WHITE PAPER

COUNCIL OF ECONOMIC ADVISERS
OFFICE OF MANAGEMENT AND BUDGET

CLIMATE-RELATED MACROECONOMIC RISKS AND OPPORTUNITIES

April 4, 2022

Introduction

Climate change is generating increased challenges to the environment, public health, and the economy. President Biden has set an ambitious goal for the United States: to rapidly reduce greenhouse gas emissions to net zero by 2050. This means that the United States will need to reduce reliance on unabated, carbon-intensive fossil fuel technologies and transition the economy to produce and make use of clean energy and other low-carbon goods and services. The President is mobilizing a whole-of-government approach to climate action through policies in his fiscal year 2023 budget that hasten and smooth the transition to a net zero emissions economy.

The economics literature provides robust evidence that the welfare benefits of well-designed climate policies exceed the costs,[1] providing a strong rationale for urgent action to address the risks of climate change. Preserving the planet's environment will benefit human health globally, reduce the risk of conflict and migration, and ensure the viability of ecosystems. Many of these benefits to human welfare are largely not valued in market transactions; given this, climate action is desirable even if climate change were to have little impact on macroeconomic aggregates.

On top of these substantial non-market benefits, there are benefits that can be valued in market transactions, which would be reflected in gross domestic product (GDP) and other macroeconomic aggregates. A primary tool to assess these aggregates are macroeconomic models, which are used to assess aggregate economic conditions with and without shifts in policy. These models incorporate what is known from the research about the relationships among macroeconomic indicators—such as labor force participation, investment levels, and economic output—to provide projections of the future path of growth.

Given both the pace of climate change and the scale and scope of the economic consequences, integrating the effects of climate change and climate policy into macroeconomic projections is increasingly important (we will use the shorthand "climate-macro" going forward). Indeed, professional macroeconomic forecasters and financial institutions have begun to incorporate climate change into their macroeconomic forecasts (Lafakis et al. 2021). Yet, at this time, most of the macroeconomic models that the Federal government relies upon do not explicitly incorporate future climate risks and opportunities.

Within the Executive Branch of the Federal government, the macroeconomic projections underlying the President's Budget provide a foundation for analysis of the macroeconomic impacts of climate change. That is why the President's "Executive Order on Climate-Related Financial Risk" tasked the Office of Management and Budget (OMB), Department of the Treasury, and policy councils with "develop[ing] methodologies to quantify climate risk within

[1] A large economic literature calculates these welfare benefits directly by estimating the social cost of greenhouse gases, which is the monetary value of the net harm to society of adding a small amount of greenhouse gases to the atmosphere (Aldy et al. 2021). Other economists prefer a risk management approach where action is motivated by the deep uncertainties and threats of extreme damages (Stern and Stiglitz 2022).

the economic assumptions … of the President's Budget." Climate risks are defined to include both the physical risks to Federal and private assets, publicly traded securities, private investments, and companies as well as the risks caused by the global transition away from carbon-intensive energy sources and industrial processes to companies, communities, and workers (Exec. Order 14030).

As part of fulfilling these tasks, this Council of Economic Advisers (CEA) and Office of Management and Budget (OMB) White Paper lays out some of the macroeconomic implications of climate change and the transition to a lower carbon economy in the United States, reviews available climate-macro research and methodologies, and identifies relevant resources in the Federal government for generating climate-macro projections. The White Paper is a first step towards climate-macro projections developed by the Federal government. Earlier this year, CEA and OMB also launched a Climate-Macro Interagency Technical Working Group (ITWG) to develop the capacity to produce climate-macro projections within the Federal government.

Climate Change Can Affect Macroeconomic Outcomes

Until recently, climate risks were primarily considered to be very-long-term challenges facing the economies of future generations. Because of the long-run nature of the climate problem, the macroeconomic models used to inform policy over shorter horizons have not accounted for climate change. However, given failures to reduce carbon emissions in a timely manner, future risks have become present-day concerns. The scale of physical threats, the necessary pace of the transition to clean energy, and the need for sound government policy make clear that macroeconomists need to assess both nearer- and longer-term impacts of climate change on economic outcomes in the context of many other evolving stressors to human-natural systems.

Currently, models that forecast future economic outcomes generally encompass a range of variables, including consumer spending, investment flows, inflation rates, labor supply, productivity, and the savings rate. When macroeconomists project future market production, measured in GDP, they combine equations of hypothesized economic relationships with historical data specifying the statistical relationships among these variables—relationships that currently do not directly account for the effects of climate change. These are used with projections of economic variables (e.g., potential energy supply) and baseline economic inputs (e.g., the rate of depreciation on the value of traditional capital–typically ignoring natural and human capital) to form the model and project future outcomes. Climate change affects many of these macroeconomic variables and the relationships between them, posing new questions about how to integrate these often complex and highly uncertain effects into the models.

Climate Change and Economic Outcomes

A growing literature suggests that as temperatures and sea levels rise, and extreme weather becomes more common, the physical damages that stem from the warming of the planet will have substantial, adverse effects on macroeconomic outcomes at the local, national, and international levels. Though not all caused by climate change, across the United States, estimated damages from storms, floods, wildfires, and other extreme weather events have grown to about $120 billion a year from 2016-2020 (Smith 2021). Climate-driven extreme events can also result in cascading damages to critical and interconnected systems such as energy, public health, ecosystems, water, and food (Reidmiller et al. 2018). These damages have a variety of effects on the economy, including but not limited to straining government budgets, changing asset values and insurance costs, and shifting migration patterns and labor supply. The economic effects vary across U.S. regions and industries and will likely disproportionately harm disadvantaged communities (Islam and Winkel 2017).

In addition to the economic damages caused by a changing climate, the adaptation and mitigation strategies we adopt in the coming decades to avoid those damages can generate a complex set of economic costs and benefits that will have important implications for the U.S. economy. Alongside the need for sustained encouragement of clean energy and other carbon-free industries, a transition to net zero emissions will affect fossil fuel industries and their assets, manufacturing processes, global supply chains, skills requirements and productivity of the labor force, and international trade relationships and flows. Few times in history have economic activities needed to shift so swiftly while facing dire risks of failure. Policymakers need appropriate economic tools to better understand, accelerate, and smooth the transition to net zero emissions.

Ever-increasing climate risk will require increased government resources to respond to and mitigate associated damages. It has long been the case that government helps citizens during both weather-related disasters and economic downturns. In the case of climate-related disasters, U.S. state, local, and Tribal government infrastructure is often self-insured or underinsured, which requires substantial Federal assistance to support disaster costs (The White House 2021d). As an insurer, lender, and guarantor, the Federal government faces significant exposure to increasing costs. As the planet continues to warm and the energy transition begins, climate-related costs may take up a larger share of government budgets (European Commission 2020).

Climate-Macro Projections Are Becoming More Widespread

The practice of incorporating climate impacts into macroeconomic projections is becoming more widespread because of the scale and scope of the physical damages due to climate change and the need to analyze policies that guide economies towards a smooth transition to net zero emissions. For example, Cai and Lontzek (2019) embed climate change in a modern dynamic stochastic general equilibrium model.

In the United States, agencies have already begun working to incorporate climate risk into their macroeconomic modeling, as have private forecasters. For example, the Congressional Budget Office (CBO) now factors in a climate-based drag to GDP in its long-term budget outlook. The CBO macroeconomic model only focuses on the physical risks from climate change and assumes no additional government response to mitigate such physical risks. The CBO estimates that climate change will "on net, reduce average annual real GDP growth by 0.03 percentage points from 2020 to 2050, relative to growth that would occur under the climatic conditions that prevailed at the end of the 20th century" (Herrnstadt and Dinan 2020). For this analysis, CBO's modelers combined econometric estimates of the effect of weather with potential hurricane damages (Herrnstadt and Dinan 2020). They conclude that by 2050, the total accumulated effects of both weather and hurricane damages will reduce real GDP by 1.0 percent per year.[2] In comparison, a recent study by the Bank of England explores a worse-than-expected warming scenario and finds that climate damages could reduce U.S. GDP by over 11 percent by 2050, underscoring the large forecasting uncertainties (see Figure 1 below).

In other countries, national agencies have analyzed the economic and budgetary impact of climate change and the environmental impacts of policies. GreenREFORM is a climate-macro model for the Danish economy that is produced in part by the Danish Ministry of Finance to "analyze the environmental and climate effects of economic policies, as well as the socio-economic effects of energy and climate policies" and to specifically look at economic transition risks (OECD and CFMCA 2021). Similarly, the Bank of Canada and the Office of the Superintendent of Financial Institutions launched a climate scenario analysis to assess the risks "that could arise from a transition to a low-carbon economy" (Bank of Canada 2022).

The United Kingdom's Climate Change Act requires that, once every five years, the government assess the risks arising from climate change. The 2021 Fiscal Risks Report from the United Kingdom's Office of Budget Responsibility includes a chapter devoted to describing various climate risks, both physical and transition (Office for Budget Responsibility 2021). The primary outcomes of interest in that chapter are fiscal outcomes like debt, but the report estimates that mid-century real GDP will be nearly 3 percentage points lower if decisive steps to reduce emissions are not taken until the 2030s.

International agencies have also piloted programs that encourage countries to better understand the impact of climate change on their treasuries and broader macroeconomic outcomes. For example, the Coalition of Finance Ministers for Climate Action was launched in 2019 to consider, promote, and mobilize solutions for both physical and transition risks of climate change to the macroeconomy when conducting fiscal planning, among other goals (Coalition of Finance Ministers for Climate Action 2021). The United States joined this Coalition in 2021.

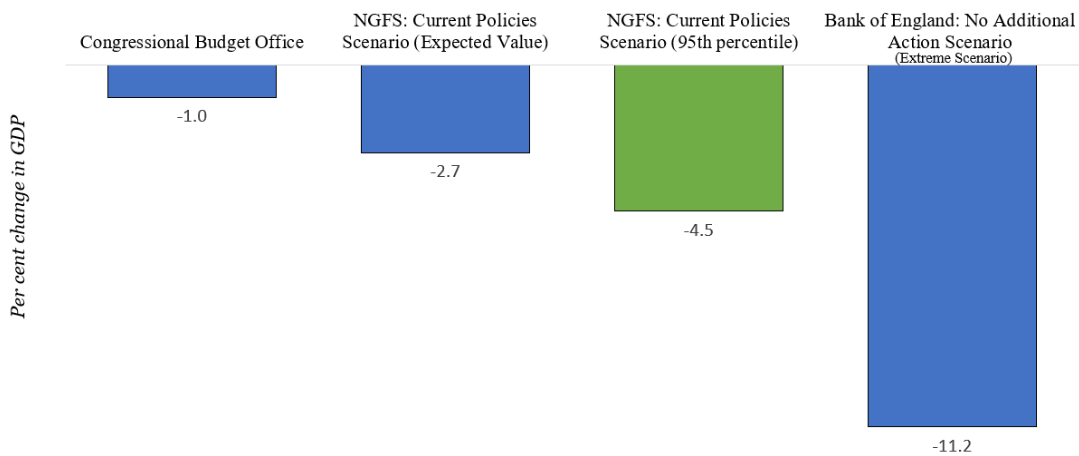
The physical damages from climate change and the effects of the transition to a lower carbon economy will both have important macroeconomic consequences, yet few efforts to date have integrated both physical and transition risks into macroeconomic projections. One exception is the Network for Greening the Financial System (NGFS), an international collaboration of over 100 central banks and financial regulators that provides climate-macro projections in an

[2] The welfare effects would be larger in this context because repair costs to replace the destroyed capital stock are included in GDP.

integrated framework (Network for Greening the Financial System 2021). The Federal Reserve joined the NGFS in 2020, and the Federal Insurance Office joined in 2022 (U.S. Department of the Treasury 2022).

To illustrate the risks of climate damages to the U.S. economy, the President's FY 2023 Budget includes a scenario from a 2021 NGFS analysis showing U.S. GDP declining by 4.5 percent below a baseline scenario over the next 25 years, based on the 95th percentile of the distribution of economic outcomes for a given emissions pathway. That is, under the risk scenario, 2047 real GDP would be only 66 percent higher than 2022 GDP, rather than 71 percent as in the Budget's long-term outlook. See Figure 1 for a comparison of the 4.5 percent case to other risk cases we have described. Reduced economic output increases primary deficits, driven by revenue reductions compared to the President's Budget policy projections. The result is a debt-to-GDP path that is 18 percentage points higher by mid-century: debt would be 129 percent of GDP, rather than 111 percent as in the Budget's long-term outlook. The exercise demonstrates that climate change presents a clear risk to the U.S. fiscal path. Further details about the NGFS analysis and the scenario used in the President's Budget are provided below.

Figure 1. Projected Impacts to U.S. GDP in 2050 under Current Policies



Sources and Notes: CBO study is by Herrnstadt & Dinan 2020 and is based off of damage projections from Kahn et al 2021, Burke & Tanutuma 2019, Colacito, Hoffmann and Phan 2019, and Deryugina & Hsiang 2014, and is based off a climate scenario that is an average between the RCP 4.5 and RCP 8.5 scenarios; NGFS: "NGFS Scenarios Portal" damages produced using Kalkuhl & Wenz 2020 in the NGFS current policy scenario; Bank of England: "Key Elements of the 2021 Biennial Exploratory Scenario: Financial Risks from Climate Change" produced using Kalkuhl & Wenz 2020 damage projections in a scenario with very high levels of warming (3.3 °C), which was done to project extreme risks from climate change.

As will be discussed later in the paper, climate-macro remains in fairly early stages of development. While NGFS offers one of the more complete frameworks, this White Paper identifies several key areas where the U.S. government will strive to develop an increasingly sophisticated approach over time.

New Climate-Macro Tools Can Support Better Policymaking

Policymakers need better evidence, data, and analytical tools to understand the effects on macroeconomic outcomes of climate change and the transition to lower carbon economies. While broad conclusions have emerged from existing climate-macro studies, such as the negative effects on GDP of higher warming levels or delayed action to achieve a given emissions target, the literature remains in a nascent stage with limited policy relevance. For example, studies of the impacts of global warming capture a subset of risks, and studies of the transition to a lower carbon economy often use carbon prices as a driver of all decarbonization actions. More generally, it is often challenging to translate the unique risks of climate change and the low-carbon transition into macroeconomic model inputs.

The United States has been among the world leaders in the sophistication of its data and analytical capabilities related to climate change and economics, and certain Federal government tools, such as EPA's Climate Change Impacts and Risk Analysis (CIRA) project, described below, can be leveraged to provide a foundation for climate-macro projections (U.S. Environmental Protection Agency 2021a; Brayton et al. 2014; Laforte 2018).

Therefore, an urgent need and a unique opportunity exists for the Federal government to provide leadership in developing high quality methods for integrating climate risks into macroeconomic forecasting. Other countries are increasingly conducting climate-inclusive macroeconomic projections. By taking on the same task in the new ITWG on Climate-Macro, the United States can contribute to global efforts to establish benchmarks for such analyses and help to define the standard for climate-inclusive macroeconomic projections going forward.

The results will be a foundation of knowledge, based on the rich literature that already exists, and provide opportunities to push the knowledge frontier forward. Ultimately, policymakers will use this information to better plan for the future, including by identifying and evaluating solutions that help the United States respond to the threats of climate change.

Prior Research and Methodological Issues

The President tasked agencies with developing methodologies to quantify climate risk within the Administration's long-term macroeconomic projections. To that end, we assess the state of knowledge on how to incorporate climate into macroeconomic modeling.

