decisions. Krusell and Smith (2022) find that capital mobility does not have first-order consequences within their model.

motivations. For instance, in Castro-Vincenzi et al. (2024), firms trade in order to diversify risks (which has the side effect of amplifying inequality in climate impacts). Future work could integrate agents' incentives to diversify climate risks into the study of trade, migration, and innovation.

Fifth, 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 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 (e.g., Baluja, 2024; **?**), 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 conduct novel policy experiments. 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 experiments to match relevant real-world policies.

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 that we see as more conceptually distinct from the bulk of existing literature.

Estimates for other key sectors. While some sectors, such as agriculture and energy, have been robustly analyzed, other sectors continue to be notably understudied. For instance, there are very few papers on construction, but that sector plays a key role as an input to nearly every other sector of the economy, is climate exposed, and is important for building both mitigation and adaptation infrastructure. Similarly, effects on long-term investment and on input-output linkages across sectors are still understudied.

Form of temperature variables. There are many ways to specify temperature variables (see Akyapı, Bellon and Massetti, 2025). Papers should be clear about whether results are robust to, for instance, alternative functional forms or provide justification for the variables considered. More importantly, they should be clear about whether their annual measures are robust to using alternative aggregation measures.[62] In addition, a substantial fraction of 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 from year to year (Lemoine and Kapnick, 2016; Kotz et al., 2021; Linsenmeier, 2023).[63] The rate and variability of warming become especially important when models have adjustment costs.

Clarity of baseline and counterfactual. The importance of future damage projections to our understanding of climate change also means that clarity in presenting projections is especially important. To aid comparison across papers, papers must be explicit about how welfare losses are calculated. Are projected losses relative to a richer future without climate change or relative to today's economy? Papers that show time paths help make this clear, but papers with projections only of end-of-century results do not always make this as clear and are ripe for misinterpretation. For example, papers that report a loss of GDP relative to a future without climate change are apt to be reported in the media as implying losses relative to *today's* GDP.

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

[63]This point is also relevant to the recent debate about whether to estimate effects on levels of output or on the growth rate of output (Pindyck, 2013*a*; Dell, Jones and Olken, 2014; Newell, Prest and Sexton, 2021). It is often claimed that effects on the growth rate of output will compound over time, but that claim assumes that these effects are driven by the level of temperature rather than by the change in temperature. Estimating the effects of levels of temperature on growth rates allows effects to compound to a high degree, whereas estimating effects of changes in temperature on levels of output would tend to make climate damages appear especially transient.

Comprehensive estimates using spatial models. A key aim of the direct damages literature and associated integrated assessment models has been to work towards comprehensive 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 more recent papers suggest impacts in the range of 5-20% of GDP, relative to a counterfactual without climate change (Rudik et al., 2022; Bilal and Rossi-Hansberg, 2023; Cruz and Rossi-Hansberg, 2024). 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 effects literature.

Nonmarginal changes and projections. Given that climate change occurs over long periods of time, nonmarginal considerations become important. Projections of future climate damage are more challenging when second-order effects become relatively more important and endogenous responses play out over longer periods of time.[64] Such forces also make damage projections more sensitive to how global climate change is mapped to the local level (**?**). In addition, nonmarginal climate change unfolds over time alongside many other changes in the world. If we were projecting climate damages using societal conditions in 1900, we would miss the structural change and income growth that have likely insulated the developed world from the worst effects of climate change (see Schelling, 1992; Bleakley and Hong, 2017). In addition, we could also miss the effects of changes in technology that might occur over long periods of time, a point emphasized as early as Easterling et al. (1993). Our ability to project future changes in income and technology is inherently limited, and it is important to recognize the uncertainty inherent to any projections (e.g., Müller, Stock and Watson, 2022).

