Macroeconomics and Climate Change

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1 Introduction

The world is experiencing increasingly severe physical consequences of climate change: flooding in 2022 that inundated one-third of Pakistan (Hong et al. 2023), temperatures exceeding 50°C in India (Mandal et al. 2025), and wildfires across Canada in the summer of 2023 that blanketed many United Sates cities in wildfire smoke for days (Jain et al. 2024). While no individual such event can be attributed solely to climate change, collectively these increasingly common and severe extremes are strongly consistent with climate models (National Academies of Science, Engineering and Medicine 2016). Driven in part by such events and facilitated by sharply declining prices of renewable power, batteries, and electric vehicles, public, corporate, and political support for climate action is broadening across developed countries, both for decarbonizing broad swaths of economic activity and for adapting to the ever-worsening physical damages of climate change to come. These trends are vast and inexorable: they will entail tens of trillions of dollars of redirected capital flows, they will change the daily lives and economic opportunities faced by billions of people.

The scale of climate change and the transition to a decarbonized economy raises important questions for macroeconomists and provides them with opportunities to meaningfully strengthen and improve the response to climate change, both by society and by those responsible for climate policy and traditional macroeconomic policy. Macroeconomists have long been involved both in estimating the economic cost of climate change and in assessing optimal climate policy. Both streams date to the seminal work of Nordhaus (1992), who developed the first formal model to integrate climate and macroeconomics—the first integrated assessment model, or IAM—which allowed estimating the monetized damages from climate change, called the social cost of carbon or SCC, and linked the optimal Pigouvian tax on carbon to the social cost of carbon. Since then, and accelerating especially over the past five years, there has been an increasing amount of work at the intersection of climate change and macroeconomics. Parts of this literature are large and mature, in particular estimates of the social cost of carbon and the long-run macroeconomics of carbon taxes, while other parts are quite new, in particular the macroeconomics of adaptation.

This paper surveys the literature on climate change and macroeconomics. Our aim is twofold: to provide an organizing framework for what can seem, to an outsider, a complex and interconnected topic that combines traditional macroeconomics with climate science and technology, and to suggest directions in which macroeconomic research on climate is particularly needed.

We adopt a capacious definition of climate change that encompasses both the physical manifestations of climate change—heat stress, storms, floods, sea level rise, and so forth—and the human and institutional activities driving, experiencing, and responding to those physical changes. These risks occur over multiple time frames, ranging from quarters in the case of an energy price shock to centuries in the case of irreversible events such as ice sheet melting.

In contrast, our definition of macroeconomics is narrow, limiting attention to aspects of climate change that potentially have meaningful implications for macroeconomic aggregates and aggregate welfare, so that the tools of macroeconomic analysis are relevant. Our framework excludes much of climate policy design, except to the extent that policy options have different macroeconomic consequences. It also excludes much of the burgeoning literature on climate finance or natural capital. For space, we focus on work studying long-run macroeconomic outcomes and do not attempt to summarize the comparatively smaller literature that analyzes the short-run, business-cycle macroeconomic implications of climate change or its fiscal implications. Importantly, our focus on long-run outcomes does not imply that we focus on phenomena that will only occur far in the future; we simply exclude those that tend to dissipate within a few years.

As with most reviews, ours is mostly backward-looking by nature. We review existing work, thereby putting more weight where work is well-developed and less weight where work is scant. There are several excellent recent complementary surveys, which we point to in the relevant sections of this review.

We structure our review by expanding the familiar pair of physical risks and transition risks highlighted in Carney's (2015) speech as governor of the Bank of England when assessing future risks facing the financial industry. We refine this classification into three categories: (i) loss and damage, (ii) mitigation and the energy transition; (iii) adaptation.

Loss and damage (Section 2) fall within Carney's "physical risk" and include long-run economic damages—the focus of the social cost of carbon and its alternatives—non-market damages, and physical tail risks. The remaining two categories fall within a broad definition of Carney's "transition risk" category. Mitigation encompasses the macroeconomics of the energy transition (Section 3). Adaptation encompasses the macroeconomics of the transition to a warmer world with rising seas, more frequent and severe weather extremes, and their macroeconomic implications such as climate migration and adaptation policy (Section 4).

While historical adaptation is implicitly part of the transmission mechanism in estimates of losses and damages, we include it as a separate section due to its importance going forward. Given continuous progress in the measurement of losses and damages, substantial price declines in renewable energy making broad mitigation potentially cost-effective, and the need to adapt to warming arising from past and near-term emissions, we view this three-pronged framework as the relevant one for this review.

2 Loss and Damage

The valuation of climate damages is an essential component of the economics of climate change, with the social cost of carbon as the centerpiece (National Academies of Science, Engineering and Medicine 2017). The social cost of carbon is defined as the dollar value to society of the incremental damage from an additional ton of carbon dioxide emissions.

The social cost of carbon is a key guide to policy because it corresponds to the optimal tax on carbon emissions in many economic frameworks. Under standard cost-benefit analysis, emissions-reduction policies that are less expensive than the social cost of carbon should be implemented, while policies that are more expensive should not. While carbon taxes are often viewed as politically impractical, they provide a useful benchmark to understand cost-benefit analyses of most alternative policies.

Thus, our first step in this review is to develop a typology to classify macroeconomic models that account for loss and damage and the social cost of carbon. We structure our discussion around the qualitative components of the social cost of carbon and provide quantitative evaluations and references at each step. The National Academies of Science, Engineering and Medicine (2017) report provides a survey of the social cost of carbon, with a median value of $42/ton. Moore et al. (2024) survey more recent estimates of the social cost of carbon, ranging from $100/ton to $240/ton, and a recent estimate by the United States Environmental Protection Agency estimates the social cost of carbon at $190/ton (2020 dollars) (US EPA 2023). The Economic Report of the President (2023) similarly discusses economic damages from climate change. Over time, the social cost of carbon has been updated upwards following improved measurement: accounting for persistent impacts and for a broader range of extreme events, either directly or through a focus on global mean temperature with some recent values exceeding $1,300/ton.

2.1 Monetizing Climate Damages: the social cost of carbon

Nordhaus (1992) first integrated climate change into macroeconomic analysis. He combined a 5-equation representation of the carbon cycle and greenhouse effect with an otherwise standard neoclassical growth model (Cass 1965, Koopmans 1963) to provide an economic framework—the dynamic integrated climate economy (DICE) model—in which emissions, warming and economic activity are jointly analyzed. This model also features abatement costs that society can decide to pay to reduce emissions.

The structure of the Nordhaus (1992) model stands as the core foundation of the social cost of carbon and climate change policy analysis. Much of the frameworks we discuss below, including other integrated assessment models, follow a similar structure. In these frameworks, the calculation of the social cost of carbon involves two modules that interact with each other.

The first module is an economic model that maps economic fundamentals, individual decisions and policy into consumption, output, energy use, emissions and welfare. A key component of economic fundamentals is the set of structural damage functions that map climatic outcomes such as global mean temperature, local temperature and precipitations, into losses to economic fundamentals, such as agricultural or labor productivity, amenities, capital depreciation, or mortality. The second module is a climate model that maps greenhouse gas emissions into climatic outcomes that enter the structural damage functions. Figure 1 below describes the prototypical integrated assessment model diagrammatically. Appendix A details the underlying mathematical structure.