Macroeconomic models and data form the backbone of economic forecasts. These tools, which economists and policy analysts use to describe relationships among macroeconomic phenomena—such as labor force participation, investment levels, and economic output—utilize a set of mathematical equations to estimate and model relationships between economic variables and data (Arnold 2018). Economists refer to data that are determined outside of the model as *exogenous*. For example, a model may use an exogenous forecast of population growth that remains static and unchanged relative to other model outputs. In turn, *endogenous* variables are estimated by the model's set of equations. For instance, CBO's Macroeconomic model consists of 900 variables and 600 stochastic equations. Of these variables, 300 are exogenously determined outside of the model, while the remaining 600 are endogenously determined within the model. The software that runs the model uses the exogenous data, actual history, the relationship between endogenous variables, and the underlying equations to generate a macroeconomic forecast that takes into account dynamic relationships and feedbacks among the model's equations and variables. Many variables within the model are simultaneously determined to account for feedbacks among the endogenous variables.

The historical economic data that these models use implicitly incorporate the impacts of previous climate change. For example, the extent to which U.S. labor supply has been affected by previous climate change has already been implicitly incorporated into the historical data on labor supply. However, climate impacts and climate policy may proceed in an unprecedented and nonlinear fashion; thus, future economic impacts may differ from past impacts in important ways. In other words, relying on macroeconomic projections based on the historical relationship between economic variables may capture only a subset of future impacts. A better understanding of how the risks of climate change and the transition to a lower carbon economy will affect particular sectors of the economy, along with an assessment of the spillover effects of these risks on other sectors of the economy, is necessary for the rigorous identification and evaluation of climate policy solutions and resource allocation decisions.

Incorporating Physical and Transition Risks into Climate-Macro

The Executive Order on Climate-Related Financial Risk follows the standard convention of categorizing climate-related risks into *physical* and *transition* risks. The intensifying impacts of climate change present *physical risk* to things we value like human health, national security, infrastructure, biodiversity and ecosystem services, productivity, publicly traded securities, private investments, and companies—such as increased extreme weather leading to supply chain disruptions. In addition, the global shift away from carbon-intensive energy sources and industrial processes presents *transition risk* to many companies, communities, and workers. At the same time, this global shift presents a once-in-a-generation opportunity to enhance U.S. competitiveness and economic growth, while also creating well-paying job opportunities for workers (The White House 2021b).

The next section of this paper describes the physical risks of climate change, including a brief literature review, a description of the macroeconomic implications, and an analysis of outstanding questions and problems. The subsequent section turns to a discussion of the transition to a lower-carbon economy, again including a brief literature review, a description of the macroeconomic implications, and an analysis of outstanding questions and problems.

Physical Risks of Climate Change

The physical risks of climate change are expected to influence macroeconomic outcomes through an array of channels. These include affecting crop yields and threatening food security (Fuglie 2021; Lobell and Asseng 2017; Moore et al. 2017; Ortiz-Bobea et al. 2021; Rising and Devineni 2020; Schlenker and Roberts 2009), increasing heat-related deaths (Bressler 2021; Lay et al. 2021), worsening air quality (Martinich and Crimmins 2019), putting large swaths of land under water (Bakkensen and Barrage 2021; Kopp et al. 2017; Sweet et al. 2022), increasing the frequency of violence and conflict (Hsiang, Burke, and Miguel 2013; Ranson 2014), exacerbating inequality (Hsiang 2019; Hsiang, Oliva, and Walker 2019; U.S. Environmental Protection Agency 2021b), and heightening migration pressure (Feng, Krueger, and Oppenheimer 2010; Missirian and Schlenker 2017). These physical risks have potentially wide-ranging economic impacts, such as detrimental shocks to aggregate supply and aggregate demand, along with shifts in labor force participation and productivity (Heal and Park 2016; Graff Zivin and Neidell 2014). However, estimating climate's impacts on macroeconomic outcomes is a complex task (Nordhaus 2019).

Here we describe two strands of the literature most relevant to the task of incorporating physical damages into macroeconomic models: (1) "top-down" studies that attempt to estimate the effect of climate change on aggregate economic outcomes like GDP directly; and (2) "bottom-up" studies that assess the effects of climate change on a specific economic sector or category of damages, which can then be aggregated across categories to estimate total damages. Examples of both groups of studies are listed in Figure 2 below, as well as Table 1 and Table 2 in the Appendix.

<u>Top-Down Studies</u>

Much of the recent literature that directly estimates the effects of climate change on GDP uses panel data and short-term variations in weather to estimate the relationship between the distribution of temperatures and GDP based on past experience (e.g. Burke, Hsiang, and Miguel 2015; Dell, Jones, and Olken 2012; Newell, Prest, and Sexton 2021; Kalkuhl and Wenz 2020). This estimated relationship is then used to project how the economy will perform as it is exposed to a different distribution of temperatures in the future. Studies show that warming could substantially reduce U.S. GDP over this century, with percentage estimates that range from the low single digits to the double digits, as shown in Figure 2 and Table 1 of the Appendix.

Top-down studies are useful for macroeconomic modeling because they directly estimate the effects of climate change on GDP, an important (albeit limited) macroeconomic variable for forecasting and budgeting. This means that these effects can be relatively easily "plugged into" an existing, off-the-shelf model that does not already explicitly incorporate climate. A further advantage of the top-down approach is that it captures feedback between different economic sectors and damage categories, which are not well-captured when economic sectors and damage categories are estimated through a bottom-up approach and then simply aggregated.

However, top-down studies also have certain methodological shortcomings that can limit their usefulness in a policymaking context. First, studies that rely on short-term variations in weather to estimate the effect of future climate change can miss longer-term and slower-moving pathways that cannot be captured by variations in weather, such as sea-level rise and ocean acidification, that are projected to cause increasing, cascading damage over time (Dell, Jones, and Olken 2014).

Second, adaptations to climate change over time, such as investments in air conditioning, may alter the estimated temperature-economic relationships. These adaptations may reduce the economic damages of climate change, and can also be costly themselves. Workers in certain industries that require outdoor work, like agriculture and construction workers, may have limited ability to adapt (Shindell et al. 2021). Top-down approaches often have difficulty projecting effects net of these adaptations (Auffhammer 2018), although there have been recent methodological advances that attempt to address this issue (Burke and Emerick 2016; Carleton et al. 2020; Fried 2021; Kalkuhl and Wenz 2020).

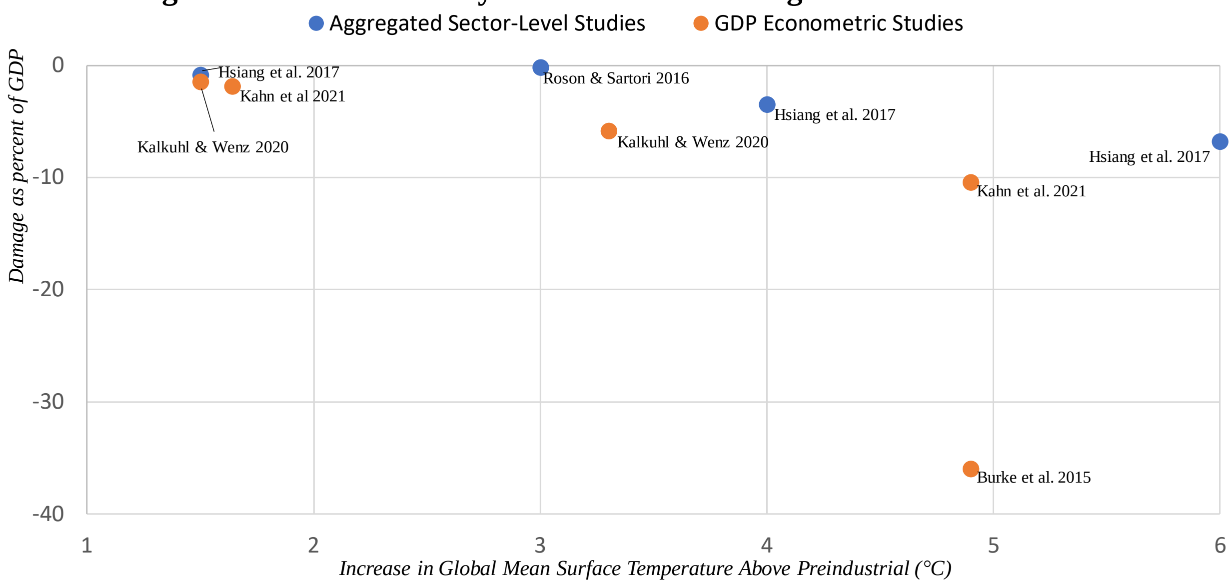
Third, because these estimates are based on historical data, using them to make projections decades into the future requires extrapolating to more severe climate scenarios. Studies often handle this by using nonlinear functional forms to model the increasingly severe effect of temperature, but there remains uncertainty around these functional form approximations.

Finally, important categories of climate impacts, such as the impact of climate change on human health, on wealth, and on migration, are not well captured by GDP. For instance, individuals may increase spending on air conditioning and healthcare in response to rising temperatures; such spending could increase GDP without improving the lives of Americans relative to a no-rising-temperatures counterfactual. Furthermore, assessing the impact of climate change on GDP without considering the impacts on individual economic sectors or damage categories risks understating or overstating the fiscal risk of climate change to the government, as government spending is more concentrated in some areas than others (Barrage 2020). For example, a large portion of U.S. mandatory spending is on healthcare through programs such as Medicare and Medicaid, and therefore, climate damages that affect health would be additionally fiscally costly.

This is further complicated by the fact that GDP includes healthcare expenditures and not health outcomes or human capital formation.

Along these lines, in 2016, the Office of Management and Budget published a "preliminary assessment" of the fiscal risks of climate change facing the Federal government, which included estimates of the increases due to climate change in annual expenditures on various federal programs over a mid- and late-century timeframe (Office of Management and Budget 2016). This exercise focused on physical damages within a specific set of government programs and is being updated and expanded for fiscal year 2023. Future versions of this report could capture impacts across a broader range of federal expenditure categories. U.S. states are also engaged in better understanding both the budgetary impacts of climate change and the transition to net zero emissions. For example, Seiger and Heller (2021) discuss specific recommendations for California to incorporate climate risk disclosure practices into direct expenditures and pension fund investments.

Figure 2. Estimates of Physical Economic Damages in the United States



We present here the difference in damages as a percentage of GDP with climate change and without climate change in 2100. Hsiang et al. 2017 90th percentile estimates are given in their main text as a function of the increase in GMST. The estimates shown in the chart are the average of the given 5th and 95th percentiles; Roson and Sartori 2016 estimates are given in their main text in table 7-1 for +3°C increase in GMST; Kahn et al. 2021 damage estimates are given in their main text for RCP 2.6 and RCP 8.5 in the year 2100.[3] *We used Magicc to convert the emissions scenario to an increase in GMST live.magicc.org; Kalkuhl and Wenz 2020 give worldwide damage estimates in their main text, but U.S. projections are available from NGFS through the NGFS Data Explorer combined with the REMIND-MAgPIE IAM available here: https://data.ene.iiasa.ac.at/ngfs/#/downloads. We present here two 2100 estimates for the lower emissions NGFS Net Zero 2050 scenario and the higher emissions NGFS Current Policies scenario. The temperature increase in these scenarios is given by the NGFS MAGICC model expected value for*

[3] The IPCC creates a number of scenarios called "Representative Concentration Pathways" (RCPs) to represent this emissions uncertainty, ranging from RCP 2.6 (low emissions and quick decarbonization resulting in under 1.5 °C warming by 2100) to RCP 8.5 (high emissions and little decarbonization resulting in ~4.8 °C by 2100) (Meinshausen, Raper, and Wigley 2011). Previously, the IPCC used a different set of scenarios described in the "Special Report on Emissions Scenarios" (SRES) (Nakicenvoic et al. 2000). This includes the A2 scenario that results in ~3.5 °C warming by 2100.

the REMIND projection with the data available through the NGFS data explorer linked above; Burke et al. 2015 do not provide country-level projections in their main text, but they have a supplementary website that shows country-level projections for the RCP 8.5 emissions scenario available here: https://web.stanford.edu/~mburke/climate/data.html We used Magicc to convert the emissions scenario to an increase in GMST, available here: live.magicc.org*. Details on the timing of these projections are given in tables 2 and 3 in the appendix.*

Bottom-Up Studies

The other strand of literature, termed here bottom-up studies, focuses on specific economic sectors (e.g. energy, agriculture) or categories of damages. These approaches more clearly illustrate the *specific* ways by which climate change is projected to affect *specific aspects* of the economy. Relevant recent papers and their core findings are listed in Table 2 of the Appendix.

An advantage of the bottom-up approach is that it can integrate impacts that, while not well-captured in GDP, nonetheless have important implications for social welfare and fiscal sustainability. In addition, while studies that take the top-down approach typically estimate damages to GDP using a single econometric framework, the bottom-up approach allows researchers to draw on a diverse range of evidence by using multiple studies across disciplines that utilize varied methodologies, e.g. by combining agricultural systems models to estimate damages to agriculture with statistical epidemiological models that estimate health impacts with economic models that estimate the impact of climate change on labor supply. Because the bottom-up approach estimates climate impacts in specific sectors/damage categories, resulting estimates can be useful for planning to invest in adaptation measures to protect parts of the economy that are most vulnerable to the potential future impacts of climate change.

A good deal of bottom-up work has focused on the effects of climate change in specific economic sectors that are projected to be especially impacted by climate change, such as agriculture. For example, Schlenker and Roberts (2009) show non-linear detrimental impacts to corn, soybean, and cotton on days that exceed around 30 °C (86 °F). This is concerning as the frequency of hot days, such as those above 30 °C, is expected to increase due to climate change (Hoegh-Guldberg et al. 2018; Kharin et al. 2018) and because corn and soybeans represent nearly half of the dollar value of crops grown in the United States—44 percent in 2018 (USDA ERS 2021). Furthermore, the combined impacts of water stress and heat stress are projected to be more damaging than the effect of heat stress alone (Haqiqi et al. 2021). There remains some uncertainty around the impacts of carbon dioxide fertilization (Taylor and Schlenker 2021) as well as the degree to which adaptations, such as crop switching, can mitigate climate impacts; one recent study that accounted for crop switching found that, in a very high emissions scenario, there was still a substantial reduction in profits for six staple crops in the United States (Rising and Devineni 2020). Globally, climate change is projected to have a negative impact on worldwide agricultural yields in aggregate, especially in places exposed to extreme heat (Lobell and Asseng 2017; Moore, Baldos, and Hertel 2017).

Other studies focus on specific categories of damages, such as the effects of climate change on labor supply, sea-level rise and flooding, mortality, migration, and inequality. For example, a wide variety of physical infrastructure including roads, rail, bridges, ports, and municipal water supplies are expected to be adversely impacted by climate change (Martinich and Crimmins 2019; Sweet et al. 2022). Furthermore, researchers have found that in the United States, higher temperatures will lead to increased morbidity and adverse impacts on labor supply and productivity (Reidmiller et al. 2018; Jagai et al. 2017; U.S. Environmental Protection Agency 2017).

Local air pollution caused by the combustion of fossil fuels has also been found to cause adverse impacts on labor supply and other economic outcomes. In 2011, EPA conducted an economic impact study of the Clean Air Act Amendments of 1990 and found that the benefits to gross domestic product (GDP) of reduced medical expenditures and work absences were comparable to the negative effects of the compliance costs on GDP as of 2010, and exceeded the negative effects of the compliance costs on GDP by 2020 (U.S. Environmental Protection Agency 2011). We can therefore expect large "co-benefits" to the U.S. economy of reduced air pollution from actions to address climate change (Scovronick et al. 2019; Deryugina et al. 2019; Graff Zivin and Neidell 2012).