Non-temperature impacts. Weather is multidimensional, and climate change itself affects dimensions of the earth system beyond weather. Most work to date focuses on impacts of higher temperatures, although we have discussed work on sea level rise and storms. There is also work on precipitation (e.g., Damania, Desbureaux and Zaveri, 2020; Palagi et al., 2022; Kotz, Levermann and Wenz, 2022), including implications for irrigation (**?**); the interaction between temperature and humidity (e.g., Barreca, 2012; Wilson et al., 2024); and the effect of a wide variety of climate variables on agriculture, including wind, humidity, and evaporation (e.g., Zhang, Zhang and Chen, 2017). In addition, rising carbon concentrations directly

[64] See Section 3.3 for a discussion of estimators that may capture second-order effects pertinent to projecting nonmarginal climate change.

affect the acidity of the oceans, plant growth, and nutrient quality.[65] Future work should consider multiple dimensions of weather simultaneously and should seek empirically grounded estimates of non-weather impacts, such as from ocean acidification (see **?**).

Channels for impacts. We have developed a transparent and extensible framework in Section 2. The direct effects papers have made much progress on capturing direct effects $\partial Y_t^A / \partial w_t^A$ and components of Γ_{At}^{now}, and the recent spillovers papers have begun to make progress on capturing the effect of weather in other locations $\Gamma_{At}^{elsewhere}$, but much less work has captured dynamic effects in Γ_{At}^{past} and Γ_{At}^{future}. Those terms each contain multiple channels of their own. Future work could continue clarifying which types of channels and sub-channels are likely to be important in which types of settings.

More global data. Relative to early integrated assessment models, the state of the literature in 2024 shows tremendous advances in data collection. For instance, the use of subnational data on mortality covering a significant share (38%) of the world's population allow for modeling advances by Carleton et al. (2022) that show substantially higher damages than was previously thought. And the use of subnational data on gross regional product enable recent GDP-climate regressions to include country fixed effects in cross-country panel regressions. Yet even both of these datasets are limited in qualitatively important ways: lower-income countries and Southern hemisphere countries tend to be missing (indeed, nearly all of Africa is missing). Similarly, many of the recent spillovers papers rely on datasets that are extrapolated from raw data (as we discuss in more detail in Section 4.3.6). This extrapolation may miss the variation in lower-income countries that does not merely parallel variation in higher-income countries. As a result, the target data for estimating and calibrating models of spillovers may distort model output in systematic ways.

Aggregation and welfare. Damages are heterogeneous across locations and people, creating inequality in climate-related outcomes. And general equilibrium adjustments can further increase inequality (Hsiao, Moscona and Sastry, 2024; Nath, 2025). This inequality, in turn, means that the overall welfare effects of climate change depend on how damages are aggregated. Much literature uses Negishi weights, which rationalize the current distribution of income.[66] Using alternative weights when aggregating damages can have a large influence on the overall consequences of climate change (Anthoff, Hepburn and Tol, 2009; Anthoff and Emmerling, 2019). Given recent advances that provide a substantially more granu-

[65] Much literature has discussed and quantified the potentially beneficial effects of CO_2 fertilization for agricultural crops (see Toreti et al., 2020). Recent scientific work suggests that higher CO_2 concentrations could make crops less nutritious (e.g., Myers et al., 2014; Zhu et al., 2018; Toreti et al., 2020). Future work could investigate this effect with a model of the economy and health (see **?**).

[66] One important exception concerns how premature mortality from climate change is valued (Bressler and Heal, 2022).

lar understanding of the spatial distribution of damages, this conceptual point has become increasingly important. Applying different weights can lead to higher values of the social cost of climate damage because climate damages are typically found to more strongly affect lower-income individuals (Bressler, 2025). This issue is also receiving increased attention, in part, due to policymakers seeking to better understand distributional effects more broadly (see, e.g., OMB, 2023).

Unifying dynamic adjustment costs with spatial spillovers. Recent literature has made much progress towards incorporating geographical spillovers into climate impacts estimates, but, as discussed in Section 4.3.6, much of this literature simplifies dynamics. All of these papers simplify dynamic decisions about investment, innovation, migration, or adaptation. In reality, we expect such decisions to account for future climate change and we expect that accounting to matter. Even when not all agents anticipate climate change perfectly, we expect financial markets to incorporate some information about climate change impacts (see Giglio, Kelly and Stroebel, 2021). Future work could continue recent progress towards studying the interaction between dynamic decisions and spatial spillovers.