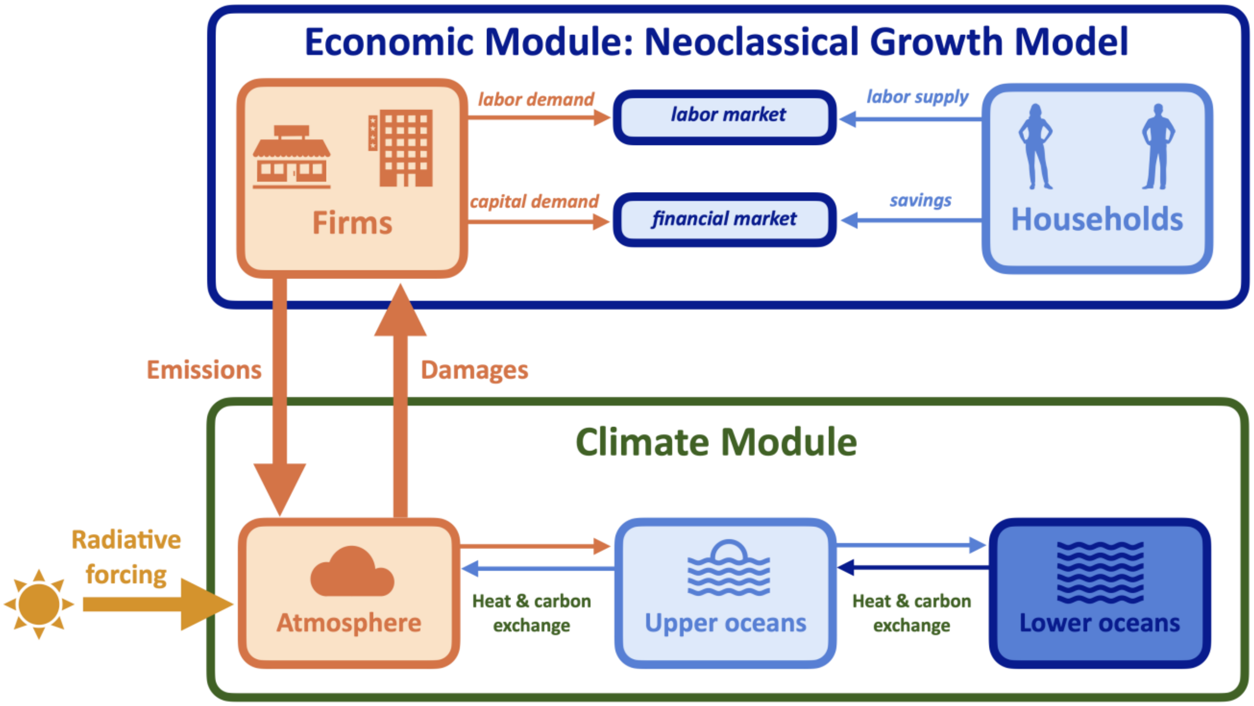

Figure 1. Dynamic Integrated Climate Economy model diagram

The social cost of carbon requires knowledge of both the economy and of the climate system. Many studies thus rely on fully specified integrated assessment models to construct the social cost of carbon, as reviewed in Metcalf and Stock (2017). Moore et al. (2024) conduct a meta-analysis of social cost of carbon values and conclude that conventional estimates typically place it between \$100 and \$250 per ton of carbon dioxide.

We will organize our discussion around the social cost of carbon with the understanding that it corresponds to underlying welfare or output losses. When no value of the social cost of carbon is reported in studies we discuss, we report the welfare or output losses.

As with any modeling exercise, each module that enters the construction of the social cost of carbon is subject to modeling choices and estimation choices. These choices have sparked virulent debate, both within the profession (Pindyck 2013, 2017, Stern 2016, and Stern and Stiglitz 2022) and between economists and natural scientists (Rising et al. 2022). The debate is not just over how to calculate the social cost of carbon, but whether it is even the right concept for a carbon price in a decarbonization effort driven not by cost-benefit analysis of marginal projects but by a temperature target (e.g., holding warming 2°C over pre-industrial temperatures) or a net-zero target date (e.g., 2050). In this review we will adopt the conventional view grounded in standard economic theory, which points to the social cost of carbon as the right concept to assess the impact of climate change from an incremental ton of emissions. Most aspects of the debate can be largely subsumed into the choice of an individual utility function, social welfare function, structural damage functions and level of aggregation.

Navigating the role of various choices can be challenging. Analytical results can help structure how consequential they are. Golosov et al. (2014) provide a richer version of the Nordhaus (1992) economy in which the social cost of carbon and its determinants can be characterized analytically. Our approach in this review is to discuss each choice and point to the trade-offs they involve.

2.2 The Economic Model in the Social Cost of Carbon

2.2.1 Representative Agent Models

The Nordhaus (1992) economy is the prototypical example of a representative agent model equipped to construct the social cost of carbon and losses from climate change. A representative household (or, equivalently, a unit measure of identical households) decides how much to consume and invest. A representative firm decides how much labor and capital to use. Production leads to emissions. Emissions feed back to temperature, which affects economic activity through damage functions.

Damage functions often take the form of a simple mapping between global mean temperature and productivity losses. This damage function can be calibrated to different types of empirical moments. There has been substantial progress in the measurement of damages in recent years.

The canonical approach is a "top-down" approach, in which damage functions are directly calibrated to country-level estimates that regress country-level output on changes in country-level temperature (see e.g. Dell et al. 2012, Burke et al. 2015, Nath et al. 2024). These estimates reflect the net effect of temperature, with possibly partially offsetting underlying mechanisms. These studies find that a 1°C increase in a country's temperature reduces output by 1 to 3% in the medium run (e.g. 5 years). Moore and Diaz (2015) and Kahn et al. (2021) calibrate damage functions in integrated assessment frameworks to the reduced-form impacts of temperature on output following Dell et al. (2012).

In the medium run, it is difficult to disentangle whether these effects on output are transitory or permanent. The central question is then how to extrapolate these medium run output responses to the long run. This question corresponds to the debate around "level" (transitory) vs. "growth" (permanent) effects. Over one century of climate change, this choice implies dramatically different evolutions. Under growth (permanent) effects, Moore and Diaz (2015) find a social cost of carbon of \$220/ton and 2100 output losses that range from 10 to 40% across countries under 4.5°C warming. When imposing level effects, the social cost of carbon is \$33/ton. Nath et al. (2024) clarify how to account for persistence consistently with the data and find that 4°C of warming implies a 7-12% decline in world output by 2100.

The canonical approach to estimating the impact of temperature on output relies on local, country-level temperature variation. While econometrically useful, this approach relies on a source of variation that is not entirely representative of climate change. Climate change represents an increase in global mean temperature, which then implies changes in local temperatures but also many other damaging climatic events that may not be correlated with local temperature, e.g. tropical storms and hurricanes. For instance, Kotz et al. (2024) show that including extreme heat and rainfall further increases damages from climate change. The challenge is then to be able to enumerate, measure and estimate the impact of the full range of weather phenomena.