Bottom-up studies can be aggregated across sectors and damage categories. This is the approach taken by, for instance, Hsiang et al. (2017) to estimate future impacts of climate change on the United States, including on agricultural yields, mortality, electricity, labor, property crime, and violent crime. They find that the monetized damages across these categories sum to the equivalent of less than 1 percent of U.S. GDP in a 1.5 °C warming scenario and to the equivalent of greater than 10 percent of GDP in a 6 °C warming scenario.

Like top-down studies, bottom-up studies suffer from some methodological challenges. The estimates omit any impacts of climate damages that are not specifically analyzed in the study. They are only beginning to include the potentially important interactions across sectors, including the potential for climate damages to cascade across interconnected systems within the economy (Reidmiller et al. 2018).

Considerations for Incorporating Physical Damages into Macroeconomic Models

While there is now a relatively rich literature on the economic impacts of climate change, producing estimates that are useful in the context of macroeconomic modeling remains a considerable challenge.

As noted earlier, econometric estimates of climate damages are typically based on historical relationships and therefore include only a subset of expected damages due to the unprecedented economic impacts that climate change is forecast to cause. Similarly, abrupt and irreversible changes (i.e. tipping points), such as the rapid melting of ice sheets, could cause systemic changes in environmental systems that are unprecedented in human history (Dietz et al. 2021).

Moreover, the literature often focuses on "most likely" outcomes, while prudent responses to large societal risks require an understanding of a wide range of possible outcomes, including low probability and high impact outcomes (Weitzman 2009). Omitting large downside risks limits the policy relevance of climate-macro projections, particularly as a risk management tool. Work on quantifying macroeconomic uncertainty induced by climate change is in its early stages (see Kiley 2021), and more attention to these risks is warranted.

Although policymakers need assessments for how climate change will affect high-level macroeconomic indicators, the most acute and policy-relevant climate risks—for example, those associated with extreme weather (Kim et al 2021)—are often specific to local economies and therefore require granular analysis to capture, with certain regions and sectors likely to be affected much more than others (Cruz and Rossi-Hansberg 2021). Macroeconomic models often do not include the granular regional or sectoral detail that may be required to capture many of the economic shocks resulting from climate change and actions in response.

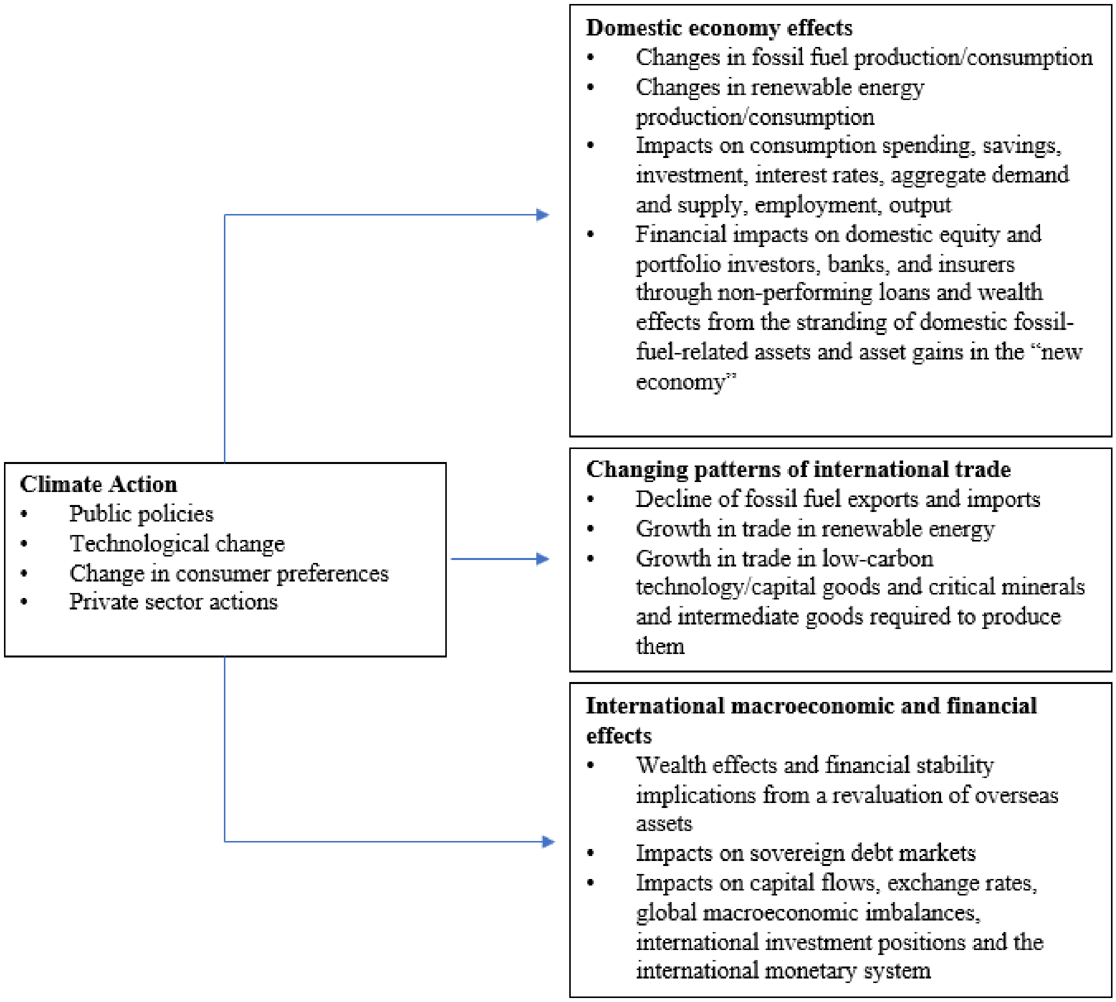
Finally, while macroeconomic projections may focus on a single country like the United States, the impacts of climate change are global and reverberate around the world. For example, extreme weather events in other places of the world can disrupt U.S. supply chains or dramatically alter global commodity prices.

The Macroeconomic Impacts of the Transition to a Net Zero Economy

President Biden has committed that by 2030 (using a 2005 baseline), the United States will halve its greenhouse gas emissions and, by 2050, achieve net zero greenhouse gas emissions, meaning that all remaining greenhouse gas emissions will be fully offset by the carbon dioxide sequestered in trees, plants, soils, products, or underground geologic formations (The White House 2021b). These goals build on climate commitments by other countries, subnational governments, and private sector actors.

While the combination of the private and public sector climate actions both domestically and abroad are already affecting the economy, the transition to a net zero emissions economy will require advancements in technologies and a host of new policy actions to encourage lower emissions, which will change the U.S. economy in important ways. Figure 3 provides a summary of the many factors driving the economic impacts of the transition (Volz et al. 2021). While the economic literature provides strong support for well-designed climate policies due to their net positive impacts on welfare, the near-term macroeconomic effects of the transition include both risks and opportunities, described below.

Figure 3. Factors Driving the Economic Effects of Transition to Clean Energy



Source: Volz et al. (2021)

Macroeconomic Risks of the Transition

Transition risks include two kinds of costs. First are the *direct costs* of climate policy actions, which include the cost of investments in climate solutions, as well as the costs of regulations and taxes to reduce reliance on fossil fuels. Second are the potential *costs of inaction* in a global economy that is moving rapidly towards cleaner technologies. Both kinds of costs are evaluated holding constant the physical risk trajectory discussed above. That is, transition risks include costs incurred when transitioning to a cleaner economy, without considering the benefits of avoiding climate damages.

The direct costs of climate policies may come from a combination of regulations, government expenditures, and taxes, which essentially constitute efforts to reduce emissions by imposing constraints on resources that cause large negative externalities. There are also costs that governments incur in order to increase the availability and affordability of alternatives, including subsidies and incentives designed to induce the innovation and deployment of clean energy solutions. The costs of the transition include a potential diversion of resources away from investments that could earn a seemingly higher rate of return, ignoring the harmful social effects of emissions (Batten 2018). At a macro level, decarbonization is typically modeled as an adverse supply shock, pushing higher production costs and negatively impacting economic output (Pisani-Ferry 2021).

The empirical estimates of the costs of reducing emissions are often summarized by the carbon prices required to achieve a given emission pathway, rather than considering the full range of potential climate policies. These estimates vary widely due to uncertainties in factors including technological progress, fuel prices, policy actions, and preferences. Stiglitz et al. (2017) conclude that the economic literature points to the need for a cost of carbon dioxide emissions of $50 to $100 per metric ton by 2030 for a pathway consistent with the Paris agreement climate goals. If clean technologies progress faster than economic models project, the costs of decarbonization could be substantially lower (Stock and Stuart 2021). The economic literature emphasizes the importance to macroeconomic outcomes of the economic efficiency of climate policies, with lower transition costs associated with more flexible, comprehensive, and market-based policies (The White House 2016; Metcalf and Stock 2020).

Moreover, to achieve a given emissions target, inaction today means the delayed implementation of climate policies, which is likely to lead to higher future transition costs due to the need to develop and deploy clean technologies even faster. Looming policy uncertainty can also be a drag on investment and therefore economic growth (Bernanke 1983; Handley and Limao 2017).

Additional costs of inaction stem from the reality that the United States' competitive position within the global economy will be affected by a rapid move towards lower-carbon technologies and fuels. Indeed, the transition has already begun; for example, while about 60 percent of electricity generated globally is from fossil fuels as of 2020, roughly 80 percent of newly-built electricity capacity comes from clean sources (Ritchie et al. 2022; Ritchie and Roser 2020; IRENA 2021). To the extent that other countries take the initiative to be at the forefront of investing in clean energy solutions, U.S. firms—and U.S. workers—could lose out.

Failing to prepare for this transition away from fossil fuels presents risks to the United States, in part because it produces more oil and natural gas than any other country (U.S. Energy Information Administration 2021). A recent analysis concludes that if the world can shift to a pathway consistent with global climate goals, the energy transition will generate "localized issues of post-industrial decline" in oil exporting countries with high-production costs, including the United States, if actions are not taken to diversify these economies (Mercure et al. 2021). Indeed, economists are considering whether the transition to clean energy risks an economic shock to certain communities akin to the "China Shock" caused by increased exposure to international trade.[4] Fortunately, such outcomes are not set in stone, because opportunities exist to shift economies toward a reliance on cleaner industries.

Economic Opportunities of the Transition

In the global race to develop, deploy, and export new technologies, the rapid growth in the global demand for clean energy technologies and other climate solutions creates important opportunities for U.S. firms. Considerable resources and a well-trained labor force have enabled U.S. firms to be global leaders across a wide range of industries (National Academies of Sciences, Engineering, and Medicine 2021). As a National Academies Panel recently noted, the United States has “abundant supplies of every type of major low-carbon energy resource,” making the country well positioned for a net zero emissions economy (National Academies of Sciences, Engineering, and Medicine 2021). Government support could improve the capacity of U.S. firms to compete effectively in emerging global markets for clean energy technologies and other climate solutions, in a global context where other countries are providing support to their own domestic firms through the energy transition (U.S. Department of Energy 2022).

Climate policies can be designed to take advantage of opportunities to create a stronger and more equitable U.S. economy, including by overcoming market failures and reducing preexisting inequities and economic distortions.

- **Overcoming market failures**. Without policy support, the private sector will underinvest in certain actions that provide large societal benefits, including technological progress and public infrastructure (CEA 2021). Targeted investments in innovation and infrastructure therefore have the potential to simultaneously boost the economy while accelerating the transition to a net zero emissions economy (CEA 2021, 15).[5] Rising sea levels and more powerful storms provide additional motivations for investments in protective infrastructure to avoid localized economic shocks (Zickfeld et al. 2017; Stott 2016).

- **Reducing pre-existing inequities, including environmental injustices**. Addressing inequities in the economy is a key policy priority of the Biden Administration, and the harms caused by fossil fuel emissions disproportionately harm low-income and historically marginalized populations (Hsiang et al. 2017). A recent National Academies

[4] Autor, Dorn, and Hanson (2021) evaluate whether the decline in coal production depressed coal-dependent local economies, akin to what they documented in their papers on the China Shock. This, however, is only one side of the transition – as production of industrial and durable goods transitions away from fossil fuels, a variety of industries, from steel to automobiles, are at risk (International Energy Agency 2022; Jadhav and Mutreja 2022).

[5] Studies of the rates of return on public investments in U.S. infrastructure show an average rate of return of 16.7 percent and median of 12.8 percent (Bivens 2017). Dechezleprêtre et al. (2014) find that “knowledge spillovers” – measured by patent citations – are larger for “clean” than “dirty” technologies, perhaps due to their more general applications and because clean innovations represent more radical forms of innovation compared to dirty innovations, which are generally incremental. This gap may decline over time as clean energy technologies mature.

panel estimated that roughly $2 trillion in incremental capital investments need to be mobilized by 2030 to put the United States on track to achieve the goal of net zero emissions by 2050 (National Academies of Science, Engineering, and Medicine 2021). Some of these investments can be targeted in ways that promote economic development and create high-quality employment opportunities, particularly in struggling and disadvantaged communities (Bartik 2020). Indeed, through the Justice40 Initiative, President Biden has promised to deliver at least 40 percent of the overall benefits from Federal investments in climate and clean energy to disadvantaged communities (The White House 2021a). The Interagency Working Group (IWG) on Coal and Power Plant Communities is helping to channel Federal funding to communities most in need (Interagency Working Group on Coal and Power Plant Communities and Economic Revitalization 2021).

- **Reducing pre-existing economic inefficiencies**. Climate policies may provide opportunities to improve the efficiency of the economy. Reducing subsidies for the production and consumption of fossil fuels could simultaneously decrease emissions and improve economic efficiency. Another example, long studied in the economics literature, is the opportunity to implement market-based climate policies that raise revenue, and then use those revenues in productivity-enhancing ways (McFarland et al. 2018; Diamond and Zodrow 2018).

These examples illustrate ways that climate action presents an opportunity to simultaneously address multiple societal priorities.

<u>Challenges Incorporating Transition Risks and Opportunities into Macroeconomic Modeling</u>

Climate-macro analyses have not captured the full range of risks and opportunities described above due to a host of analytical and data challenges, limiting the policy relevance of the existing literature.

Analyses commonly focus on simplified policy proxies, like carbon prices, which do not fully capture the diversity of climate policy strategies seen around the world and proposed by the Biden Administration. In particular, although government expenditures via subsidies and investments commonly contribute to decarbonization strategies, existing climate-macro models often struggle to reflect the trade-offs associated with government spending and related policy tools.

Macroeconomic models typically are not designed to analyze transitions, nor fundamental shifts in global supply changes, including the rapid changes to the economy required to achieve domestic and international climate goals. Such models often lack sufficient sectoral or regional detail and sometimes assume a fixed supply of labor and full employment, which limit their usefulness in assessing transitional dynamics.

More broadly, any model built to mimic the economy or energy system as it exists today struggles to depict the rapid progress in emerging technologies and the associated effects on macroeconomic outcomes (Way et al. 2021).

Employment impacts of the transition

The impact on jobs of the transition to a net zero emissions economy is a topic that garners particular interest. Effects on employment include the jobs gained in clean sectors as technologies (e.g. wind and solar energy) gain market share and the jobs lost in carbon-intensive sectors. However, the effects of the transition on employment across the economy will be far more wide-ranging; for example, companies that produce goods and services that substitute or complement those in the directly affected sectors will experience changes in labor demand. The jobs lost and gained will often be in different sectors and locations (Saha and Cyrs 2021).