Financial market effects. We have discussed climate change consequences that are called "physical risks" in the climate finance literature (Carney, 2015). There, physical risks are often analyzed alongside transition risks within a broader category of climate risks. Among other topics (see Giglio, Kelly and Stroebel, 2021), the climate finance literature considers how physical climate risks may differentially affect the cost of capital (e.g., Anttila-Hughes, 2016; Acharya et al., 2022), the riskiness of debt (e.g., Painter, 2020; Huynh and Xia, 2021; Nguyen et al., 2022; Goldsmith-Pinkham et al., 2023), or the value of coastal real estate (e.g., Bernstein, Gustafson and Lewis, 2019; Baldauf, Garlappi and Yannelis, 2020; Keys and Mulder, 2020; Bakkensen and Barrage, 2022). It also considers whether markets and analysts properly anticipate impacts (e.g., Hong, Li and Xu, 2019; Pankratz, Bauer and Derwall, 2023), whether markets pay attention to weather and climate forecasts (e.g., Kruttli, Roth Tran and Watugala, 2019; Schlenker and Taylor, 2021; Lemoine and Kapnick, 2024), how markets perceive biodiversity risk (e.g., Giglio et al., 2023), and how hedging strategies can offer protection against climate risk (e.g., Engle et al., 2020). Evidence suggests that financial markets may assist in weathering temperature shocks, both ex ante (Pérez-González and Yun, 2013) and ex post (Brown, Gustafson and Ivanov, 2021). Future work could integrate financial markets into models of climate adaptation in order to evaluate how access to finance may itself serve as an adaptation strategy and may interact with other adaptation options, in partial equilibrium as well as in general equilibrium.

Tipping points. Even over short periods of time, changes in the climate need not be small, smooth, or slow (Lenton et al., 2008; Armstrong McKay et al., 2022). Tipping points—such

as the collapse of the Atlantic meridional overturning circulation (AMOC)—raise the threat of rapid, large-magnitude changes that could have especially severe consequences in a world with large adjustment costs. Recent work has made technical progress on incorporating tipping points into climate IAMs. This work varies in how it models tipping points and their impacts. In some papers, tipping points cause exogenously specified damages (e.g, Cai, Lenton and Lontzek, 2016; Cai and Lontzek, 2019). In other papers, the damages induced by triggering a tipping point emerge endogenously, depending on how the post-tipping earth system evolves. Some of these papers integrate models of tipping processes into an IAM, either with policy optimized in knowledge of the tipping process (e.g., **?**) or with the evolution of the earth system and the economy taken as exogenous (e.g., Dietz et al., 2021). In other of these papers, a stylized, discrete tipping point is uncertain and the evolution of the earth system and the economy depend on how emission and investment policies adapt to having triggered the tipping point (e.g., Lemoine and Traeger, 2014, 2016). All of this work has been constrained by the state of scientific knowledge, using simplified models of tipping processes, impacts, and information. 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; van Westen, Kliphuis and Dijkstra, 2024).

Catastrophic risks. Uncertainty about future climate change damage is inherently large (a point we return to below), meaning that it is important both to take such uncertainty seriously and to develop policies that are robust to it. In fact, some have argued that the threat of catastrophe should dominate economic analysis of climate change (Weitzman, 2007, 2009; Pindyck, 2013*a*,*b*; Heal, 2017; **?**).[67] An important complement to the traditional focus on average outcomes would be analysis of the distribution of outcomes with particular focus on the effect of potential tail risks. This work could, for example, combine quantile estimators with structural models that aim to explain heterogeneity in weather sensitivity.