To address this challenge, Bilal and Känzig (2024) directly estimate the full impact of global temperature changes on world output using time series techniques and use these estimates to estimate structural damage functions in a framework similar to Nordhaus (1992). They find substantially larger impacts than in the panel approach, with a social cost of carbon of $1,367/ton in 2024. Under local temperature damages, they find a social cost of carbon below $178/ton, seven times smaller. They reconcile their much larger impact with the canonical panel approach by showing that global temperature shocks predict a much larger rise in a wide array of extreme climactic events beyond local temperature changes.

Another critical object in Nordhaus (1992) and related framework is the rate of time preference—individual or societal preferences for different time horizons. Climate damages occur largely in the future from any given initial period's perspective, implying back-loaded damages. Standard discounting arguments then imply that even small changes in the discount rate imply dramatic shifts in the social cost of carbon. Quantitatively, Rennert et al. (2022) show that changing the discount rate from 3% annually to 2% annually shifts the social cost of carbon from $80/ton to $185/ton. In this review, we do not attempt to argue in favor of one or other value of the discount rate, but simply flag its importance.

2.2.2 Models with Heterogeneity

A key feature of climate change is that it has unequal impacts that may vary by region, sector/industry and type of households. Even if aggregate damages are equal to their representative agent value in a model that features heterogeneity, their welfare impact and the corresponding social cost of carbon may differ widely in the presence of heterogeneity. The next paragraphs list macroeconomic models that feature heterogeneity relevant to the analysis of climate change loss and damage.

2.2.2.1 Geography

The impact of climate change varies dramatically by region. While Sweden will likely experience agricultural productivity benefits from additional warming, the opposite will presumably hold in

Mali. Thus, taking spatial variation into account is key to account accurately for losses and damage from climate change.

Nordhaus and Yang (1996) extend the Nordhaus (1992) framework to a regional setting, the Regional Integrated Climate Economy (RICE) model, to assess climate impacts across countries. It mirrors the structure in Nordhaus (1992), but with multiple countries that may act as independent decision-makers or as cooperative agents. Countries do not interact through trade in goods or capital nor through migration: they only interact through the global climate, that is a function of all countries' emissions.

Spatially disaggregated economic models can now be specified at much finer levels of spatial aggregation. A literature leveraged recent progress in modeling techniques for spatial economics––reviewed in Redding and Rossi-Hansberg (2017)—to specify macroeconomic models of climate change at a fine degree of spatial resolution: see for instance Desmet et al. (2021), Balboni (2021), Cruz and Rossi-Hansberg (2023), Krusell and Smith (2023), Bilal and Rossi-Hansberg (2023), and references therein. Collectively, these settings incorporate migration across a near-arbitrary number of locations, trade in goods and capital across these regions, and dynamic, micro-founded decision-making. They cover loss and damage channels such as labor productivity, amenities, slow-onset sea level rise, extreme heat and storms.

Desmet and Rossi-Hansberg (2024) provide an excellent review of the role of geography for climate damages loss and damage and adaptation. They show that accounting for regional heterogeneity at the 1° x 1° latitude and longitude cell level can double the social cost of carbon relative to a country-level or world-level representation. Across this literature, damage functions affect varying subsets of productivity, amenities, and capital depreciation. Depending on target differences in target moments and modeling choices, the present welfare cost of moderate climate change ranges from 1% to 5%. Recent computational advances in large-scale dynamic spatial models (Caliendo Dvorkin Parro 2019, Bilal 2023, Bilal and Rossi-Hansberg 2023) allow to efficiently solve and estimate these frameworks at increasingly fine resolutions that mirror the resolution of empirical analysis.

2.2.2.2 Sectors and Industries

Climate damages affect different sectors and industries differently.[1] Just as for geography, the economic model may also be specified at various levels of sectoral, or industrial, disaggregation. Agricultural productivity losses feature prominently in the social cost of carbon literature (see for instance Moore et al. 2017, Rennert et al. 2022, Nath 2024), for two reasons. The first reason is

[1] In traditional economics jargon, ``sectors'' designate a classification of economic activity into agriculture, manufacturing, services, and so on. In the climate change literature, ``sectors'' sometimes take on a somewhat different definition that encompasses both market and non-market impacts, e.g. mortality, violent crime, civil conflict, as well as particular channels through which climate change affects society, e.g. sea-level rise, migration, as reviewed in Carleton Hsiang (2016). Both definitions are of course valid, but their co-existence can sometimes lead to ambiguity. In this review we will use ``sectors'' in the traditional economics meaning.

that agricultural yields drop precipitously when temperature exceeds crop-specific thresholds and precipitation falls, making agriculture a sector that is particularly exposed to climate change. The second reason is that most low- and middle-income countries have large agricultural sectors, implying that over a quarter of the world's employment works in this highly exposed sector. Cruz (2024) and Rudik et al. (2022) include granular industrial composition in addition to regional heterogeneity.

Blanc and Schlenker (2017) review the panel-based literature that studies the impact of climate change on agricultural productivity (Schlenker Roberts 2009, Schlenker Lobell 2010). There are substantial and nonlinear impacts of climate change on agricultural output. For instance, corn yields are largely unaffected until temperature reaches 25-30°C, and then drop by 2% for any additional day over 35°C. These estimates imply that moderate climate change is expected to reduce agricultural yields by more than 30% worldwide by 2100. These effects pervade high-income and lower-income, warmer countries (Lobell, Schlenker and Costa-Roberts 2011). Integrating these findings into an IAM, Rennert et al. (2022) find that worldwide agricultural losses account for a partial social cost of carbon of $84/ton.

The country-level and world-level estimates in Dell et al. (2012), Burke et al. (2015) and Bilal and Känzig (2024) all point to substantial impacts of climate change beyond agriculture. For instance, Cachon et al. (2012) find that productivity in the United States auto industry falls by 8% when temperature exceeds 90°F. Wilson (2017) finds broad-based damages from temperature across United States counties. Somanathan et al. (2021) find that an increase of 1°C in all days of the year lowers annual output by 2% in Indian manufacturing plants. Cruz (2024) and Rudik et al. (2022) estimate structural damage functions by broad industry.

A rapidly expanding literature in macroeconomic studies the role of input-output networks for aggregate economic activity (starting with Hulten 1978, Long and Plosser 1983, and further developed more recently by Baqaee and Farhi 2020). With very few exceptions (Zappalà 2024), these analyses have not yet directly been used to evaluate the consequence of climate change, though they appear relevant.

2.2.2.3 Households

Within locations and industries, households with different characteristics may be exposed differently to climatic shocks. Household heterogeneity pervades modern macroeconomic research in inequality and monetary economics (Huggett 1993, Aiyagari 1994, Moll et al. 2018). This literature has shown that household heterogeneity has critical implications for the impact of fiscal and monetary policy. A strand of work explores the impact of household heterogeneity for climate change impacts, generally concluding that heterogeneity tends to increase societal average impacts to the extent that damages are more concentrated on poorer households (Anthoff 2016, Fried 2022, Benveniste et al. 2022, Fried 2024, Del Campo et al. 2024, Priest et al 2024). We hope that more work will assess the role of household heterogeneity in the future.

2.2.3 Natural Disasters and Weather Extremes

Some of the costliest manifestations of climate change are likely natural disasters and extreme weather. Examples include extreme heat, wind, precipitation, flooding, hurricanes, etc. A broad empirical literature finds substantial effects of extreme events on economic outcomes (Hsiang 2010, Deschênes and Greenstone 2011, Hornbeck 2012, Deryugina, 2013, Hsiang and Jina 2014, Geiger et al. 2016, Kruttli et al. 2024, Gourio and Fries 2020, Kim et al. 2022, Tran and Wilson 2023). These studies sometimes find differences in sign, perhaps due to differences in controls for background demographic trends, governmental aid, and reconstruction efforts.