Shifting to clean energy technologies often requires considerable labor-intensive economic activities like construction and installations, implying that short-term employment effects of the transition may be positive, while labor productivity may decrease (Batten 2018). These effects could dissipate over time as technologies progress (Fankhauser et al. 2008). However, for an economy near full employment, climate policies are unlikely to have noticeable impacts on aggregate employment across the economy (U.S. Environmental Protection Agency 2021c). Still, there will be important localized gains and losses due to the many frictions of labor reallocation.

Policy structures matter a great deal for employment outcomes. The transition presents opportunities to implement policies that encourage the creation of not only jobs, but *high-quality* jobs with living wages, strong benefits, and safe working conditions. Government investments and incentives can encourage domestic supply chains in certain sectors and associated employment opportunities (U.S. Department of Energy 2022). Particularly given the propensity of Americans to stay in their communities even after economic dislocations occur (Autor, Dorn, and Hanson 2021), policies can help to direct job opportunities toward the geographic regions that are most in need, including the local economies that have been historically reliant on carbon-intensive industries. For example, the Interagency Working Group on Coal and Power Plant Communities and Economic Revitalization, which was created by President Biden in January 2021, has identified over $30 billion in existing federal funding that could be used to help fossil fuel-dependent communities, and the Bipartisan Infrastructure Law will spend billions of dollars on investments that target local communities with economies that rely on energy production (Interagency Working Group on Coal and Power Plant Communities and Economic Revitalization 2021; The White House 2021c).

An Integrated Approach to Climate-Macro Projections

Few efforts have integrated both the physical risks of climate change and the impacts of the transition to a net zero emissions economy into macroeconomic projections. However, both will have important macroeconomic consequences, as described above.

Moreover, there are important interactions between physical and transition risks, especially in the medium to long run. For example, projected economic costs from physical damages are highly sensitive to expected emissions, with much higher damages calculated in high emissions scenarios than in low emissions scenarios (see, e.g., Kahn et al. 2021).[6] Moreover, infrastructure that is critical for the transition needs to be built to withstand future changes to the climate (Woetzel et al. 2020).

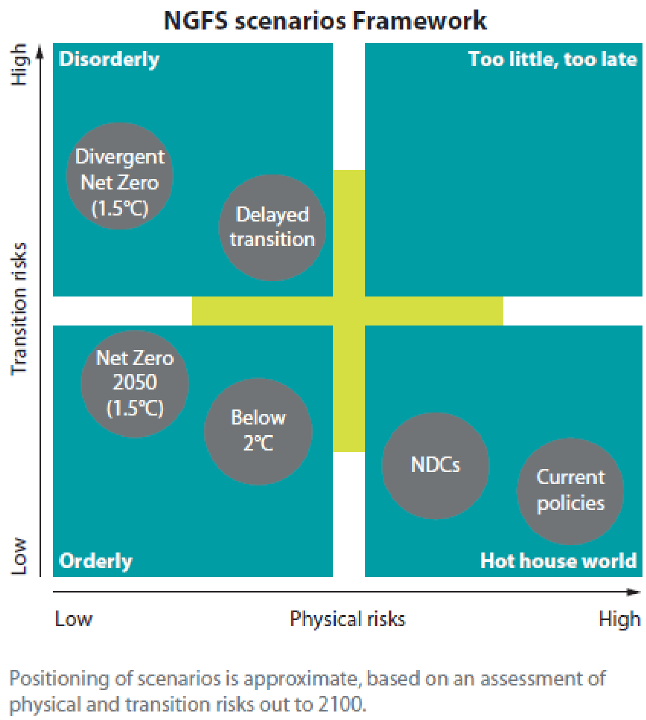
One prominent study that provides integrated estimates of the macroeconomic impacts of both physical and transition risks is from the Network for Greening the Financial System (NGFS), an international collaboration of over 100 central banks and financial regulators (Network for Greening the Financial System 2021).

The remainder of this section describes the NGFS exercise and findings. The purpose is not to suggest that the Federal government will take the same approach as NGFS in its future climate-macro work. Indeed, the NGFS exercise is subject to the limitations and caveats described in the previous sections, including the focus on a subset of risks that can be observed in the historical data. Instead, we provide a detailed discussion of NGFS due to its somewhat unique integration of physical and transition risks in a global, widely-used, and publicly-available climate-macro framework.

The NGFS approach starts with six different scenarios that cover potential future emissions trajectories, ranging from global net zero by 2050 (limiting global warming to ~1.5 ºC above preindustrial) to preserving existing climate policies with no new policy (leading to ~3 ºC above preindustrial by 2100) (Network for Greening the Financial System 2020, 2022). NGFS considers both the total amount of warming resulting from a climate scenario (the physical risks) as well as the speed and coordination of decarbonization efforts (the transition risks), as shown in Figure 4 below.

[6] The IPCC creates a number of scenarios to represent this emissions uncertainty, ranging from RCP 2.6 (low emissions and quick decarbonization resulting in under 1.5 °C warming by 2100) to RCP 8.5 (a very high emissions scenario resulting in ~4.8 °C by 2100) (Meinshausen, Raper, and Wigley 2011).

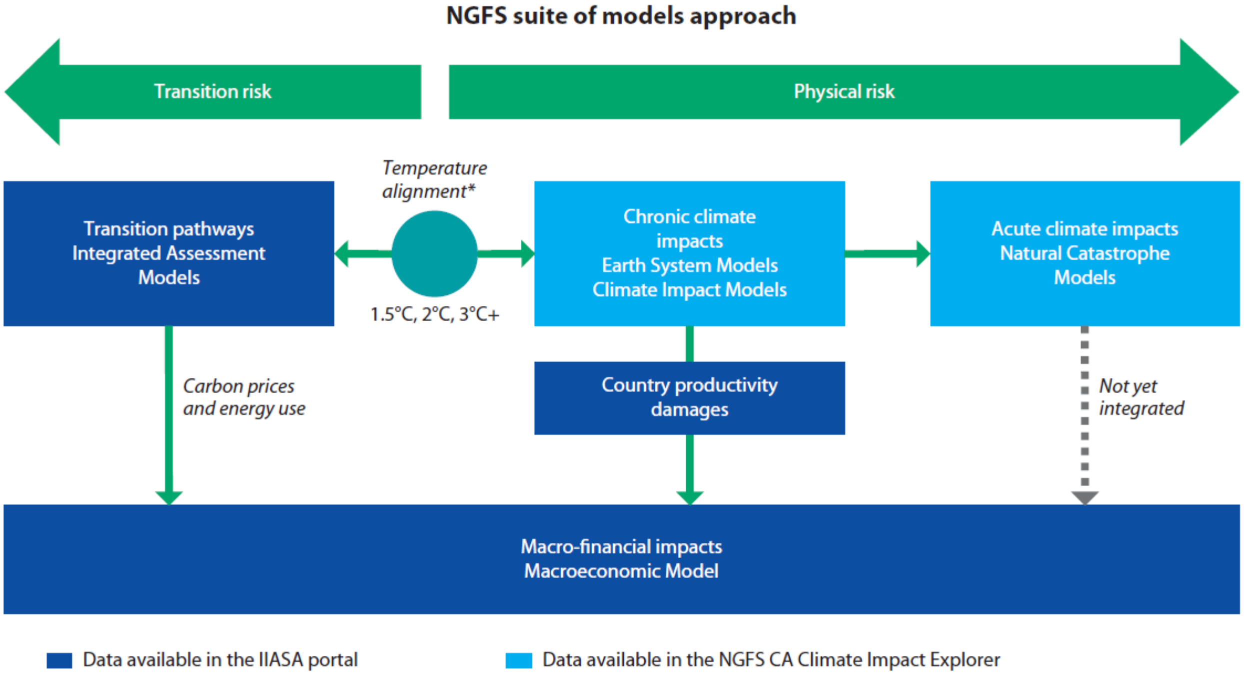
Figure 4. Network for Greening the Financial System Scenarios Framework



Source: NGFS 2021

NGFS introduces the physical and transition impacts exogenously into a macroeconomic model called NiGEM (National institute Global Econometric Model) at a country level (Figure 5). NiGEM is an econometric model used for forecasting and scenario analysis, creating quarterly projections through 2050 (NGFS 2021). It consists of individual country models linked together through trade in goods and services and integrated capital markets. For inputs, the model uses country-level data provided by detailed integrated assessment models with a high degree of granularity in the energy system. NGFS aggregates across the transition risks and physical risks to project the net effect of climate change on macroeconomic outcomes.

Figure 5. Network for Greening the Financial System Suite of Models Approach



Source: NGFS 2021

Additional key assumptions and methodological choices NGFS made when conducting its analysis include the following:

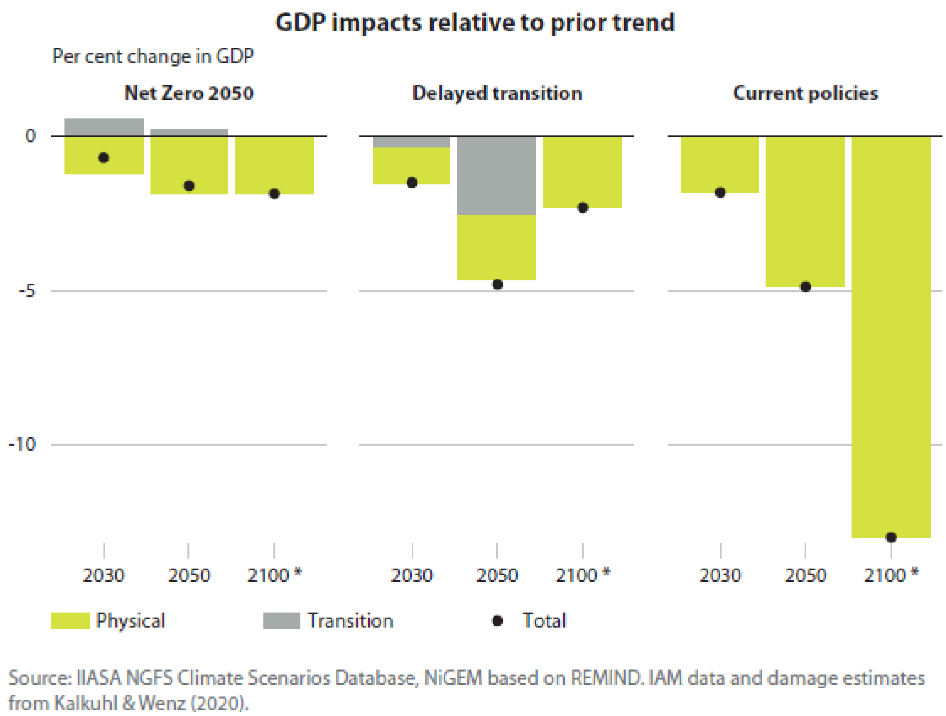
- To model transition pathways (i.e. the policies and technologies required to achieve a specific emissions scenario), NGFS uses three integrated assessment models (IAMs).[7] IAMs represent linkages between economic and natural systems, which can provide richer detail than typical macroeconomic models for industries that are particularly important for the transition towards a low-carbon economy, such as the energy and agricultural sectors.
- To determine the effect of the transition pathway on other variables, including demand for energy, energy prices, required energy investments, demand for other commodities, other commodity prices, emissions, and land use, NGFS also uses IAMs.
- To model climate policies, NGFS uses carbon pricing as a simplified proxy. These carbon prices are sensitive to international emissions targets, policy timing, the distribution of policy measures across sectors and regions, and technology assumptions.
- To project country-level physical macroeconomic impacts, NGFS uses a single study: Kalkuhl and Wenz (2020). This study primarily captures productivity impacts (e.g. labor and land productivity) and capital depreciation related to changes in temperature; its

[7] The three models are GCAM, MESSAGEix-GLOBIOM and REMIND-MAgPIE. These models are well-established, peer-reviewed, and have been used in several assessment reports.

estimate of gross regional product includes subnational granularity and covers nearly the entire world, making it especially useful and logical for the scope of the NGFS exercise.

As shown in Figure 6, NGFS finds that across most scenarios and time horizons, the global macroeconomic impacts of the physical damages are larger than the transition risks and opportunities. However, transition risks are larger under a delayed and "disorderly" transition towards a climate target compared to scenarios where coordinated decarbonization action begins immediately. Physical risks are primarily determined by the degree of warming that may occur under a given climate change scenario.

Figure 6. Global GDP Impacts Relative to Prior Trend



Source: NGFS. Note that for the Current Policies scenario, the physical damages shown in the chart represent the 95th percentile temperature change to account for tail physical risks.
**Economic impacts are modelled out to 2050. To obtain an estimate of impacts in 2100, NGFS uses 2050 physical risk impacts based on the damage function and assumed no transition risk impacts after 2050 (i.e., the GDP loss is solely due to physical risk).*

Federal Government Capabilities

As part of ongoing work by the ITWG on Climate-Macro to develop methodologies to capture climate risks and opportunities in macroeconomic projections, OMB and CEA have begun to catalog relevant efforts of the U.S. Federal government related to climate-macro analysis. We divide resources into five categories, described below. We define a *model* as a tool capable of taking input data and producing output data, with the potential to be directly relevant to a climate/macro analysis.

Full-Economy Macro-econometric Models

Macroeconomic models are models focused specifically on economic outcomes. They have the potential to incorporate projections of the physical and transition risks related to climate change into a macroeconomic forecast. For example, climate damages could adversely affect the capital stock, or the decarbonization process could lead to higher energy prices or stranded productive assets—both effects that would in turn affect macroeconomic outcomes. As noted earlier, the NGFS is using the National institute Global Econometric Model (NiGEM) model to incorporate outputs from models of transition and physical risks and produce an integrated set of climate-related macroeconomic projections.

Macro-econometric models are largely grounded in the historical relationships between economic data. These models may be relatively well-suited to analyze near-term impacts but they are not primarily designed to analyze impacts over longer periods, particularly if major changes to the economy are being analyzed (EPA Science Advisory Board 2017, 50).

The Federal government has access to various macro-econometric models that could, in principle, be adapted to account for climate-related risks and opportunities. These include the Macroadvisers/United States (MAUS) Model (IHS Markit), the Federal Reserve Board/United States (FRBUS) model (Brayton et al. 2014; Laforte 2018), and the Moody's Analytics Global Macroeconomic Model (Hopkins 2018).

Full-Economy Computable General Equilibrium Models

Computable general equilibrium (CGE) economic models represent a second class of macroeconomic models. These typically depend upon microeconomic theory; consumers are modeled based on consumer choice theory, and firms are modeled as profit maximizers. CGEs can be short- or long-term in their analyses, include anywhere from a single firm to hundreds of sectors, and can be of regional, national, or international scope. Generally, CGE models may be better than macro-econometric models in analyzing long-run equilibria and capturing broader welfare measures, but are poor at modeling near-term transitions or granular policy impacts (Arora 2013; EPA Science Advisory Board 2017). This raises questions about the suitability of CGE models for analyzing the transition to a net zero emissions economy.