Nonmarket damages. 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 lumber. Come what may, the Earth will lose a substantial fraction of its natural heritage (**?**IPCC, 2018). In time, a new equilibrium may emerge, with its own arrangements

[67] An extreme interpretation of Weitzman (2009) is that the nonnegligible risk of catastrophe makes cost-benefit analysis irrelevant. This interpretation has been subject to much criticism (Karp, 2009; Nordhaus, 2011; Millner, 2013; Horowitz and Lange, 2014).

of species and ecosystems, 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 Hanley and Perrings, 2019; Bastien-Olvera and Moore, 2020), in addition to ethical considerations analogous to those involved in the choice of standard discount rates and equity weights. Prior work has formally explored discounting under damages to natural capital (e.g., Hoel and Sterner, 2007; Heal, 2009*b*; Gollier, 2010) and numerically assessed implications for the social cost of carbon (e.g., Sterner and Persson, 2008; 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 values change as the environment changes. It is important to obtain a sense of the scale of these costs, as there is a chance that focusing on more readily measured market impacts misses the major part of the story.

Model validation. Structural models must be validated, to make sure that both their structure and calibration are sensible. Climate science relies heavily on structural models based on physical relationships, and there has long been an emphasis on evaluating models through benchmark simulations (e.g., Tebaldi and Knutti, 2007; Taylor, Stouffer and Meehl, 2012). Climate economics lacks a similar 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 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 simulate aggregate data from other regions and time periods. Without established benchmarks, validation tests run the risk of experimenter cherry-picking and it becomes difficult to assess models' relative accuracy.

Using multiple approaches to get a richer picture of adaptation and spillovers. We have emphasized that no one approach is likely to robustly and credibly estimate impacts that match those of the climate change experiment (see Section 3). In fact, a combination of approaches could provide a fruitful path toward improving our understanding of some issues we raise. 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.

New quasi-experimental designs. As described in Section 3, the dominant source of empirical credibility in the climate impacts literature has been the deployment of fixed effects

to reduce variation in weather to plausibly exogenous shocks. This identification strategy has the drawback of making estimates less relevant to climate change. There are other sources of quasi-experimental variation that one might employ, 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, in this journal). Or researchers may take advantage of quasi-exogenous variation in public adaptation projects to estimate their influence on climate impacts and individuals' choices (e.g., Kelly and Molina, 2023). We anticipate the emergence of creative quasi-experimental designs in the coming years.

Bounds and partial identification. The literature to date has focused on providing point estimates for impacts, with any confidence intervals expressing statistical uncertainty. We have discussed how identification of point estimates has come at the cost of experimental mismatch, with weather substituting for climate. Extending literature described in Section 3.5, future work could formally examine to what extent climate impacts are partially identified: what can we say about climate impacts under minimal assumptions (see Manski, 2020)? The output may come in the form of bounds, which in turn may require rethinking IAMs in order to incorporate other types of estimates. Future work could even reformulate damage estimation as a statistical decision problem, using an IAM to define the loss function.

6 Concluding Discussion

The path to paradise begins in hell.

– Dante Alighieri, *Inferno*

New science on climate change continues to emerge, and the 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.

Beyond the concrete next steps from Section 5, there are additional, deeper challenges that 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 economics. 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, experimental design 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 2025. 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 could target moments that correspond to the experiments attainable from 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 (Lemoine and Rudik, 2017; Dietz, Gollier and Kessler, 2018; Lemoine, 2021; van den Bremer and van der Ploeg, 2021; Traeger, 2023). And recent governmental updates to the social cost of carbon have begun incorporating econometric uncertainty, 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 develop measures of 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 source of uncertainty that economists are more comfortable presenting.

Third, economists should devote more effort to developing policy frameworks that do not rely on firm 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 (e.g., Baumol, 1972; Weitzman, 2009). Some economists explore carbon pricing under concerns about model uncertainty (e.g., 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 (e.g., 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.