A nascent literature incorporates extreme events in structural models (Fried 2022, Cantelmo et al. 2022, Bakkensen and Barrage 2021, Jia et al. 2022, Phan Schwartzman 2024, Rudik et al. 2022, Castro-Vincenzi 2023). Bilal and Rossi-Hansberg (2023) construct a comprehensive estimate of the impact of extreme events on United States economic activity, combining new county-level estimates with a structural model of the United States disaggregated into over 3,000 counties. They find that coastal storms are as important as heat stress for the United States and thus double climate damages.

2.2.4 Risk and Uncertainty

Traditionally, environments similar to Nordhaus (1992) have been used to project the impacts of future climate change in deterministic scenarios, without incorporating uncertainty about future emissions, the climate sensitivity, tail events and other aspects of the framework. In practice, the risk involved is considerable. Here, we refer to risk in the traditional sense: a known probability distribution over warming scenarios, the climate sensitivity, damage functions, etc. We refer to uncertainty as an unknown probability distribution over these same variables.

With risk-averse individuals, risk may translate into much larger perceived damages than under a median deterministic scenario. Cai and Lontzek (2019) incorporate risk into the social cost of carbon in simulations in an integrated assessment model. Van den Bremer and van der Ploeg (2021) derive analytical formulas in integrated assessment economy that delivers a risk adjustment to the social cost of carbon. Both studies find that the sign of the impact of risk critically depends on the Elasticity of Intertemporal Substitution (EIS). Risk increases the social cost of carbon if and only if the EIS is above 1, due to the semi-elasticity structure of damage functions. Both studies find that risk can double (or halve) the social cost of carbon depending on parameter values. Daniel et al. (2019) argue that the risk involved in climate damages as well as mitigation evolves over time and affects the shape of carbon dioxide price paths. All these papers use dynamic decision-making models that resemble those typically used in asset pricing models that distinguish between the elasticity of intertemporal substitution and risk-aversion (Epstein Zin 1990 preferences). The valuation of risk also depends on the correlation between climate damages and consumption (Dietz, Gollier, and Kessler 2018). A burgeoning literature incorporates climate risk in firm or institutional decision-making (Castro-Vincenzi 2024, Castro-Vincenzi et al. 2024, Balboni et al. 2024, Ayyub et al. 2024). Much more work is required to incorporate a quantitatively accurate role for risk into the social cost of carbon.

Most of the probability distributions of climate damages are not know with certainty (for instance the speed of the West Antarctic ice sheet melting and ensuing coastal flooding). The presence of such uncertainty calls for the use of an ambiguity-averse decision-making setup that has deep roots in decision theory (Gilboa 1987). Examples of such analysis can be found in Weitzman (2014), Barnett et al. (2023), Barnett et al. (2024). Additional work is needed at least as much for uncertainty than for risk.

2.2.5 Non-Market Outcomes and Welfare

Climate change impacts not only market outcomes typically included in integrated assessment models such as output, investment and consumption, but also several non-market outcomes that have critical importance for welfare: the amenity valuation of various locations, mortality, violent crime, civil unrest and migration. These outcomes directly affect individual well-being, but do not directly appear in output.

There is a large empirical literature that evaluates the impact of rising temperature on mortality. Deschênes and Greenstone (2011) find that each additional day above 32°C increase mortality rates by 0.1% in the United States). Burgess et al. (2017) find that this impact is six times larger in developing countries. Carleton et al. (2022) and Rennert et al. (2022) find that the global mortality-induced (partial) social cost of carbon ranges from $36/ton to $90/ton. Health co-benefits from reducing emissions, which can be substantial, are frequently overlooked in social cost of carbon calculations. Dell et al. (2012), Ranson (2014) and Hsiang et al. (2017) find significant effects of temperature on crime, violence, and political instability.

Originally, integrated assessment models have not included non-market impacts of climate change (Nordhaus 1992, Nordhaus Yang 1996). This omission is problematic from a welfare perspective. Over time, more recent social cost of carbon assessments have incorporated some of these channels using standard monetization methods. For instance, Rennert et al. (2022) find that mortality damages account for about half of their social cost of carbon value of $185/ton. Crime and political instability are more difficult to monetize without more structure but may account for some of the costliest consequences of climate change. More research is needed in these areas.

2.3 The Climate Model in the Social Cost of Carbon

For space, this review focuses on the economic module in the construction of the social cost of carbon and only briefly discusses the climate models. The National Academies of Science, Engineering and Medicine (2017) report, Dietz et al. (2021) and Folini et al. (2024) provide excellent reviews of the climate science and how it interacts with the economic module.

Most economists use small-scale, simplified climate models when paired with an economic model because large-scale models are extremely computationally intensive even on their own. If paired with the typical but additional fixed point problem involved in finding an equilibrium in an economic model, the problem would become computationally intractable.

However, for many applications of interest, simplified climate models that relate worldwide emissions to global mean temperature together can suffice. When regional impacts are needed, statistical downscaling that projects local weather on global mean temperature can often provide a useful first pass, as in Cruz and Rossi-Hansberg (2023), Bilal and Rossi-Hansberg (2023) and Krusell and Smith (2023).

3 Mitigation

Throughout the twentieth century and for at least the first ten years of this century, there were few economical alternatives to the use of fossil fuels for energy, so the main way to reduce emissions of carbon dioxide was simply to use less energy. For this reason, until very recently, the goal of reducing carbon emissions essentially reduced to encouraging energy conservation. Unsurprisingly, economists naturally gravitated to carbon taxation which introduced a Pigouvian tax that internalized the carbon externality. Nordhaus (1977) introduced carbon taxation as a way to address global warming. In Nordhaus (1992), the optimal carbon tax equals the social cost of carbon. Building on this result, there is now an extensive literature on carbon taxes and their cousins, cap-and-trade systems, which together are generally referred to as carbon pricing mechanisms.

The situation now is very different than it was a decade ago: wind and solar generation, paired with storage to address intermittency, are now competitive with fossil thermal generation in many parts of the world, and battery electric vehicles are already cost-competitive with internal combustion engine vehicles on a full cost of ownership basis for several vehicle classes. Those developments, driven by inventions, learning-by-doing, and scale economies, highlight the importance of other policies: research and development policies, standards, green demand subsidies, and supply-side subsidies (green industrial policy).

This section surveys macroeconomic models that are well-suited to analyze the impact of energy policy. We start with a brief overview of models of energy resources. Next, we review models used to analyze carbon pricing, innovation towards cleaner technology, and their implications for factor markets.

3.1 Energy Use Models

A long tradition in economics models the dynamics of exhaustible resources such as fossil fuels (Hotelling 1931, Dasgupta and Heal 1974, Solow 1974, Stiglitz 1974, 1976, Salo and Tahvonen 2001, Fröling 2011). While standard exhaustible resource models predict that the price of the resource eventually rises precipitously as reserves run out, this literature emphasizes that technical change and increasing returns can offset these effects and allow the economy to sustain economic growth in the long run (for instance, in the context of energy, the fracking boom or improvements in offshore drilling). In fact, technological progress is stimulated and directed by rising prices and naturally offsets gradual depletion (Hassler, Krussel, and Olovson 2021). Depending on the structure of property rights and other production distortions, there can be under- or -over-extraction (Bohn and Deacon 2000, Copeland and Taylor 2009, Asker et al. 2019).