- **Applied Dynamic Analysis of the Global Economy (RTI-ADAGE):** ADAGE is a recursive dynamic, multi-region, and multi-sector computable general equilibrium model. It has rich details on energy, agriculture, biofuel, and land. ADAGE has been used in several settings, especially while being linked with other models, to study electricity markets, carbon policies, and agricultural productivities (Delzeit et al. 2020; RTI International 2013).
- **Future Agricultural Resources Model (FARM) at the U.S. Department of Agriculture (USDA):** FARM is a global computable general equilibrium (CGE) economic model that simulates agricultural demand, supply, and land use for 13 world regions through 2054. FARM can be used to assess climate impacts on the agricultural sector, including the effect of a changing climate on global land use, agricultural production, and international trade. FARM also includes a detailed electricity production sector, and performs energy and climate policy simulations using a CGE framework, integrating both energy and agricultural systems in a balanced approach. The model allows researchers to identify the effects of adverse productivity shocks from climate change, enabling the assessment of global trade patterns in agricultural goods, agriculture sector demand, and overall agricultural yields (Sands et al. 2014).
- **CGE model of the U.S. economy ("SAGE") from the Environmental Protection Agency (EPA):** Developed to support cost-benefit analysis of EPA regulatory activity, SAGE allows for the analysis of medium- or long-term policy effects on directly regulated sectors and their indirect effects on other sectors. SAGE models the U.S. economy in aggregate, accounting for a variety of domestic industries (e.g., manufacturing, agriculture, energy, services, and healthcare) as well as domestic and international trade flows. More specifically, SAGE has the capability to estimate the expected value of household expenditure under the presence and absence of various regulations (Marten et al. 2019, 2021).
- **Inter-Temporal General Equilibrium Model (IGEM):** IGEM is a dynamic model of the U.S. economy incorporating changes in capital, technology, and population. It is a multi-sector model that tracks changes in the composition of outputs and inputs (including energy use) by industry. Other pathways include demographic changes and their influence on consumption patterns, as well as price and income effects. IGEM has been used to examine the welfare impacts of carbon taxes (Jorgenson et al. 2018).
- **US Regional Energy Policy Model (MIT-USREP) from MIT:** MIT-USREP is designed to assess energy and environmental policies and vary the analysis by region, sector, and household income. It has previously been used in research to analyze policy efficiency, equity, fiscal issues, carbon leakage through trade, and air pollution co-benefits (Yuan et al. 2019). USREP has been linked to a detailed heterogeneous household model to better examine equity and to explore power sector transitions (Garcia-Muros, Morris, and Paltsev 2021).
- **Economic Project and Policy Analysis (MIT-EPPA) Model from MIT:** The MIT-EPPA Model aims to project world economic development and its implications for emissions, land-use, food demand, and use of natural resources. EPPA incorporates economic implications of climate and environmental damages, as well as policies aiming to reduce GHGs, pollutants, or trade; it also captures the effects of technology developments, resource depletion, land-use change, and emission projections. While

designed primarily to look at emissions, broad economic effects, and the energy sector, EPPA also models a number of non-energy sectors, including agriculture, energy-intensive industry, manufacturing, and transportation (MIT Joint Program on the Science and Policy of Global Change 2021a, 2021b).

Detailed Sectoral Models

Sector-specific models clarify and outline complex relationships between specific economic sectors, rather than the economy as a whole. They provide much more granularity compared to typical full-economy macroeconomic models, and are therefore especially relevant for assessing the effects of transition risks and opportunities on important sectors of the economy.

- **National Energy Modeling System (NEMS) within the Department of Energy:** NEMS combines the IHS Markit Model discussed above with an integrated set of U.S. energy system models and is used to produce the Annual Energy Outlook by the Energy Information Administration (EIA). NEMS projects trends in emissions, energy supply, and energy demand at detailed geographic, industry, and emissions source levels out to 2050. NEMS can be used to analyze the effects of regulations related to energy production and use, the potential ramifications of new technologies in the energy sector, the impact and cost of greenhouse gas control, the effect of increased use of renewable energy sources, and the potential savings from increased efficiency of energy use. NEMS currently incorporates the effect of temperature on energy demand, but does not currently account for many other physical risks to the energy sector, although it could in theory. NEMS can also capture the effects on the U.S. energy system of climate policy-driven transition impacts in the energy sector (U.S. Energy Information Administration 2019, 2020).
- **Global Change Analysis Model (GCAM) at the Pacific Northwest National Laboratory:** GCAM is a global model of relationships within and between the energy system, water system, agriculture and land systems, economy, and climate. The model was originally developed to calculate the magnitude of mid-21st-century global emissions of fossil fuel CO_2. Over time GCAM has expanded its scope to include emissions of non-CO_2 greenhouse gases, agriculture and land use, water supplies and demands, and physical Earth systems, along with a wider set of energy producing, transforming, and using technologies. GCAM has been used to produce scenarios for national and international assessments including the United States Long Term Climate Strategy and the Network for Greening the Financial System (Pacific Northwest National Laboratory 2021).
- **Forest and Agricultural Sector Optimization Model Greenhouse Gas Version (FASOM-GHG) at the U.S. Environmental Protection Agency:** FASOM-GHG is a global model analyzing resource allocation and land transfers within the agricultural and forestry sectors in the United States by simulating prices, consumption, production, and other indicators under specific policy scenarios. The original version of this model, FASOM, was developed to analyze both welfare and market impacts of policies impacting these sectors. This model can examine policies addressing public timber harvest, bioenergy, pulpwood production, GHG mitigation, and federal farm programs (U.S. Environmental Protection Agency 2015a).

- **Global Timber Model (GTM) at the U.S. Environmental Protection Agency:** GTM models the land-use, management, and trade behavior of the global forestry sector in response to policy changes. The model provides information in 10-year increments on a number of variables impacting timber supply and carbon uptake, including afforestation, timberland management, and harvest in different forest types (U.S. Environmental Protection Agency 2015b). Due to forestry's interaction with the agriculture sector for land use, this model also includes land supply functions, which can shift over time depending on future development and agriculture needs (Kindermann et al. 2008). GTM has also been used in academic papers analyzing the impacts of timber harvests on carbon emissions and flux (U.S. Environmental Protection Agency 2015b).
- **Regional Environment and Agriculture Programming (REAP) at the U.S. Department of Agriculture:** REAP helps model agricultural production and relevant environmental outcomes. Combining survey data with simulated input data from the Environmental Productivity and Integrated Climate (EPIC) model, REAP produces output in the form of land use, crop mix, and acreage allocations, as well as regional production from a basket of 10 crops and 13 livestock categories. Historically, REAP has been used in many policy discussions, including those associated with soil conservation, environmental credit trading, climate change mitigation policy, and regional heterogeneity from trade agreements (Malcolm et al. 2012).

"Economy-Wide" Climate Damage Functions

There are a number of studies covered in the physical risks section that use economy-wide climate impact models (e.g. Kahn et. al. 2021, Kalkuhl and Wenz 2020, and Burke et al. 2015). Federal agencies have the capability to utilize these studies, along with the full-economy macro-econometric models described above, to project the macroeconomic impacts of climate change. As noted earlier, NGFS integrates the NiGEM macro-econometric model with the Kalkuhl and Wenz (2020) study to project some of the macroeconomic impacts of the physical damages of climate change.

Detailed Damage Models

The capabilities in this section are designed to project the impact of climate change on specific relevant outcomes rather than the economy as a whole. In general, capabilities in this section focus on dynamics within, or effects of, Earth and climatic systems or effects on economy-relevant variables.

- **Agricultural Model Intercomparison and Improvement Project (AgMIP) at the USDA:** AgMIP is a project that develops and runs models of the effects of climate change on food security, poverty, and agriculture. Broadly, the models seek to understand how climate conditions, such as weather, water supply, and temperature affect agricultural outcomes, including crop supply and productivity. This knowledge feeds in to forecasts of future agricultural outcomes (Rosenzweig et al. 2016).
- **Climate Change Impacts and Risk Analysis (CIRA) at the EPA:** CIRA is an EPA-led collaborative modelling effort that includes analytical teams within the Federal government and scientists from academic institutions and consulting firms. It is focused

on assessing the physical and economic damages of climate change to U.S. health, infrastructure, electricity, water resources, agriculture, and ecosystems. CIRA has produced a number of peer-reviewed publications in high-impact journals estimating the physical and economic damages of climate change in the United States under different climate scenarios. CIRA studies typically analyze physical damages, but do not account for transition risks of climate change. Within some sectors, CIRA also provides information on disproportionate impacts to vulnerable populations and the benefits of proactive adaptation (U.S. Environmental Protection Agency 2017).[8]

- **Reproduction of external studies:** The Federal government can reproduce externally-developed frameworks for estimating bottom-up climate damages to the economy. Because such analyses can help clarify the relationship between GHG emissions and economic damages in particular sectors, these resources could serve as inputs to broader macroeconomic models, or help parameterize relationships between emissions and sectoral variables within such models. See Appendix Tables 1 and 2 for examples of external frameworks and studies that could be developed and implemented with a governmental macroeconomic model.

Other Relevant Executive Agency Capabilities

- **National Climate Assessment:** The National Climate Assessment outlines the observed and projected impacts of climate change on environmental and economic resources across the country. The Fourth National Climate Assessment included economic analysis using estimates from Hsiang, et. al. (2017) and EPA's CIRA. Work on the Fifth National Climate Assessment is currently underway with an expected release in late 2023.
- **USDA agricultural markets projections:** The Economic Research Service (ERS) and the Office of the Chief Economist (OCE) within USDA produce projections of what will happen to agricultural commodity markets over next the decade. In principle, these projections could be modified to account for physical and transition climate risks.
- **ERS Agricultural Productivity in the US:** ERS analyzes productivity and growth across the agricultural sector. This data includes price and quantity indices, as well as inputs (energy, total labor, pesticides, and fertilizers) and outputs (crop, livestock, and other). This data could be helpful in further developing macroeconomic models involving the agriculture sector, which is both largely impacted by and itself influences climate indicators.
- **National Center for Environmental Information (NCEI) datasets at NOAA:** NCEI has an extensive array of climate-related datasets, including data on hurricanes, air and sea temperatures, regional climate conditions, wildfires, precipitation, and billion-dollar disasters. These data could conceivably contribute to estimates of the economic impacts of environmental variables, which in turn could serve as inputs to macroeconomic or detailed sector models.
- **U.S. Geological Survey water data:** This resource contains data from approximately 1.9 million sources across the United States on real-time trends and histories of surface-

[8] For more information on EPA's CIRA project, see the project website at: www.epa.gov/cira

water, groundwater, and water quality. Combined with projections of the impact of climate change on freshwater sources, these data sources could be useful inputs to economic models.

- **USDA agricultural variables:** USDA has extensive datasets that include data on agricultural loss (and reasons for loss) over time, county-level data on agricultural acreage and yield across the country, geospatial data on agricultural conditions, and data on agricultural disasters that occur in near real-time. These data may be helpful for estimating the physical risks of climate change on the agriculture sector, as well as for forecasting near-term GDP based on present agricultural conditions.
- **data.gov/climate:** This resource collates various federal datasets on the effects of climate change on economic or economic-adjacent variables. The database contains hundreds of datasets and resources related to coastal flooding, food resilience, water, ecosystem vulnerability, human health, energy infrastructure, transportation, and the Arctic region.
- **Wildfire data from USDA, DOI, and NASA:** These resources contain spatial and temporal data that give details to American wildfires and various causes, such as volcanoes, gas flares, and lightning. Similar to the NCEI datasets above, these resources may be helpful in estimating economic and environmental impacts of disasters.
- **Climate Change Indicators at EPA:** Aggregating data from more than 50 government agencies, academic institutions, and other organizations, EPA has compiled indicators on a number of variables depicting physical and social changes related to the climate, including greenhouse gas emissions, global temperature, drought, ocean acidity, heat-related deaths, and wildfires (U.S. Environmental Protection Agency 2022). This extensive dataset could be helpful in delineating historical trajectories of the climate as an input to macroeconomic modeling.

Conclusion and Next Steps

Building on the existing resources described above, the Climate-Macro ITWG will develop capabilities to assess the future risks and impacts of climate change and integrate physical and transition risks of climate change into macroeconomic projections for the Federal government. Those capabilities can be continually improved as more and better evidence becomes available. Doing so will enable better understanding of and better communication about the threats that climate change poses to the U.S. economy. A methodology that captures climate-related threats and opportunities is necessary to identify and evaluate policies that can reduce these threats and take advantage of opportunities to meet other economic and social goals. It is also consistent with the Biden-Harris Administration's whole-of-government approach to addressing climate change, and it will encourage resource sharing and communication across many agencies' economic and environmental staff.

References

Aldy, Joseph E., Matthew J. Kotchen, Robert N. Stavins, and James H. Stock. 2021. "Keep Climate Policy Focused on the Social Cost of Carbon." *Science* 373, no. 6557: 850-852. https://www.science.org/doi/full/10.1126/science.abi7813.

Arnold, R.W. 2018. "How CBO Produces Its 10-Year Economic Forecast." Congressional Budget Office Working Paper 2018-02. Washington DC: Congressional Budget Office. https://www.cbo.gov/system/files/115th-congress-2017-2018/workingpaper/53537-workingpaper.pdf.

Arora, V. 2013. "Models for Use at EIA." EIA Working Paper. Washington, DC: U.S. Energy Information Administration. https://www.eia.gov/workingpapers/pdf/macro_models-vipin-wappendix.pdf.

Auffhammer, M. 2018. "Quantifying Economic Damages from Climate Change." *Journal of Economic Perspectives* 32, no. 4: 33–52. https://doi.org/10.1257/jep.32.4.33.

Autor, D., D. Dorn, and G.H. Hanson. 2021. "On the Persistence of the China Shock." NBER Working Paper 29401. Cambridge, MA: National Bureau of Economic Research. https://www.nber.org/papers/w29401.

Bakkensen, L. A., and L. Barrage. 2021. "Going Underwater? Flood Risk Belief Heterogeneity and Coastal Home Price Dynamics." *The Review of Financial Studies*. https://doi.org/10.1093/rfs/hhab122.

Bank of Canada. 2022. "Using Scenario Analysis to Assess Climate Transition Risk." https://www.bankofcanada.ca/wp-content/uploads/2021/11/BoC-OSFI-Using-Scenario-Analysis-to-Assess-Climate-Transition-Risk.pdf.

Bank of England. 2021. "Key Elements of the 2021 Biennial Exploratory Scenario: Financial Risks from Climate Change." https://www.bankofengland.co.uk/stress-testing/2021/key-elements-2021-biennial-exploratory-scenario-financial-risks-climate-change.

Barrage, L. 2020. "The Fiscal Costs of Climate Change." *AEA Papers and Proceedings* 110: 107–112. https://doi.org/10.1257/pandp.20201082.

Bartik, T. 2020. "Using Place-Based Jobs Policies to Help Distressed Communities." *Journal of Economic Perspectives* 34, no. 3: 99-127. https://www.aeaweb.org/articles?id=10.1257/jep.34.3.99.

Batten, S. 2018. "Climate Change and the Macro-Economy: A Critical Review." Bank of England Working Paper 706. https://doi.org/10.2139/ssrn.3104554.

Bernanke, B.S. 1983. “Irreversibility, Uncertainty, and Cyclical Investment.” *The Quarterly Journal of Economics* 98, no. 1: 85-106. https://doi.org/10.2307/1885568.

Bivens, J. 2017. "The Potential Macroeconomic Benefits from Increasing Infrastructure Investment." Economy Policy Institute. https://www.epi.org/publication/the-potential-macroeconomic-benefits-from-increasing-infrastructure-investment/.

Bosello, F., F. Eboli, and R. Pierfederici. 2012. “Assessing the Economic Impacts of Climate Change - An Updated CGE Point of View.” FEEM Working Paper 2.2012. https://doi.org/10.2139/ssrn.2004966.

Brayton, F., T. Laubach, and D. Reifschneider. 2014. “The FRB/US Model: A Tool for Macroeconomic Policy Analysis.” FEDS Notes. https://www.federalreserve.gov/econresdata/notes/feds-notes/2014/a-tool-for-macroeconomic-policy-analysis.html.

Bressler, R.D. 2021. “The Mortality Cost of Carbon.” *Nature Communications* 12, no. 1: 4467. https://doi.org/10.1038/s41467-021-24487-w.