At the same time, economists do now know more about damages than we did. Weather has been shown to matter for just about everything. Because climate change manifests via weather, it is also likely to matter for just about everything. But important gaps remain. Thirty years ago, in an evaluation of one of the first climate change damage assessments (Smith and Tirpak, 1989), Fisher and Hanemann (1993) criticized optimistic assumptions about adaptation. They emphasized the dynamic nature of adaptation, which will be constrained by capital adjustment costs, imperfect information, and natural constraints. We have emphasized the importance of dynamic adaptation as well, as it is the channel through which the persistent and anticipated nature of climate change becomes important. The literature is only beginning to capture the process of adjusting to climate change.

Fisher and Hanemann (1993) also criticized the limited scope of the original damage estimates, which covered only some sectors and some types of changes in weather—and not necessarily the ones that were expected to be most important. They observed that researchers might be (unfortunately) following the dictate: "If you can't measure what's important, then play up the importance of what you can measure." Much progress has been made since that time on improving the scope of damage estimates (albeit with some persistent omissions), but a modern version of this concern is "If you can't causally identify what's important, then play up the importance of what you can causally identify," with a similar concern holding for what can and cannot be tractably modeled. There has been substantial progress isolating the effects of one-off, 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 experimental fit 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.

More broadly, uncertainty over quantification is not a new challenge in environmental economics. In the back-and-forth over valuation of damages from the Exxon-Valdez oil spill (Kling, Phaneuf and Zhao, 2012), this was framed as the question of whether some number is better than no number. Going back further, in writing about the social discount rate for cost-benefit analysis, Baumol (1968, p. 789) said that we are "hunt[ing] for a solution in the dark jungles of the second best." Limited information is better than no information, and acting on limited information is better than waiting on complete information that will never arrive.

Finally, we have seen that adaptation is a complex phenomenon, depending on relationships among people over space, on history, and on forward-looking decisions made by people who are aware things are changing. Infrastructure, trade, and migration will each respond

to the history of weather around the world and to people's expectations of what weather in each place will be in the future. These responses will reshape the geographic distribution of economic activity, sometimes in ways that are not entirely obvious from the direct effects of weather. Indeed, climate change may well be one of the biggest forces reshaping the distribution of economic activity over the next decades. These consequences will not always show up in the aggregate damage functions on which economists have focused much of their attention. But they will be important for the lives of the people involved and for the policies that might improve those lives.

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Online Appendix

Derivations for Section 2

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

$$V^A(K_t^A, K_t^B, w_t^A, w_t^B) = \max_{\ell_{Yt}^A} \max_{q_{Bt}^A} \Bigg\{ W^A(Y^A(\ell_{Yt}^A, K_t^A, w_t^A) - p_t q_{Bt}^A, q_{Bt}^A) + \frac{1}{1+r} E_t \left[V^A\left(f(L^A - \ell_{Yt}^A) + (1-\delta)K_t^A, K_{t+1}^B, w_{t+1}^A, w_{t+1}^B \right) \right] \Bigg\}. \tag{8}$$

The first-order condition for q_{Bt}^A yields:

$$p_t = \frac{\frac{\partial W^A(q_{At}^A, q_{Bt}^A)}{\partial q_{Bt}^A}}{\frac{\partial W^A(q_{At}^A, q_{Bt}^A)}{\partial q_{At}^A}}. \tag{9}$$

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

Recognizing that agents are price-takers, problem (8) becomes:

$$\begin{aligned} &V^A(K_t^A, K_t^B, w_t^A, w_t^B) \\ &= \max_{\ell_{Yt}^A} \Bigg\{ W^A\Big(Y^A(\ell_{Yt}^A, K_t^A, w_t^A) - p_t q_B^A(p_t, Y^A(\ell_{Yt}^A, K_t^A, w_t^A)),\ q_B^A(p_t, Y^A(\ell_{Yt}^A, K_t^A, w_t^A)) \Big) \\ &\quad + \frac{1}{1+r} E_t \left[V^A\left(f(L^A - \ell_{Yt}^A) + (1-\delta)K_t^A, K_{t+1}^B, w_{t+1}^A, w_{t+1}^B \right) \right] \Bigg\}. \end{aligned} \tag{10}$$