There is long tradition of work that provides rich representations of energy systems, consumption and emissions, that studies optimal or constrained decarbonization pathways (Edmonds and Reilly 1983, Clarke et al. 2007, Calvin et al. 2019). Jebaraj and Iniyan (2006) review the earlier stage of this body of work. This line of work shares many features with integrated assessment models in the tradition of Nordhaus (1992), with varying degrees of detail associated with different modules. Work in the energy systems literature highlights granular representations of energy types and uses, and a detailed climate and environment module. The traditional economics literature tends to emphasize a fully micro-founded representation of agents' decisions. Many of the papers described below feature both.

3.2 Carbon Pricing Models

Fossil fuels produce carbon emissions, leading to the well-known free-riding problem that makes climate change a difficult problem to solve. Carbon pricing is the theoretically natural resolution of that difficulty. Carbon pricing is typically achieved through one of two instruments: carbon taxes or a cap-and-trade system. Timilsina (2022) comprehensively surveys the literature on carbon taxes. Stern and Stiglitz (2017) provide a broad overview of the goals and means of carbon pricing. We complement their survey by categorizing the economics of carbon pricing through the lens of economic models.

3.2.1 Carbon Taxes vs. Cap-and-Trade

Cap-and-trade and carbon taxes are equivalent under certainty in a static model but differ under risk (Weitzman 1974). Both provide contemporaneous incentives to reduce emissions, based on their price: the tax rate or the price of the tradeable allowances. In practice, cap-and-trade systems, intensity standards, and portfolio standards have been implemented more broadly than carbon taxes. All are carbon pricing schemes although that term is commonly used only for carbon taxes and quantity-based cap-and-trade.

How elastic are carbon emissions to carbon pricing in pratice? There are many empirical estimates of this elasticity, and several models that incorporate that elasticity. In the context of the European Union, Metcalf and Stock (2023) find that a $40 per ton carbon tax leads to cumulative emissions reductions of 4 to 6% when 30% of the economy is covered by the tax, amounting to a 13 to 20% reduction within the covered sector. Colmer et al. (2023) find similar elasticities for the European Emissions Trading System prices: 14-16% emissions reduction for $20-40 carbon prices.[2]

Of course, declines in emissions due to a carbon tax could be accompanied by rising energy prices, with adverse effects on output and employment. How costly is abatement for the economy? Shapiro and Metcalf (2023) study this trade-off in a model with green energy, highlighting that substitution towards green energy is key in mitigating the possible adverse effects of rising carbon prices.

Using panel methods, Metcalf and Stock (2023) and Colmer et al. (2023) find that even substantial increases in carbon taxes lead to no losses in output or employment growth in the context of the European Union. Konradt and Weder di Mouro (2023) find no evidence of carbon pricing on aggregate inflation, though some evidence on energy price increases. Using time series methods for the European Union Energy Trading System, Känzig (2023) finds evidence of a starker trade-off between carbon pricing and economic activity: every 1% increase in energy prices translates into a 1% reduction in emissions and more than a 1% decline in output and a 0.2 p.p. increase in the unemployment rate. Pisani-Ferry (2021) discusses additional reallocative costs of the energy transition which may take place for deeper decarbonization than that seen historically. While much of the available research has focused on developed countries due to data availability, more research is needed in the context of developing countries.

These estimates can be put in perspective with estimates of historical energy prices. Känzig (2021) shows that output reacts less to historical energy price changes than to carbon prices. Similarly, Moll et al. (2023) and Chiacchio et al. (2023) show that the energy price spikes that followed

[2] Using synthetic control methods, Leroutier (2022) finds that an increase in the carbon price of 13 British pounds in the UK ($20) led to a 50% decline in power generation carbon emissions, largely due to a shift away from coal. This larger estimate could be due to the smaller number of countries used in the analysis.

Russia's invasion of Ukraine led to only moderate economic losses, if any at all. These estimates highlight the importance of substitution through technology, but also trade (which, for carbon pricing, amounts to carbon leakage).

Carbon pricing risk can affect these conclusions. Because the price of the tradable allowances fluctuates—for example, in 2023-2024 the price of emissions permits under the European Emissions Trading System ranged from 54 euros/ton to 102 euros/ton—tradable allowance systems provide less certainty about payoffs of expensive low-carbon projects. This risk can discourage investment as they provide different dynamic investment incentives, as indicated by standard investment theory (Dixit and Pindyck 1994) and modeled in the context of tradeable emissions projects by Aldy and Armitage (2022).

The same argument applies more broadly to risk in general carbon policy, as emphasized by Fried et al. (2022). Ren et al. (2022) confirm this channel empirically using the climate policy uncertainty series from Gavriilidis (2021).

3.2.2 Optimal vs. Second-Best Policy

A carbon tax or emission trading system are flexible policy tools and can be used either to equate the tax rate to marginal benefits (that is, to equal the social cost of carbon or a modification of the social cost of carbon to address multiple preexisting taxes and leakage) or to achieve a given climate path, for example to stay under a predetermined temperature target.

The European Union tends to operate under a precautionary principle and uses a temperature ceiling: avoid warming above 2°C. While the first-best approach under traditional cost-benefit analysis is to compare abatement costs to the social cost of carbon, the second-best temperature target approach amounts to an optimal use of the finite resource of the carbon budget—that is, Hotelling pricing—adjusted to take into account increasing marginal abatement costs and, in principle, endogenous technical change in green technologies. Fitzpatrick and Kelly (2017) and Kaufman et al. (2020) study temperature targets and how they interact with risk in integrated assessment models

Other instruments can also be used to reduce emissions. Dietz et al. (2018) study corporate targets around the world, and Levinson (2019) shows that energy efficiency standards can be more regressive than energy taxes.

3.2.3 International Coordination

The free-riding problem in carbon emissions arises because any given country bears only a fraction of the consequences of its carbon emissions, and thus does not find it beneficial to engage in unilateral decarbonization. In Nordhaus and Yang (1996), non-cooperative carbon policy leads to substantially lower carbon prices than global cooperation, although the resulting difference in emissions is moderate under their calibration.

Trade policy is often viewed as a possible enforcement mechanism to influence other countries in a non-cooperative setting. The idea originates in Markusen (1975), who uses a simple trade model to show that tariffs can be used to reduce other countries' production of a globally harmful externality such as carbon dioxide. In a small open economy model, Brander and Taylor (1997) show that trade can lower welfare in presence of an open access resource, whose depletion accelerates under trade.

As a result, there is increasing interest in using carbon border adjustments or other trade-based policies to incentivize other countries to adopt ambitious climate policies by solving the leakage problem: high domestic carbon prices lead fossil-fuel intensive production to move abroad, and possibly be re-imported. In the economics literature, this idea stems from Nordhaus's (2015) "climate club" proposal, where countries in the club would impose high carbon prices and countries outside the club would be incentivized to participate through trade policy. The climate club concept addresses the free rider problem and goes beyond the theory of border adjustment which typically does not assume an endogenous response.