Bressler, R.D., F.C. Moore, K. Rennert, and D. Anthoff. 2021. “Estimates of Country Level Temperature-Related Mortality Damage Functions.” *Scientific Reports* 11, no. 1: 20282. https://doi.org/10.1038/s41598-021-99156-5.

Burke, M., and K. Emerick. 2016. "Adaptation to Climate Change: Evidence from U.S. Agriculture." *American Economic Journal: Economic Policy* 8, no. 3: 106-40. https://www.aeaweb.org/articles?id=10.1257/pol.20130025.

Burke, M., S.M. Hsiang, and E. Miguel. 2015. “Global Non-Linear Effect of Temperature on Economic Production.” *Nature* 527: 235–39. https://doi.org/10.1038/nature15725.

Burke, M., and V. Tanutama. 2019. “Climatic constraints on aggregate economic output.” NBER Working Paper 25779. Cambridge, MA: National Bureau of Economic Research. https://www.nber.org/system/files/working_papers/w25779/w25779.pdf.

Cai, Y., and T. Lontzek. 2019. "The Social Cost of Carbon with Economic and Climate Risks." *Journal of Political Economy* 127, no. 6: 2684-2734. https://www.journals.uchicago.edu/doi/abs/10.1086/701890?journalCode=jpe.

Carleton, T.A., A. Jina, M.T. Delgado, M. Greenstone, T. Houser, S.M. Hsiang, A. Hultgren, R.E. Kopp, K.E. McCusker, I.B. Nath, J. Rising, A. Rode, H.K. Seo, A. Viaene, J. Yuan, and A.T. Zhang. 2020. "Valuing the Global Mortality Consequences of Climate Change Accounting for Adaption Costs and Benefits." NBER Working Paper 28466. Cambridge, MA: National Bureau of Economic Research. https://www.nber.org/system/files/working_papers/w27599/w27599.pdf.

Coalition of Finance Ministers for Climate Action. 2021. "About US." https://www.financeministersforclimate.org/about-us.

Colacito, R., B. Hoffmann, and T. Phan. 2019. "Temperature and Growth: A Panel Analysis of the United States." *Journal of Money, Credit, and Banking* 51, no 2-3: 313-368. https://doi.org/10.1111/jmcb.12574.

Council of Economic Advisers (CEA). 2021. "Innovation, Investment, and Inclusion: Accelerating the Energy Transition and Creating Good Jobs." CEA White Papers. https://www.whitehouse.gov/wp-content/uploads/2021/04/Innovation-Investment-and-Inclusion-CEA-April-23-2021-1.pdf.

Cruz, J., and E. Rossi-Hansberg. 2021. "The Economic Geography of Global Warming." NBER Working Paper 28466. Cambridge, MA: National Bureau of Economic Research. https://doi.org/10.3386/w28466.

Dechezleprêtre, A., R. Martin, and M. Mohnen. 2014. "Knowledge Spillovers from Clean and Dirty Technologies." CEP Discussion Papers (CEPDP1300). http://eprints.lse.ac.uk/60501/.

Dell, M., B. Jones, and B. Olken. 2008. "Climate Change and Economic Growth: Evidence from the Last Half Century." NBER Working Paper 14132. Cambridge, MA: National Bureau of Economic Research. https://doi.org/10.3386/w14132.

Dell, M., B.F. Jones, and B.A. Olken. 2012. "Temperature Shocks and Economic Growth: Evidence from the Last Half Century." *American Economic Journal: Macroeconomics* 4, no. 3: 66-95. https://www.aeaweb.org/articles?id=10.1257/mac.4.3.66.

Dell, M., B.F. Jones, and B.A. Olken. 2014. "What Do We Learn from the Weather? The New Climate-Economy Literature." *Journal of Economic Literature* 52, no. 3: 740–98. https://doi.org/10.1257/jel.52.3.740.

Delzeit, R., R. Beach, R. Bibas, W. Britz, J. Chateau, F. Freund, J. Lefevre, F. Schuenemann, T. Sulser, H. Valin, B. van Ruijven, M. Weitzel, D. Willenbockel, and K. Wojtowicz. 2020. "Linking Global CGE Models with Sectoral Models to Generate Baseline Scenarios: Approaches, Challenges, and Opportunities." *Journal of Global Economic Analysis* 5, no. 1: 162–195. https://jgea.org/ojs/index.php/jgea/article/view/93.

Deryugina, T., G. Heutel, N.H. Miller, D. Molitor, and J. Reif. 2019. "The Mortality and Medical Costs of Air Pollution: Evidence from Changes in Wind Direction." *American Economic Review* 109, no. 12: 4178-4219. https://www.aeaweb.org/articles?id=10.1257/aer.20180279.

Deryugina, T., and S. Hsiang. 2014. “Does the Environment Still Matter? Daily Temperature and Income in the United States.” NBER Working Paper 20750. Cambridge, MA: National Bureau of Economic Research. https://doi.org/10.3386/w20750.

Deschênes, O., and M. Greenstone. 2011. "Climate Change, Mortality, and Adaptation: Evidence from Annual Fluctuations in Weather in the US." *American Economic Journal: Applied Economics* 3, no. 4: 152-85. https://pubs.aeaweb.org/doi/pdfplus/10.1257/app.3.4.152.

Diamond, J.W., and G.R. Zodrow. 2018. "The Effects of Carbon Tax Policies on the U.S. Economy and the Welfare of Households." Independent Report: Columbia SIPA Center on Global Energy Policy. https://energypolicy.columbia.edu/sites/default/files/pictures/CGEP_Effects_of_CarbonTaxPolicies_US_Economy_Welfar_of_Households.pdf.

Dietz, S., J. Rising, T. Stoerk, and G. Wagner. 2021. "Economic Impacts of Tipping Points in the Climate System." *Proceedings of the National Academies of Science,* 118, no. 34: e2103081118. https://doi.org/10.1073/pnas.2103081118.

EPA Science Advisory Board. 2017. “SAB Advice on the Use of Economy-Wide Models in Evaluating the Social Costs, Benefits, and Economic Impacts of Air Regulations.”

European Commission. 2020. "Supporting Climate Action Through the EU Budget." https://ec.europa.eu/clima/eu-action/funding-climate-action/supporting-climate-action-through-eu-budget_en#ecl-inpage-1588.

Exec. Order No. 14030, 86 Fed. Reg. 27967 (May 25, 2021). https://www.federalregister.gov/documents/2021/05/25/2021-11168/climate-related-financial-risk.

Fankhaeser, S., F. Sehlleier, and N. Stern. 2008. "Climate Change, Innovation and Jobs." *Climate Policy* 8, no. 4: 421-429. https://www.tandfonline.com/doi/abs/10.3763/cpol.2008.0513.

Feng, S., A.B. Krueger, and M. Oppenheimer. 2010. “Linkages among Climate Change, Crop Yields and Mexico-US Cross-Border Migration.” *Proceedings of the National Academy of Sciences* 107, no. 32: 14257–62. https://doi.org/10.1073/pnas.1002632107.

Fried, S. 2021. "Seawalls and Stilts: A Quantitative Macro Study of Climate Adaptation." Federal Reserve Bank of San Francisco Working Paper 2021-07. San Francisco, CA: Federal Reserve Bank of San Francisco. https://doi.org/10.24148/wp2021-07.

Fuglie, K. 2021. “Climate Change Upsets Agriculture.” *Nature Climate Change* 11, no. 4: 294–

295. https://www.nature.com/articles/s41558-021-01017-6.

Garcia-Muros, X., J. Morris, and S. Paltsev. 2022. "Toward a Just Energy Transition: A Distributional Analysis of Low-Carbon Policies in the USA." *Energy Economics* 105: 105769. https://www.sciencedirect.com/science/article/pii/S0140988321006113.

Graff Zivin, J., and M. Neidell. 2012. “The Impact of Pollution on Worker Productivity.” *American Economic Review* 102, no. 7: 3652-73. https://www.aeaweb.org/articles?id=10.1257/aer.102.7.3652.

Graff Zivin, J., and M. Neidell. 2014. “Temperature and the Allocation of Time: Implications for Climate Change.” *Journal of Labor Economics* 32, no. 1: 1–26. https://doi.org/10.1086/671766.

Handley, K. and N. Limao. 2017. “Policy Uncertainty, Trade, and Welfare: Theory and Evidence for China and the United States.” *American Economic Review* 107, no. 9: 2731-83. https://www.aeaweb.org/articles?id=10.1257/aer.20141419.

Haqiqi, I., D.S. Grogan, T.W. Hertel, and W. Schlenker. 2021. "Quantifying the Impacts of Compound Extremes on Agriculture." *Hydrology and Earth System Sciences* 25, no. 2: 551-564. https://www.pches.psu.edu/bib-items/Haqiqi2021-fm/.

Heal, G., and J. Park. 2016. “Reflections—Temperature Stress and the Direct Impact of Climate Change: A review of an Emerging Literature.” *Review of Environmental Economics and Policy* 10, no. 2: 347–362. https://doi.org/10.1093/reep/rew007.

Herrnstadt, E., and T. Dinan. 2020. “CBO’s Projection of the Effect of Climate Change on U.S. Economic Output.” Congressional Budget Office Working Paper Series 2020-06. Washington, DC: Congressional Budget Office. https://www.cbo.gov/system/files/2020-09/56505-Climate-Change.pdf.

Hoegh-Guldberg, O., D. Jacob, M. Taylor, M. Bindi, S. Brown, I. Camilloni, A. Diedhiou, R. Djalante, K.L. Ebi, F. Engelbrecht, J.Guiot, Y. Hijioka, S. Mehrotra, A. Payne, S.I. Seneviratne, A. Thomas, R. Warren, and G. Zhou. 2018. “Impacts of 1.5°C of Global Warming on Natural and Human Systems.” In *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, edited by V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I.Gomis, E. Lonnoy, T.Maycock, M.Tignor, and T. Waterfield. IPCC. https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Chapter3_Low_Res.pdf.

Hopkins, M. 2018. "About the Moody's Analytics Global Macroeconomic Model." Moody's Analytics. https://www.moodysanalytics.com/-/media/whitepaper/2018/global-macroeconomic-model-description-short-version.

Hsiang, S. 2019. "Statement of Solomon Hsiang." United States House Committee on the Budget. https://budget.house.gov/sites/democrats.budget.house.gov/files/documents/House_Testimony_Hsiang_6_10_19_final.pdf.

Hsiang, S., M. Burke, and E. Miguel. 2013. "Quantifying the Influence of Climate on Human Conflict." *Science* 341, no. 6151: 1235367. https://doi.org/10.1126/science.1235367.

Hsiang, S.M., and A.S. Jina. 2014. "The Causal Effect of Environmental Catastrophe on Long-Run Economic Growth: Evidence From 6,700 Cyclones." NBER Working Paper 20352. Cambridge, MA: National Bureau of Economic Research. https://doi.org/10.3386/w20352.

Hsiang, S., R. Kopp, A. Jina, J. Rising, M. Delgado, S. Mohan, D. J. Rasmussen, R. Muir-Wood, P. Wilson, M. Oppenheimer, K. Larsen, and T. Houser. 2017. "Estimating Economic Damage from Climate Change in the United States." *Science* 356, no. 6345: 1362–69. https://doi.org/10.1126/science.aal4369.

Hsiang, S., P. Oliva, and R. Walker. 2019. "The Distribution of Environmental Damages." *Review of Environmental Economics and Policy* 13, no. 1: 83–103. https://doi.org/10.1093/reep/rey024.

IHS Markit. "US Economic Modeling and Forecasting Services." S&P Global. https://ihsmarkit.com/products/US-economic-modeling-forecasting-services.html#Macro.

Interagency Working Group on Coal and Power Plant Communities and Economic Revitalization. 2021. "Initial Report to the President on Empowering Workers Through Revitalizing Energy Communities." https://netl.doe.gov/sites/default/files/2021-04/Initial%20Report%20on%20Energy%20Communities_Apr2021.pdf.

International Energy Agency. 2022. "Iron and Steel." https://www.iea.org/reports/iron-and-steel.

International Renewable Energy Agency (IRENA). 2021. "Renewable Capacity Statistics 2021." https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Apr/IRENA_RE_Capacity_Statistics_2021.pdf.

Islam, S.N., and J. Winkel. 2017. "Climate Change and Social Inequality." DESA Working Paper 152. New York, NY: United Nations. https://www.un.org/esa/desa/papers/2017/wp152_2017.pdf.

Jadhav, A. and S. Mutreja. 2022. "Electric Vehicle Market by Type (Battery Electric Vehicle, Plug-in Hybrid Electric Vehicle, and Fuel Cell Electric Vehicle), Vehicle Type (Two-Wheelers, Passenger Cars, and Commercial Vehicles), Vehicle Class (Mid-Priced and Luxury), Top Speed (Less Than 100 MPH, 100 to 125 MPH, and More Than 125 MPH) and Vehicle Drive Type (Front Wheel Drive, Rear Wheel Drive, and All Wheel Drive): Global Opportunity Analysis and Industry Forecast, 2021-2030." Allied Market Research. https://www.alliedmarketresearch.com/electric-vehicle-market.

Jagai, J.S., E. Grossman, L. Navon, A. Sambanis, and S. Dorevitch. 2017. "Hospitalizations for Heat-Stress Illness Varies between Rural and Urban Areas: An Analysis of Illinois Data, 1987–2014." *Environmental Health* 16, no. 1: 1-10. https://link.springer.com/article/10.1186/s12940-017-0245-1.

Jorgenson, D.W., R.J. Goettle, M.S. Ho, and P.J. Wilcoxen. 2018. "The Welfare Consequences of Taxing Carbon." *Climate Change Economy* 9, no. 1: 1840013-1–1840013-39. https://www.worldscientific.com/doi/abs/10.1142/S2010007818400134.

Kahn, M.E., K. Mohaddes, R.N.C. Ng, M.H. Pesaran, M. Raissi, and J. Yang. 2021. "Long-Term Macroeconomic Effects of Climate Change: A Cross-Country Analysis." *Energy Economics* 104: 105624. https://www.sciencedirect.com/science/article/pii/S0140988321004898.

Kalkuhl, M., and L. Wenz. 2020. "The Impact of Climate Conditions on Economic Production. Evidence from a Global Panel of Regions." *Journal of Environmental Economics and Management* 103: 102360. https://doi.org/10.1016/j.jeem.2020.102360.

Kharin, V.V., G.M. Flato, X. Zhang, N.P. Gillett, F. Zwiers, and K.J. Anderson. 2018. "Risks from Climate Extremes Change Differently from 1.5°C to 2.0°C Depending on Rarity." *Earth's Future* 6, no. 5: 704–15. https://doi.org/10.1002/2018EF000813.

Kiley, M. T. 2021. "Growth at Risk From Climate Change." Finance and Economics Discussion Series 2021-054. Washington: Board of Governors of the Federal Reserve System, https://www.federalreserve.gov/econres/feds/growth-at-risk-from-climate-change.htm.

Kim, H. S., Matthes, C., and T. Phan. 2021. "Extreme Weather and the Macroeconomy." Federal Reserve Bank of Richmond Working Paper, no. 21-14. Richmond, VA: Federal Reserve Bank of Richmond. http://dx.doi.org/10.2139/ssrn.3918533

Kindermann G., M. Obersteiner, B. Sohngen, J. Sathaye, K. Andrasko, E. Rametsteiner,

B. Schlamadinger, S. Wunder, and R. Beach. 2008. "Global Cost Estimates of Reducing Carbon Emissions Through Avoided Deforestation." *Proceedings of the National Academy of Sciences of the United States of America* 105, no. 30: 10302–10307. pnas.org/doi/10.1073/pnas.0710616105.