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 (9):

$$0 = \frac{\partial W_t^A}{\partial q_{At}^A} \frac{\partial Y_t^A}{\partial \ell_{Yt}^A} - f'(\ell_{Kt}^A) \frac{1}{1+r} E_t \left[\frac{\partial V^A(K_{t+1}^A, K_{t+1}^B, w_{t+1}^A, w_{t+1}^B)}{\partial K_{t+1}^A} \right]. \tag{11}$$

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 (11) 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. Observe that:

$$\frac{\mathrm{d}\ell_{Yt}^A}{\mathrm{d}C} = \frac{\partial \ell_{Yt}^A}{\partial C} + \frac{\partial \ell_{Yt}^A}{\partial K_t^A}\frac{\mathrm{d}K_t^A}{\mathrm{d}C} + \frac{\partial \ell_{Yt}^A}{\partial K_t^B}\frac{\mathrm{d}K_t^B}{\mathrm{d}C} + \frac{\partial \ell_{Yt}^A}{\partial \ell_{Yt}^B}\frac{\mathrm{d}\ell_{Yt}^B}{\mathrm{d}C}. \tag{12}$$

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

$$\begin{aligned}\left[1 - \frac{\partial \ell_{Yt}^B}{\partial \ell_{Yt}^A}\frac{\partial \ell_{Yt}^A}{\partial \ell_{Yt}^B}\right]\frac{\mathrm{d}\ell_{Yt}^A}{\mathrm{d}C} = &\underbrace{\frac{\partial \ell_{Yt}^A}{\partial C} + \frac{\partial \ell_{Yt}^A}{\partial K_t^A}\frac{\mathrm{d}K_t^A}{\mathrm{d}C} + \frac{\partial \ell_{Yt}^A}{\partial K_t^B}\frac{\mathrm{d}K_t^B}{\mathrm{d}C}}_{\zeta_{At}} \\ &+ \frac{\partial \ell_{Yt}^A}{\partial \ell_{Yt}^B}\Bigg[\underbrace{\frac{\partial \ell_{Yt}^B}{\partial C} + \frac{\partial \ell_{Yt}^B}{\partial K_t^A}\frac{\mathrm{d}K_t^A}{\mathrm{d}C} + \frac{\partial \ell_{Yt}^B}{\partial K_t^B}\frac{\mathrm{d}K_t^B}{\mathrm{d}C}}_{\zeta_{Bt}}\Bigg].\end{aligned} \tag{13}$$

Applying the implicit function theorem to equation (11) and using the second-order condition for an optimum, 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{\partial W_t^A}{\partial q_{At}^A}\frac{\partial^2 Y_t^A}{\partial \ell_{Yt}^A \partial K_t^A}\frac{\mathrm{d}K_t^A}{\mathrm{d}C} + \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}\frac{\mathrm{d}K_t^A}{\mathrm{d}C} \\
& + \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}\frac{\mathrm{d}K_t^A}{\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]^2}\right]\frac{\mathrm{d}K_t^A}{\mathrm{d}C}, \\
\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 (13), we find:

$$\begin{aligned}
\frac{\mathrm{d}\ell_{Yt}^A}{\mathrm{d}C} = & \frac{1}{1 - \frac{\partial \ell_{Yt}^B}{\partial \ell_{Yt}^A}\frac{\partial \ell_{Yt}^A}{\partial \ell_{Yt}^B}}\left[\gamma_{At}^{now} + \gamma_{At}^{future} + \gamma_{At}^{past} + \gamma_{At}^{elsewhere}\right] \\
& + \frac{1}{1 - \frac{\partial \ell_{Yt}^B}{\partial \ell_{Yt}^A}\frac{\partial \ell_{Yt}^A}{\partial \ell_{Yt}^B}}\frac{\partial \ell_{Yt}^A}{\partial \ell_{Yt}^B}\left[\gamma_{Bt}^{now} + \gamma_{Bt}^{future} + \gamma_{Bt}^{past} + \gamma_{Bt}^{elsewhere}\right]. \qquad (14)
\end{aligned}$$