In a static framework with a limited number of regions, Nordhaus (2015) finds that large climate clubs are sustainable only if the social cost of carbon remains low enough, which in his calibration turns out to be $50. At a higher level, trade sanctions on defecting members become too costly for remaining club members, and the club disintegrates.

One reason why climate clubs can be unstable is carbon leakage. Kortum and Weisbach (2024) and Weisbach et al. (2023) derive jointly domestically optimal domestic carbon taxes and carbon tariffs to influence the rest of the world and control carbon leakage in a two-country setting. Farrokhi and Lashkaripour (2022) show in a quantitative trade model that climate clubs can be more effective than carbon border adjustment mechanisms because most emissions are not embedded in traded goods.

In practice, trade policy is far even from these second-best benchmarks. Shapiro (2021) shows that tariff rates are lower on dirty industries. Cicala et al. (2023) show how to best design tariffs on dirty imports. In line with this body of work, the European Union has started rolling out a Carbon Border Adjustment Mechanism, that imposes a tariff on the carbon content of imports (European Commission 2021). More work is needed to evaluate its effect on European Union emissions and spillover effects on its trading partners.

International spillovers of carbon policy can also occur through other channels than trade. Sinn (2008) argues that demand-side policies such as carbon pricing enacted by a subset of countries are ineffective if supply does not react strongly to demand. In the extreme, if fossil fuel supply is fixed, a demand reduction by some countries is exactly offset by an increase in demand from other countries due to falling prices. Linsenmeier et al. (2022) emphasize that carbon policy adoption is associated with adoption in neighboring countries.

3.3 Models of Innovation and Technological Progress

When there is the possibility of technological progress in green energy generation, innovation policy is a powerful complement to carbon pricing. From a first-best perspective, carbon pricing is necessary regardless of the presence of innovation. But innovation in green and possibly in less emissions-intensive dirty technologies requires an additional set of policies. Blanchard, Gollier and Tirole (2022) and Bistline et al. (2023) review how green innovation policies complement carbon pricing.[3]

3.3.1 Directed Innovation

There is a long tradition in economics that models innovation (Romer 1990, Grossman and Helpman 1991, Aghion and Howitt 1992, Acemoglu 2002). Knowledge is a public good, so firms can only capture a fraction of the benefits that innovation brings to society in the form of research and development or learning by doing. Therefore, market forces will provide insufficient incentives for innovation. Under-investment in innovation is a generic feature of innovation, and applies just as well to the energy transition. A carbon price that is too low will further worsen innovation in clean energy. But under-investment will remain even if the carbon price is set right. See Newell (2010) for a review.

As for any market activity, innovation flows towards sectors where marginal returns are highest: technical change is directed, but the allocation across sectors needs not be efficient (Acemoglu 2002). Goulder and Schneider (1999), Nordhaus (2002), van der Zwaan et al. (2002), Popp (2004) and Fried (2018) analyze endogenous technological change in integrated assessment models. Relative to models without directed technical change, they find earlier though modest emissions reductions and lower carbon taxes.

Fischer and Newell (2008), Acemoglu et al. (2012), Gerlagh et al. (2014), Hassler et al. (2021) and Chateau et al. (2022) analyze rich models of directed green technical change. Collectively, these papers find that optimal policy features both carbon taxes and green innovation subsidies; carbon taxes need only be transitory to permanently redirect innovation to green energy; fossil fuel scarcity contributes to direct technical change; and increasing the elasticity of substitution between

[3] Coady et al. (2019) estimate that, relative to the optimal carbon tax, implicit global fossil fuel subsidies remain large, though direct, actual subsidies are much lower.

green and dirty energy sources helps lower optimal carbon taxes. Acemoglu et al. (2023) analyze the ambiguous implications of technological progress in shale gas, an energy source with intermediate carbon intensity. Aghion et al. (2023) find that consumers' environmental concerns direct innovation towards greener energy use in the automobile industry.

In studies of specific mechanisms, Capelle et al. (2023) demonstrate that the slow adoption of greener capital vintages slows the transition to green energy. Arkolakis and Walsh (2023) provides a spatial theory of clean growth and show that the resulting price declines have large beneficial effects for households.

Empirical evidence confirms that innovation is directed by market forces. Popp (2002), Aghion et al. (2016), Moscona and Sastry (2022), Dugoua and Gerarden (2023) find that green technical change responds to energy prices or market needs. Farmer and Lafond (2016) show that green technology prices follow a version of Moore's law. Wiser et al. (2021) and Way et al. (2022) find consistent evidence, and that renewable cost declines have consistently outperformed expectations.

3.3.2 Diffusion of Technology

Knowledge and technology do not remain confined within country or industry borders. They diffuse across countries and industries, making green technological progress a powerful instrument to reduce carbon emissions across the globe. Eaton and Kortum (1999), Sampson (2016) and Buera and Oberfield (2020) develop and refine theories of international technology diffusion. See Keller (2004) for an early review.

Pigato et al. (2020) provide an extensive review of green technology diffusion with an emphasis on developing countries. Hémous (2016) demonstrates that green innovation subsidies alleviate environmental degradation in the presence of international diffusion. Barrett (2021) shows quantitatively in a multi-region integrated assessment model with green innovation and diffusion that international diffusion can halve long-run warming. Gerarden (2023) proposes a related analysis specifically for solar panels. Donald (2024) develops a framework of green technology diffusion in production networks within countries. More work is needed in this area to quantify the importance of technological diffusion for emissions reductions.

3.4 Factor Market Reallocation

In most models discussed so far, the reallocation of production inputs—labor, capital—is assumed to occur frictionlessly between green and dirty industries. In practice, recent examples of large factor market reallocation have shown that it can be difficult and protracted. For instance, the rise of Chinese import penetration in the United States has left many communities persistently exposed to joblessness (Autor et al. 2013). Given that the green transition is a similar change in the comparative advantage of industries, the green transition may well share some of these features.

3.4.1 Labor

There is a large literature in economics that evaluates the consequences of frictional labor reallocation in the face of industrial or spatial shocks. To just cite a few recent examples, Traiberman (2019) and Caliendo et al. (2019) propose rich structural models to assess labor market adjustments to trade liberalizations. Grossman and Rossi-Hansberg (2008) and Acemoglu and Restrepo (2022) propose frameworks to evaluate the reallocation of workers across production tasks in response to trade and automation shocks. Originating with Hopenhayn (1992) and Hopenhayn and Rogerson (1993), a long tradition of papers has studied the reallocation of workers across firms (see for instance Bilal et al. 2022 for a more recent example).

This structural literature is less developed when it comes to the energy transition. Hafstead and Williams (2019) review the key trade-offs associated with the energy transition. Shapiro and Metcalf (2023) evaluate the general equilibrium impacts of a carbon tax in a framework with unemployment and find that long-run effects depend on green technology adoption. Conte et al. (2023) study the spatial consequences of carbon taxes in the presence of agglomeration externalities.

Walker (2011, 2013) empirically estimates the displacement effects of plant-level contractions on workers due to the enforcement of the Clean Air Act. He finds worker-level impacts consistent with conventional estimates of displacement effects, but that these costs are small compared to the benefits from regulation. Much more work is needed to assess the impact of the energy transition on labor market reallocation.