Kopp, R.E., R.M. DeConto, D.A. Bader, C.C. Hay, R.M. Horton, S. Kulp, M. Oppenheimer, D. Pollard, and B.H. Strauss. 2017. "Evolving Understanding of Antarctic Ice-Sheet Physics and Ambiguity in Probabilistic Sea-Level Projections." *Earth's Future* 5, no. 12: 1217-1233. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2017EF000663.

Lafakis, C., J. Lee, J. Licari, and P. Zemcik. 2021. "Climate Risk Macroeconomic Forecasting." Moody's Analytics. https://www.moodysanalytics.com/-/media/article/2021/Climate-Risk-Macroeconomic-Forecasting.pdf.

Laforte, J. 2018. "Overview of the Changes to the FRB/US Model (2018)." FEDS Notes. https://www.federalreserve.gov/econres/notes/feds-notes/overview-of-the-changes-to-the-frb-us-model-2018-20181207.htm.

Lay, C., M. Sarofim, A. Vodonos Zilberg, D. Mills, R. Jones, J. Schwartz, and P. Kinney. 2021. "City-level Vulnerability to Temperature-related Mortality in the USA and Future Projections: A Geographically Clustered Meta-regression." *The Lancet Planetary Health* 5, no. 6: 338-346. https://www.sciencedirect.com/science/article/pii/S2542519621000589.

Lobell, D.B., and S. Asseng. 2017. "Comparing Estimates of Climate Change Impacts from Process-based and Statistical Crop Models." *Environmental Research Letters* 12: 015001. https://iopscience.iop.org/article/10.1088/1748-9326/aa518a/pdf.

Malcolm, S., E. Marshall, M. Aillery, P. Heisey, M. Livingston, and K. Day-Rubenstein. 2012. "Agricultural Adaptation to a Changing Climate: Economic and Environmental Implications Vary by U.S. Region." *U.S. Department of Agriculture Economic Research Service* 136. https://www.ers.usda.gov/webdocs/publications/44987/28911_err136.pdf?v=8317.4

Marten, A., R. Garbaccio, and A. Wolverton. 2019. "Exploring the General Equilibrium Costs of Sector-Specific Environmental Regulations." NCEE Working Paper 18-06. Washington, DC: National Center for Environmental Economics. https://www.epa.gov/sites/default/files/2018-10/documents/2018-06.pdf.

Marten, A., A. Schreiber, and A. Wolverton. 2021. "SAGE Model Documentation (2.0.1)." U.S. Environmental Protection Agency. https://www.epa.gov/sites/default/files/2020-12/documents/sage-model-documentation-version-2.0.0_0.pdf.

Martinich, J., and A. Crimmins. 2019. "Climate Damages and Adaptation Potential Across

Diverse Sectors of the United States." *Nature Climate Change* 9, no. 1: 397–404. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6483104/.

McFarland, J.R., A.A. Fawcett, A.C. Morris, J.M. Reilly, and P.J. Wilcoxen. 2018. "Overview of the EMF 32 study on U.S. Carbon Tax Scenarios." *Climate Change Economics* 9, no. 1: 1840002. https://doi.org/10.1142/S201000781840002X.

Meinshausen, M., S.C.B. Raper, and T.M.L. Wigley. 2011. "Emulating Coupled Atmosphere-Ocean and Carbon Cycle Models with a Simpler Model, MAGICC6–Part 1: Model Description and Calibration." *Atmospheric Chemistry and Physics* 11, no. 4: 1417–56. https://acp.copernicus.org/articles/11/1417/2011/.

Mercure, J., P. Salas, P. Vercoulen, G. Semieniuk, A. Lam, H. Pollitt, P.B. Holden, N. Vaikifard, U. Chewpreecha, N.R. Edwards, and J.E. Vinuales. 2021. "Reframing Incentives for Climate Policy Action." *Nature Energy* 6: 1133-1143. https://www.nature.com/articles/s41560-021-00934-2.

Metcalf, G.E., and J.H. Stock. 2020. "The Macroeconomic Impact of Europe's Carbon Taxes." NBER Working Paper 27488. Cambridge, MA: National Bureau of Economic Research. https://www.nber.org/system/files/working_papers/w27488/w27488.pdf.

Missirian, A., and W. Schlenker. 2017. "Asylum Applications Respond to Temperature Fluctuations." *Science* 358, no. 6370: 1610–14. https://doi.org/10.1126/science.aao0432.

MIT Joint Program on the Science and Policy of Global Change. 2021a. "EPPA Model Structure." https://globalchange.mit.edu/research/research-tools/eppa.

MIT Joint Program on the Science and Policy of Global Change. 2021b. "Human System Model: Economic Projection & Policy Analysis (EPPA) Model." Massachusetts Institute of Technology. https://globalchange.mit.edu/research/research-tools/human-system-model.

Moore, F.C., U. Baldos, and T. Hertel. 2017. "Economic Impacts of Climate Change on Agriculture: A Comparison of Process-Based and Statistical Yield Models." *Environmental Research Letters* 12, no. 6: 065008. https://doi.org/10.1088/1748-9326/aa6eb2.

Moore, F.C., U. Baldos, T. Hertel, and D. Diaz. 2017. "New Science of Climate Change Impacts on Agriculture Implies Higher Social Cost of Carbon." *Nature Communications* 8: 1607. https://www.nature.com/articles/s41467-017-01792-x.

Nakicenovic, N., O. Davidson, G. Davis, A. Grubler, T. Kram, E. La Rovere, B. Metz, T. Morita, W. Pepper, H. Pitcher, A. Sankovski, P. Shukla, R. Swart, R. Watson, and Z. Dadi. 2000. "A Special Report of Working Group III of the Intergovernmental Panel on Climate Change."

Intergovernmental Panel on Climate Change Special Report. https://www.ipcc.ch/site/assets/uploads/2018/03/sres-en.pdf.

National Academies of Sciences, Engineering, and Medicine. 2021. "Accelerating Decarbonization of the U.S. Energy System." Washington, DC: The National Academies Press. https://earthdata.nasa.gov/learn/toolkits/wildfires

National Aeronautics and Space Administration (NASA). 2022. "Wildfires." https://earthdata.nasa.gov/learn/toolkits/wildfires.

Network for Greening the Financial System (NGFS). 2020. “Climate Scenarios Database: Technical Documentation.” https://www.ngfs.net/sites/default/files/ngfs_climate_scenario_technical_documentation_final.pdf.

Network for Greening the Financial System (NGFS). 2021. "NGFS Climate Scenarios for Central Banks and Supervisors". https://www.ngfs.net/sites/default/files/media/2021/08/27/ngfs_climate_scenarios_phase2_june2021.pdf.

Network for Greening the Financial System (NGFS). 2022. “Scenarios Portal.” https://www.ngfs.net/ngfs-scenarios-portal/explore/.

Newell, R.G., B.C. Prest, and S.E. Sexton. 2021. “The GDP-Temperature Relationship: Implications for Climate Change Damages.” *Journal of Environmental Economics and Management* 108: 102445. https://doi.org/10.1016/j.jeem.2021.102445.

Nordhaus, W. 2019. "Climate Change: The Ultimate Challenge for Economics." *American Economic Review* 109, no. 6: 1991–2014. https://doi.org/10.1257/aer.109.6.1991

Office for Budget Responsibility. 2021. "Fiscal Risks Report." Controller of Her Majesty’s Stationery Office. https://obr.uk/docs/dlm_uploads/Fiscal_risks_report_July_2021.pdf.

Office of Management and Budget. 2016. "Climate Change: The Risks Facing the Federal Government. A Preliminary Assessment." https://obamawhitehouse.archives.gov/sites/default/files/omb/reports/omb_climate_change_fiscal_risk_report.pdf.

Organisation for Economic Co-operation and Development and The Coalition of Finance Ministers for Climate Action (OECD and CFMCA). 2021. "Introductory Note on Integrating Climate into Macroeconomic Modelling: Drawing on the Danish Experience." OECD. https://www.oecd.org/gov/budgeting/integrating-climate-into-macroeconomic-modelling.pdf.

Ortiz-Bobea, A., T. Ault, C. Carrillo, R. Chambers, and D. Lobell. 2021. “Anthropogenic

Climate Change has Slowed Global Agricultural Productivity Growth." *Nature Climate Change* 11, no. 4: 306–312. https://www.nature.com/articles/s41558-021-01000-1.

Pacific Northwest National Laboratory. 2021. "Global Change Analysis Model." Joint Global Change Research Institute. http://www.globalchange.umd.edu/gcam/.

Pisani-Ferry, J. 2021. "Climate Policy is Macroeconomic Policy, and the Implications will be Significant." Peterson Institute for International Economics. No. PB21-20. https://www.piie.com/system/files/documents/pb21-20.pdf.

Pretis, F., M. Schwarz, K. Tang, K. Haustein, and M.R. Allen. 2018. "Uncertain Impacts on Economic Growth when Stabilizing Global Temperatures at 1.5 °C or 2 °C Warming." *Philosophical Transactions of the Royal Society A* 376: 20160460. https://royalsocietypublishing.org/doi/pdf/10.1098/rsta.2016.0460.

Ranson, M. 2014. "Crime, Weather, and Climate Change." *Journal of Environmental Economics and Management* 67, no. 3: 274–302. https://doi.org/10.1016/j.jeem.2013.11.008.

Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart. 2018. "Impacts, Risks, and Adaptation in the United States: The Fourth National Climate Assessment, Volume II." U.S. Global Change Research Program. https://doi.org/10.7930/NCA4.2018.

Rising, J., and N. Devineni. 2020. "Crop Switching Reduces Agricultural Losses from Climate Change in the United States by Half under RCP 8.5." *Nature Communications* 11, no. 1: 4991. https://doi.org/10.1038/s41467-020-18725-w.

Ritchie, H. and M. Roser. 2020. "Electricity Mix." Our World in Data. https://ourworldindata.org/electricity-mix.

Ritchie, H., P. Rosado, E. Mathieu, and M. Roser. 2022. "Data on Energy by Our World in Data." Our World in Data. https://github.com/owid/energy-data.

Rode, A., T. Carleton, M. Delgado, M. Greenstone, T. Houser, S. Hsiang, A. Hultgren, et al. 2021. "Estimating a Social Cost of Carbon for Global Energy Consumption." *Nature* 598, no. 7880: 308–14. https://www.nature.com/articles/s41586-021-03883-8.

Rosenzweig, C., J.M. Antle, A.C. Ruane, J.W. Jones, J. Hatfield, K.J. Boote, P. Thorburn, R.O. Valdivia, K. Descheemaeker, C.H. Porter, S. Janssen, W.L. Bartels, A. Sulivan, and C.Z. Mutter. 2016. "Protocols for AgMIP Regional Integrated Assessments Version 7.0." UK Aid. https://agmip.org/wp-content/uploads/2018/08/AgMIP-Protocols-for-Regional-Integrated-Assessment-v7-0-20180218-1-ilovepdf-compressed.pdf.

Roson, R., and M. Sartori. 2016. “Estimation of Climate Change Damage Functions for 140 Regions in the GTAP9 Database.” Policy Research Working Paper 7728. Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/24643.

RTI International. 2013. “The Applied Dynamic Analysis of the Global Economy (RTI ADAGE) Model (2013): U.S. Regional Module Final Release.” https://www.rti.org/publication/applied-dynamic-analysis-global-economy-rti-adagetm-model-2013/fulltext.pdf.

Saha, D., and T. Cyrs. 2021. “5 Graphics that Explain Clean Energy Jobs in Rural America.” World Resources Institute. https://www.wri.org/insights/clean-energy-jobs-rural-communities-us-5-graphics.

Sands, R.D., C.A. Jones, and E.P. Marshall. 2014. “Global Drivers of Agricultural Demand and Supply.” United States Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/webdocs/publications/45272/49035_err174.pdf?v=8649.4.

Schlenker, W., and M.J. Roberts. 2009. “Nonlinear Temperature Effects Indicate Severe Damages to U.S. Crop Yields under Climate Change.” *Proceedings of the National Academy of Sciences* 106, no. 37: 15594–98. https://doi.org/10.1073/pnas.0906865106.

Scovronick, N., M. Budolfson, F. Dennig, F. Errickson, M. Fleurbaey, W. Peng, R.H. Socolow, D. Spears, and F. Wagner. 2019. “The Impact of Human Health Co-Benefits on Evaluations of Global Climate Policy.” *Nature Communications* 10, no. 2095. https://doi.org/10.1038/s41467-019-09499-x.

Seiger, A., and T. Heller. 2021. "Developing Climate Risk Disclosure Practices for the State of California." Steyer-Taylor Center for Energy Policy and Finance. https://law.stanford.edu/publications/developing-climate-risk-disclosure-practices-for-the-state-of-california/.

Shindell, D., M. Ru, Y. Zhang, K. Seltzer, G. Faluvegi, L. Nazarenko, G. Schmidt, L. Parsons, A. Challapalli, L. Yang, and A. Glick. 2021. "Temporal and Spatial Distribution of Health, Labor, and Crop Benefits of Climate Change Mitigation in the United States." *Earth, Atmospheric, and Planetary Sciences* 118, no. 46: 1-8. https://www.pnas.org/doi/10.1073/pnas.2104061118.

Shindell, D., Y. Zhang, M. Scott, M. Ru, K. Stark, and K.L. Ebi. 2020. “The Effects of Heat Exposure on Human Mortality Throughout the United States.” *GeoHealth* 4, no. 4. https://doi.org/10.1029/2019GH000234.

Short, K.C. 2017. "Spatial Wildfire Occurrence Data for the United States, 1992-2015 [FPA_FOD_20170508]." *U.S. Department of Agriculture Research Data Archive* 4. https://www.fs.usda.gov/rds/archive/catalog/RDS-2013-0009.4

Smith, A. 2021. "2020 U.S. Billion-Dollar Weather and Climate Disasters in Historical Context." NOAA National Centers for Environmental Information. https://www.climate.gov/disasters2020.

Stern, N., and J. Stiglitz. 2022. "The Economics of Immense Risk, Urgent Action and Radical Change: Towards New Approaches to the Economics of Climate Change." *Journal of Economic Methodology*: 1-36. https://www.tandfonline.com/doi/pdf/10.1080/1350178X.2022.2040740.

Stiglitz, J.E., N. Stern, M. Duan, O. Edenhofer, G. Giraud, G. M. Heal, E. La Rovere et al. 2017. "Report of the High-Level Commission on Carbon Prices." Carbon Pricing Leadership Coalition. https://www.connect4climate.org/sites/default/files/files/publications/CarbonPricingReportFinal.pdf.

Stock, J.H., and D.N. Stuart. 2021. "Robust Decarbonization of the U.S. Power Sector: Policy Options." NBER Working Paper 28677. Cambridge MA: National Bureau of Economic Research. https://www.nber.org/system/files/working_papers/w28677/w28677.pdf.

Stott, P. 2016. "How Climate Change Affects Extreme Weather Events." *Nature* 352, no. 6293. https://www.science.org/doi/pdf/10.1126/science.aaf7271.

Sweet, W., B. Hamlington, R. Kopp, C. Weaver, P. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A. Genz, J. Krasting, E. Larour, D. Marcy, J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak. 2022. "Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines." NOAA Technical Report. Silver Spring, MD: National Oceanic and Atmospheric Administration. https://aambpublicoceanservice.blob.core.windows.net/oceanserviceprod/hazards/sealevelrise/noaa-nos-techrpt01-global-regional-SLR-scenarios-US.pdf.