Observe that:

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

Substituting for $\gamma_{Bt}^{elsewhere}$ in (14), using the implicit function theorem with equation (11) to obtain $\partial \ell_{Yt}^A / \partial \ell_{Yt}^B$, and collecting terms, we have equation (2), 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} \\ &\qquad + \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} \\ &\qquad + \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 K_t^A}\frac{\mathrm{d}K_t^A}{\mathrm{d}C} \\ &\qquad - \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} determines how investment in region A responds to investment in region B, via the expected change in subsequent periods' prices. It multiplies terms that describe how climate affects investment in region B.

Now relate the channels within each Γ that are informally described in Section 2 to the formal expressions. Γ_{At}^{now} has four components. The first three are from γ_{At}^{now}: the change in

weather may directly alter the marginal product of labor (first term on first line in γ_{At}^{now}), the change in 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_{At}^{now}), and the change in weather may alter prices (second line in γ_{At}^{now}). The fourth component reflects how the change in weather may alter investment decisions in region B (terms with χ_{At} in Γ_{At}^{now}).

Γ_{At}^{future} has two components: how expected changes in weather directly alter the marginal product of region A's capital in future periods (in γ_{At}^{future}), 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_{At}^{future}).

In Γ_{At}^{past}, the time t capital stock may affect the time t marginal product of labor (first term on the first line in γ_{At}^{past}), the time t value of that marginal product at constant prices (second term on the first line in γ_{At}^{past}), time t prices (second line in γ_{At}^{past}), and/or the expected marginal product of capital in later periods, whether directly (third line in γ_{At}^{past}) or by affecting investment in region B (terms with χ_{At} in Γ_{At}^{past}).

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

To derive the effect of climate on period welfare in region A, observe that

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

The expression in the main text follows from using the equilibrium price in (9).

To derive the effect of climate change in intertemporal welfare in region A, differentiate the maximized value function from equation (10), substitute in the first-order condition for ℓ_{Yt}^A, and substitute for p_t from equation (9):

$$\begin{aligned}\frac{\mathrm{d}V_t^A}{\mathrm{d}C} =&\frac{\partial W_t^A}{\partial q_{At}^A}\left(1 - \frac{\partial p_t}{\partial Y_t^A}q_{Bt}^A\right)\left(\frac{\partial Y_t^A}{\partial w_t^A}\theta_A + \frac{\partial Y_t^A}{\partial K_t^A}\frac{\mathrm{d}K_t^A}{\mathrm{d}C}\right) - \frac{\partial W_t^A}{\partial q_{At}^A}\frac{\partial p_t}{\partial Y_t^B}q_{Bt}^A\left(\frac{\partial Y_t^B}{\partial w_t^B}\theta_B + \frac{\partial Y_t^B}{\partial K_t^B}\frac{\mathrm{d}K_t^B}{\mathrm{d}C}\right) \\ &+ \frac{1}{1+r}E_t\left[\frac{\mathrm{d}V_{t+1}^A}{\mathrm{d}C} + f'(\ell_{Kt}^A)\frac{\mathrm{d}V_{t+1}^A}{\mathrm{d}K_{t+1}^A}\frac{\mathrm{d}\ell_{Yt}^A}{\mathrm{d}C}\right].\end{aligned}$$

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 the expression in the main text.

Formalizing Approach to Adaptation Cost Recovery in 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, $c(A(C_i(t)))$ 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.

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:

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

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

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

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

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

Optimal adaptation in each instant t solves the following first-order condition:

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

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:

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

To recover the integrand, recall regression (7):

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

Carleton et al. (2022) assume

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

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.

Using that equivalence, adaptation costs are

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

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

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

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, adaptation to different climates over time is equivalent to observed cross-sectional adaptation to different climates over space. Second, 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.

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