3.4.2 Capital

A rapidly expanding literature studies green capital investment. Bistline et al. (2023) propose an organizing framework to assess the role of subsidies on green capital investment. Varga et al. (2022), Coenen et al. (2023) and Hinterlang et al. (2023) develop quantitative models with green and dirty capital and a rich nesting structure to evaluate institutional climate targets.

There is a large literature studying the reallocation of capital across firms with or without financial frictions (see e.g. Kahn and Thomas 2008, Winberry 2021, and reference therein). There is comparatively less work using these frameworks to evaluate capital reallocation across firms and sectors in the face of the energy transition.

In a model of firm dynamics with capital vintages, Capelle and al. (2023) find that the costs of carbon taxation are smaller than without capital vintages due to reallocation across firms. Lanteri and Rampini (2023) propose a similar analysis in the context of shipping. Arkolakis and Walsh (2023) develop a framework that integrates economic development, investment in energy production, and trade in electricity, finding that broad declines in energy prices deliver substantial welfare gains. Abuin (2024) assesses the impact of United States shale gas exports on renewable adoption around the world. Empirically, Semieniuk et al. (2022) documents that fossil-fuel assets stranded because of 2060 net zero policies imply major losses for investors: $1.4 trillion globally with over half in OECD countries. More work is needed to assess the impact of the energy transition on capital market reallocation.

4 Adaptation

With more than 1°C of warming already sunk in past emissions and modest progress in mitigation to date, societies will need to adapt to climate change. Countries vary not only in their exposure to climate change, but also in their economic and institutional capacity to adapt. This adaptation can be reactive or proactive.

Macroeconomics has started studying climate change adaptation only recently, but it is a topic of increasing importance. Technological improvements, changes in individual behavior, the ability of trade insure against climate risk, movements of labor away from exposed areas, reallocation of capital, and climate-related insurance, all constitute forms of adaptation. Yet, estimates of adaptation costs representative of all sectors of the economy are still scarce (Fifth National Climate Assessment 2023) and much more work is needed in this area. Burke et al. (2024) provide a recent review of empirical estimates of adaptation.

4.1 When Does Adaptation Matter?

A common criticism of the canonical damage approach is that it uses short-run weather variation to identify the impact of long-run, slow-moving changes in the climate. These impacts may differ for multiple reasons: they may reflect fundamentally different changes in the climatic system, and society may adapt differently to temporary and permanent changes in the climate.

Hsiang and Deryugina (2017) structure this "weather vs. climate" debate. Using a simple envelope argument, they show that adaptation does not matter for welfare to a first order: to the extent that households or firms are already at the margin before the climate changes, the value of adaptation is nil. Of course, adaptation may still matter more for larger shocks that violate a first-order approximation, or for slow-onset adaptation.

Empirically, the evidence on whether adaptation to climate change impacts is taking place is mixed. Barecca et al. (2016) find a strong decline in the heat-mortality relationship in the United States that they attribute to the adoption of air conditioning. Kahn (2005) shows that mortality in richer countries is less responsive to natural disasters, and Carleton et al. (2022) find that richer countries display smaller heat-mortality sensitivities. All papers interpret their results as evidence of adaptation.

Using a related approach that assesses whether the sensitivity of outcomes to temperature changes over time, Burke et al. (2024) find limited evidence of adaptation across a wide range of sectors (output, mortality, conflict, etc.). More work is needed to unpack whether and why adaptation may have been limited historically, and whether it may become more prevalent as climate change progresses and becomes more salient.

4.2 Reallocation of Production

In areas exposed to climate change, a natural way to adapt is to shift activity to sectors that suffer less from climate change. For agriculture, Costinot et al. (2016) develop a high-resolution model of crop switching and find that agricultural losses from climate change are three times larger if farmers cannot adapt by switching crops. By contrast, Burke and Emerick (2016) compare empirically the impact of long-run changes in the climate to short-run heat fluctuations in the context of agricultural productivity in the United States. They find similar impacts and conclude that long-run adaptation to extreme heat is likely weak in agriculture. Nath (2024) emphasizes that non-homothetic food demand limits the reallocation of workers away from agriculture in the face of climate stress. Hsiao et al. (2024) show empirically that trade policy responds to climate shocks: governments protect domestic consumers and producers of agricultural goods.

Given the specialization of locations in particular sectors, changes in sectoral comparative advantage across space naturally leads to trade as a potential adaptation mechanism. Building on an earlier literature (Reilly and Hohmann 1993, Rosenzweig and Parry 1994, Hertel and Randhir 2000), Costinot et al. (2016) find that allowing trade in agricultural products is less important than crop switching. Carleton et al. (2023) show that trade in water-intensive agricultural goods reduces aquifer depletion in regions where water is scarcest.

Cruz (2024), Conte et al. (2022) and Rudik et al. (2022) develop multisector models of economic activity that incorporate the adaptation benefits from sectoral switching and trade for the broader economy. Cruz and Rossi-Hansberg (2024) find a moderate role for trade, perhaps because they do not model sectoral comparative advantage. By contrast, Conte et al. (2022) find a larger role for trade when considering a range of sectors broader than agriculture.

Trade itself leads to emissions. Cristea et al. (2013) document that emissions related to trade are substantial, yet Shapiro (2016) finds that the gains from trade are substantially larger than climate damages associated with trade-related emissions.

4.3 Reallocation of Labor and Migration

There has been enormous progress in the spatial economics literature in the last decade. Redding and Rossi-Hansberg (2017) review these advances that allow to model and analyze location choices at highly granular levels. Desmet and Rossi-Hansberg (2024) review the role of migration in shaping adaptation to climate change through the lens of the spatial economics literature.

Building on this literature, a recent strand of macroeconomic models of climate change are specified at a fine degree of spatial resolution and study internal and international migration in response to climate change (Desmet et al. 2021, Balboni 2025, Cruz and Rossi-Hansberg 2024, Krusell and Smith 2023, Bilal and Rossi-Hansberg 2023, and references therein). Recent computational advances in large-scale dynamic spatial models (Caliendo, Dvorkin and Parro 2019, Bilal 2023, Bilal and Rossi-Hansberg 2023) allow to efficiently solve and estimate these frameworks at increasingly fine resolutions.

Empirically, there is some evidence that migration responds to climate change within developed countries (Leduc and Wilson 2023, Bilal and Rossi-Hansberg 2023). Across countries, the evidence is more mixed (Cattaneo and Peri 2016, Missirian and Schlenker 2017, Benveniste et al. 2024). More work is needed to understand the migration responses to climate change.

4.4 Reallocation of Capital

There is a large literature on housing and the allocation of capital in macroeconomics (Piazzesi et al. 2007, Kaplan et al. 2020, Greaney 2023, and references therein) but relatively little literature that uses these frameworks to assess how the allocation of private capital responds to climate change. Conte et al (2021) and Desmet et al (2021) study the reallocation of knowledge capital across locations under climate stress. Fried (2022) assesses the impact of storm risk on capital accumulation with rich household heterogeneity and stylized spatial heterogeneity. Bilal and Rossi-Hansberg (2023) model local capital investment in response to heat and storm shocks with rich spatial heterogeneity, and find that investment and capital ultimately reallocate away from the South-East Atlantic coast of the United States.