Taylor, C., and W. Schlenker. 2021. "Environmental Drivers of Agricultural Productivity Growth: CO_2 Fertilization of U.S. Field Crops." NBER Working Paper 29320. Cambridge, MA: National Bureau of Economic Research. https://www.nber.org/system/files/working_papers/w29320/w29320.pdf.

The White House. 2016. "United States Mid-Century Strategy for Deep Decarbonization." United Nations Framework Convention on Climate Change.

https://unfccc.int/files/focus/long-term_strategies/application/pdf/mid_century_strategy_report-final_red.pdf.

The White House. 2021a. "Fact Sheet: President Biden Takes Executive Actions to Tackle the Climate Crisis at Home and Abroad, Create Jobs, and Restore Scientific Integrity Across Federal Government." *The White House* Blog. https://www.whitehouse.gov/briefing-room/statements-releases/2021/01/27/fact-sheet-president-biden-takes-executive-actions-to-tackle-the-climate-crisis-at-home-and-abroad-create-jobs-and-restore-scientific-integrity-across-federal-government/.

The White House. 2021b. "Fact Sheet: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies." *The White House* Blog. https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/.

The White House. 2021c. “President Biden's Bipartisan Infrastructure Law.” https://www.whitehouse.gov/bipartisan-infrastructure-law/#electricvehicle.

The White House. 2021d. “U.S. Climate-Related Financial Risk Executive Order 14030: A Roadmap to Build a Climate-Resilient Economy.” https://www.whitehouse.gov/wp-content/uploads/2021/10/Climate-Finance-Report.pdf.

U.S. Department of Agriculture Economic Research Service (USDA ERS). 2010. “Agricultural Productivity in the U.S.” https://www.ers.usda.gov/data-products/agricultural-productivity-in-the-u-s/.

U.S. Department of Agriculture Economic Research Service (USDA ERS). 2021. "Cash Receipts by Commodity." https://data.ers.usda.gov/reports.aspx?ID=17845#P8d4e736d729844e0a7c34faf02a26a0b_2_17iT0R0x0.

U.S. Department of Energy. 2022. "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition." https://www.energy.gov/sites/default/files/2022-02/America%E2%80%99s%20Strategy%20to%20Secure%20the%20Supply%20Chain%20for%20a%20Robust%20Clean%20Energy%20Transition%20FINAL.docx_0.pdf.

U.S. Department of the Treasury. 2022. “Treasury’s Federal Insurance Office Continues Efforts on Climate-Related Financial Risks in the Insurance Sector, Joins the NGFS.” https://home.treasury.gov/news/press-releases/jy0598.

U.S. Energy Information Administration. 2019. "The National Energy Modeling System: An Overview 2018." Independent Statistics & Analysis. https://www.eia.gov/outlooks/aeo/nems/overview/pdf/0581(2018).pdf.

U.S. Energy Information Administration. 2020. "Residential Demand Module of the National Energy Modeling System: Model Documentation 2020." Independent Statistics & Analysis. https://www.eia.gov/outlooks/aeo/nems/documentation/residential/pdf/m067(2020).pdf.

U.S. Energy Information Administration. 2021. "United States Continued to Lead Global Petroleum and Natural Gas Production in 2020." International Energy Statistics. https://www.eia.gov/todayinenergy/detail.php?id=48756.

U.S. Environmental Protection Agency. 2011. "Benefits and Costs of the Clean Air Act 1990–2020, the Second Prospective Study." https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=OAP&dirEntryId=82963.

U.S. Environmental Protection Agency. 2015a. "Forest and Agricultural Sector Optimization Model Greenhouse Gas Version (FASOM-GHG)." https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=OAP&dirEntryId=82963.

U.S. Environmental Protection Agency. 2015b. "Global Timber Model (GTM)." https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=OAP&dirEntryId=198002.

U.S. Environmental Protection Agency. 2017. "Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment." EPA 430-R-17-001. https://www.epa.gov/sites/default/files/2021-03/documents/ciraii_technicalreportfornca4_final_with_updates_11062018.pdf.

U.S. Environmental Protection Agency. 2021a. "Climate Change Impacts and Risk Analysis." https://www.epa.gov/cira.

U.S. Environmental Protection Agency. 2021b. "Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts." https://www.epa.gov/system/files/documents/2021-09/climate-vulnerability_september-2021_508.pdf.

U.S. Environmental Protection Agency. 2021c. "Final Rule to Revise Existing National GHG Emissions Standards for Passenger Cars and Lights Trucks Through Model Year 2026." *Federal Register* 86, no. 248: 74434-74526. https://www.govinfo.gov/content/pkg/FR-2021-12-30/pdf/2021-27854.pdf.

U.S. Environmental Protection Agency. 2022. "Climate Change Indicators in the United States." https://www.epa.gov/climate-indicators.

Volz, U., E. Campiglio, E. Espagne, J. Mercure, W. Oman, H. Pollitt, G. Semieniuk, R. Svartzman. 2021. "Transboundary Climate-related Risks: Analysing the Impacts of a Decarbonisation of the Global Economy on International Trade, Finance, and Money." International Monetary Fund Statistical Forum. https://www.imf.org/-/media/Files/Conferences/2021/9th-stats-forum/23final-paperulrich-volz.ashx.

Way, R., M. Ives, P. Mealy, and J.D. Farmer. 2021. "Empirically Grounded Technology Forecasts and the Energy Transition." INET Oxford Working Paper No. 2021-01. Oxford: Institute for New Economic Thinking at the Oxford Martin School. https://www.inet.ox.ac.uk/files/energy_transition_paper-INET-working-paper.pdf.

Weitzman, M.L. 2009. "On Modeling and Interpreting the Economics of Catastrophic Climate Change." *Review of Economics and Statistics* 91, no 1: 1-19. https://scholar.harvard.edu/weitzman/publications/modeling-and-interpreting-economics-catastrophic-climate-change.

Woetzel, J., D. Pinner, H. Samandari, H. Engel, M. Krishnan, B. Boland, P. Cooper, and B. Ruby. 2020. "Will Infrastructure Bend or Break under Climate Stress?" McKinsey Global Institute. https://www.mckinsey.com/~/media/mckinsey/business%20functions/sustainability/our%20insights/will%20infrastructure%20bend%20or%20break%20under%20climate%20stress/will-infrastructure-bend-or-break-under-climate-stress-case-study-old.pdf.

Yuan, M., S. Rausch, J. Caron, S. Paltsev, and J. Reilly. 2019. "The MIT U.S. Regional Energy Policy (USREP) Model: The Base Model and Revisions." *MIT Joint Program on the Science and Policy of Global Change.* https://globalchange.mit.edu/sites/default/files/MITJPSPGC_TechNote18.pdf.

Zickfeld, K., S. Solomon, and D.M. Gilford. 2017. "Centuries of Thermal Sea-Level Rise due to Anthropogenic Emissions of Short-Lived Greenhouse Gases." *Proceedings of the National Academy of Sciences* 114, no. 4: 657-662. https://www.pnas.org/doi/10.1073/pnas.1612066114.

Appendix

Table 1. Top-down Estimates of Climate Change on GDP in the Literature (Not Comprehensive)

Study	Region	Year	Emissions Scenario[9]	Projected Impact Due to Climate Change
Kahn et al. 2021	United States	2100	RCP 8.5	GDP per capita is reduced by 10.5%
Kahn et al. 2021	United States	2100	RCP 2.6	GDP per capita is reduced by 1.9%
Kalkuhl and Wenz 2020	United States	2100	NGFS Current Policies	GDP is reduced by 5.9% (through NGFS Data Explorer; combined with REMIND-MAgPIE)
			NGFS Net Zero 2050	GDP is reduced by 1.5% (through NGFS Data Explorer; combined with REMIND-MAgPIE)
Deryugina and Hsiang 2014	United States	2100	RCP 8.5	U.S. annual GDP growth rate is lowered by 0.06 to 0.16 percentage points
Burke, Hsiang, Miguel 2015	United States	2099	RCP 8.5	GDP per capita is reduced by 36% (see https://web.stanford.edu/~mburke/climate/data.html)
Kahn et al. 2021	Global	2100	RCP 8.5	GDP per capita is reduced by 7%
Newell, Prest, Sexton 2021	Global	2100	RCP 8.5	GDP is reduced by 1-3% based on damages to GDP levels.
Kalkuhl and Wenz 2020	Global	2100	3.5 °C warming	GDP is reduced by 7-14%
Pretis et al. 2018	Global	2100	1.5 °C warming	GDP per capita is reduced by 8%
			2 °C warming	GDP per capita is reduced by 13%
Burke, Hsiang, Miguel 2015	Global	2100	RCP 8.5	GDP is reduced by 23%
Dell, Jones, Olken 2008	Global	2100	A2	GDP is reduced by 0.3%

[9] The IPCC creates a number of scenarios called "Representative Concentration Pathways" (RCPs) to represent this emissions uncertainty, ranging from RCP 2.6 (low emissions and quick decarbonization resulting in under 1.5 °C warming by 2100) to RCP 8.5 (high emissions and little decarbonization resulting in ~4.8 °C by 2100) (Meinshausen, Raper, and Wigley 2011). Previously, the IPCC used a different set of scenarios described in the "Special Report on Emissions Scenarios" (SRES) (Nakicenvoic et al. 2000). This includes the A2 that results in ~3.5 °C warming by 2100.

Table 2. Bottom-up Global Climate Impact Projections in the Literature (Not Comprehensive)

Study	Sector/ Impact	Region	Year	Emissions Scenario[10]	Projected Impact Due to Climate Change
Hsiang et al. 2017	Aggregated Sector-Level Impacts	United States	2080-2099	8 °C warming	Damages aggregated across sectors are equal to 6.4 to 15.7% of GDP
				6 °C warming	Damages aggregated across sectors are equal to 3.6 to 10.0% of GDP
				4 °C warming	Damages aggregated across sectors are equal to 1.5 to 5.6% of GDP
				1.5 °C warming	Damages aggregated across sectors are equal to -0.1 to 1.7% of GDP
Roson and Sartori 2016	Aggregated Sector-Level Impacts	United States	N/A	3 °C warming	Damages aggregated across sectors are equal to 0.2% of GDP.
Bosello et al. 2012	Aggregated Sector-Level Impacts	Global	2050	1.9 °C warming	Damages aggregated across sectors are equal to 0.5% of GDP.
Rising and Devineni 2020	Agriculture	United States	2070	RCP 8.5	Total agriculture profits drop by 31% when crop locations are held constant; drop by 16% when crop lands are reallocated to avoid yield decreases and take advantage of yield increases.
Schlenker and Roberts 2009	Agriculture	Eastern United States	2099	A1FI	Annual yields of corn, soybeans, and cotton are reduced by 63-82% assuming fixed growing regions.
				B1	Annual yields of corn, soybeans, and cotton are reduced by 30-46%

[10] The IPCC creates a number of scenarios called "Representative Concentration Pathways" (RCPs) to represent this emissions uncertainty, ranging from RCP 2.6 (low emissions and quick decarbonization resulting in under 1.5 °C warming by 2100) to RCP 8.5 (high emissions and little decarbonization resulting in ~4.8 °C by 2100) (Meinshausen, Raper, and Wigley 2011). Previously, the IPCC used a different set of scenarios described in the "Special Report on Emissions Scenarios" (SRES) (Nakicenvoic et al. 2000). This includes the B1 scenario that results in just under ~2 °C warming by 2100, the A1B scenario that results in just under ~3 °C warming by 2100, the A2 scenario that results in ~3.5 °C warming by 2100, and the A1F1 scenario that results in ~4 °C warming by 2100. The DICE baseline emissions scenario was developed by the economist William Nordhaus as part of his Dynamic Integrated Climate-Economy (DICE) model, and it results in just over 4 °C warming by the end of the century.

					assuming fixed growing regions.
Hsiang, Burke, Miguel 2013	Conflict	Global	N/A	N/A	Each 1-SD change in climate toward warmer temperatures or more extreme rainfall increases the frequency of interpersonal violence by 4% and intergroup conflict by 14% (median estimates).
Rode et al. 2021	Energy Consumption	United States	2099	RCP 8.5	Consumption of electricity increases by 2.7% of current levels; consumption of other fuels decrease by 7.6% of current levels.
Deschenes and Greenstone 2011	Energy Consumption	United States	2100	A1FI	Climate change increases annual residential energy consumption by 11%.
Rode et al. 2021	Energy Consumption	Global	2099	N/A	Consumption of electricity increases by 7% of current consumption per 1°C of warming; consumption of other fuels decreases by 7% of current consumption per 1°C of warming.
U.S. Environmental Protection Agency 2017	Labor Supply	United States	2090	RCP 8.5	1.9 billion labor hours across the national workforce are lost annually by due to the effects of extreme temperature on suitable working conditions, totaling over $160 billion in lost wages per year.
				RCP 4.5	970 million labor hours across the national workforce are lost annually by due to the effects of extreme temperature on suitable working conditions, totaling $80 billion in lost wages per year.
Feng, Krueger, Oppenheimer 2010	Migration	United States	2080	B1	Climate change induces 1.4 to 6.7 million adult Mexicans to emigrate into the United States as a result of declines in agricultural productivity alone.
Missirian and Schlenker 2017	Migration	Global into EU	2099	RCP 8.5	Asylum applications into the EU increase by 188%.
				RCP 4.5	Asylum applications into the EU increase by 28%.

Kopp et al. 2017	Sea-Level Rise	Global	2100	RCP 8.5	Sea levels rises by 1.5 meters, submerging land currently occupied by 153 million people.
			2300	RCP 8.5	Sea levels rises by 11.7 meters, submerging land currently occupied by 950 million people.
Bressler et al. 2021	Temperature-related Mortality	United States	2080-2099	RCP 8.5	Without accounting for the benefits of income-related adaptation, climate change increases the mortality rate by 2.2%. Accounting for the benefits of income-based adaptation, climate change increases the mortality rate by 0.3%.
				RCP 4.5	Without accounting for the benefits of income-related adaptation, climate change increases the mortality rate by 0.4%. Accounting for the benefits of income-based adaptation, climate change decreases the mortality rate by 0.3%.
Shindell et al. 2020	Temperature-related Mortality	United States	2100	RCP 8.5	Deaths from heat exposure increase by 85,000 per year with benefits of adaptation accounted for.
				RCP 4.5	Deaths from heat exposure increase by 24,000 per year with benefits of adaptation accounted for.
Deschenes and Greenstone 2011	Temperature-related Mortality	United States	2100	A1FI	Climate change increases the mortality rate by 3% without benefits of adaptation accounted for.
Bressler 2021	Temperature-related Mortality	Global	2020-2100	DICE Baseline	83 million projected cumulative excess deaths between 2020 -2100 from temperature-related mortality with benefits of adaptation accounted for; adding 4,434 metric tons of carbon dioxide in 2020 (equivalent to the lifetime emissions of 3.5 average Americans) causes one excess death globally between 2020-2100.

Carleton et al. 2020	Temperature-related Mortality	Global	2100	RCP 8.5	The impact of climate change on mortality with benefits of adaptation accounted for will be comparable globally to leading causes of death today, such as cancer and infectious disease.
Hsiang and Jina 2014	Tropical Cyclones	Global	2010-2090	A1B	The present discounted value of lost long-run growth to 2090 is worth $9.7 trillion in net present value.
Ranson 2014	Violent Crime	United States	2010-2099	A1B	Climate change causes an additional 22,000 murders, 180,000 cases of rape, 1.2 million aggravated assaults, 2.3 million simple assaults, 260,000 robberies, 1.3 million burglaries, 2.2 million cases of larceny, and 580,000 cases of vehicle theft.