Information provision is key for an efficient allocation of housing capital. Fairweather et al. (2024) show that housing markets react to information about flood risk. Boomhower et al. (2024) document that housing insurance provision fails when insurers use coarse risk pricing models.

The empirical literature on capital reallocation tends to focus on specific policies or mechanisms. Barreca et al. (2016) show that adoption of air conditioning lowers the sensitivity of mortality to heat stress in the United States. Fowlie et al. (2018) show that home weatherization programs have much lower energy savings benefits than previously thought, explaining the low take-up among households.

4.5 Policy-Driven Adaptation

Public policy is a key margin of adaptation (Economic Report of the President 2023, Analytical Perspectives—Budget of the United States Government 2023). Infrastructure investment is a prime example. Balboni (2024) uses a quantitative spatial framework to study public infrastructure investment in flood-prone coastal areas, and finds that they can have substantial costs by keeping economic activity exposed. Hsiao (2023) shows that time-inconsistency problems can lead governments to respond inefficiently with defensive investments such as a sea wall in Jakarta.

Governmental post-disaster transfers also play an important role, and are likely to rise in magnitude with climate change. Deryugina (2017) shows that automatic stabilizers such as unemployment insurance and medical insurance pay out larger sums than direct disaster aid after hurricanes. Henkel et al. (2023) document that post-hurricane transfers are more generous in election years. Hsiao et al. (2024) show that government respond to agricultural losses due to extreme heat by implementing import and export policies.

5 Conclusion

The size of the sections of this review speak for themselves: the literatures on macroeconomic damages and mitigation are well-developed and still undergoing important progress. The literature on adaptation is comparatively less developed, particularly from a macroeconomic perspective. It remains unclear how much societies will manage to adapt to climate change impacts. We hope that adaptation to climate change will keep growing as a topic and take a prominent place within the field of macroeconomics.

Adaptation involves a host of individual and institutional decisions at various levels of aggregation: households and firms; local, state and federal governments; and groups of countries. We hope that future work will make the most of detailed, large datasets that can inform the behavior of these agents. Many detailed datasets on exposure are constructed by institutions and private businesses (e.g. flooding risk by the First Street Foundation, or property values by CoreLogic), but can have varying degrees of verifiability (Schubert et al. 2024). We expect that fruitful collaborations between these institutions, governmental agencies and academics will improve the quality of available datasets.

Assessing the impact of climatic events unfolding over decades is necessarily challenging because, by definition, data is available only for the past. While creative data collection efforts are continuously improving the information available to researchers, we view the combination of the best possible data with structural models as a promising avenue to evaluate the macroeconomic implications of climate change.

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A. Appendix: The DICE Model

A.1. Economic Growth

The economic module of the DICE model resembles the neoclassical growth model. The main differences are the inclusion of climate damages (similar to productivity shocks) and to abatement costs.

Gross output at time t is $Y_t = A_t K_t^{\alpha} L_t^{\alpha}$, where A_t denotes total factor productivity, K_t is the capital stock and L_t is the stock of labor. $\alpha \in [0,1]$ is the capital share in production. The paths of A_t, L_t are exogenously given.

Output net of climate damages and abatement costs then writes: $Y_t^{net} = \left(1 - \Omega(T_t)\right)Y_t - \Lambda(\mu_t)Y_t$. $\Omega(T_t)$ is the damage function that depends on temperature. $\Lambda(\mu_t)$ is the abatement cost function expressed as a share of output, and depends on the fraction of emissions abated μ_t, with $\Lambda(0) = 0$.

Capital accumulates according to $\mathrm{K}_{t+1} = (1 - \delta_\mathrm{K})\,\mathrm{K_t} + \mathrm{I_t}$, where I_t denotes investment and δ_K is the capital depreciation rate. Aggregate consumption is then $C_t = Y_t^{net} - I_t$.

Households have standard time-separable preferences with flow utility function U and discount factor β.

A.2. Emissions, Temperature and the Carbon Cycle

Emissions are given by $E_t = \sigma_t(1-\mu_t)Y_t + E_t^{land}$, where land emissions E_t^{land} are exogenously given. The first component $\sigma_t(1-\mu_t)Y_t$ represents emissions from economic activity and is proportional to gross output Y_t, the fraction of unabated emissions $1-\mu_t$, and the exogenous emissions intensity of production σ_t. A secular decline in σ_t can capture technological progress in low-emission energy sources.

The standard climate module posits: $M_t = (\mathrm{Id} + B)M_{t-1} + E_t$, where $M_t = [M_t^{AT}, M_t^{UO}, M_t^{LO}]$ is the vector of carbon masses in the three main reservoirs: the atmosphere, the upper oceans and the lower oceans. Id denotes the identity 3×3 matrix, and B is a 3×3 matrix to be calibrated that represents carbon mass transfer between the reservoirs, with $\sum_j B_{ij} = 0$ by mass conservation.

Radiative forcing takes the form: $F_t = F_0\, log(M_t^{AT}/\bar{M}) + F_t^{EX}$, where F_0 is the climate sensitivity, $\bar{M}$ is the long-run mass of atmospheric carbon absent anthropogenic emissions, and F_t^{EX} is exogenous forcing.

Temperatures in the atmosphere and the oceans then follow: $T_{t+1}^{AT} = T_t^{AT} + c_1\Big(F_t - \lambda T_t^{AT} - c_2(T_t^{AT} - T_t^{OC})\Big)$ and $T_{t+1}^{OC} = T_t^{OC} + c_3(T_t^{AT} - T_t^{OC})$. The coefficients c_1, c_2, c_3 capture heat exchange between the atmosphere and the oceans. The coefficient λ represents radiative feedback.

A.3. Decision Problem

A world planner chooses the optimal path of investment and abatement to solve:

$$max_{\{\mu_t,C_t\}_t} \sum_{t=0}^{+\infty} \beta^t L_t U(C_t/L_t)$$

$$\text{subject to: (1) } C_t + K_{t+1} = [1 - \Omega(T_t) - \Lambda(\mu_t)]A_t K_t^{\alpha} L_t^{\alpha} + (1-\delta_K)K_t$$
$$\text{(2) climate module}$$

In the decentralized equilibrium, dynasties of households and firms make individual decisions. Firms make zero profits due to constant returns to scale, and thus we can directly write the household problem in terms of output rather than prices. Households do not internalize the benefits from decarbonization since each household is atomistic, and so households always set $\mu_t = 0$ and only choose:

$$max_{\{C_t\}_t} \sum_{t=0}^{+\infty} \beta^t L_t U(C_t/L_t)$$

subject to: (1) $C_t + K_{t+1} = [1 - \Omega(T_t)]K_t^\alpha L_t^\alpha + (1 - \delta_K)K_t$

(2) given the path of T_t *from the climate module*

Common functional forms include $U(c) = \frac{c^{1-\gamma}-1}{1-\gamma}$, $\Omega(T) = 1 - \frac{1}{1-\Omega_1 T - \Omega_2 T^2}$ and $\Lambda(\mu) = \Lambda_0 \sigma_t \mu^2$.

Loss and damage (Section 2) amounts to specifying and parametrizing the damage function $\Omega(T)$. Mitigation (Section 3) amounts to specifying and parametrizing the abatement cost curve and technological progress $\Lambda(\mu), \sigma_t$. Adaptation (Section 4) amounts to adding more choices and margins to the planner or the representative households in the decision problem.