

Extreme Weather Events and Climate Change: Economic Impacts and Adaptation Policies

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climate change policy, natural disasters, climate adaptation, risk management, climate extremes

Abstract

This article reviews the literature on the economic impacts of disasters caused by extreme weather and climate events to draw lessons on how societies can better manage these risks. While evidence that richer, better-governed societies suffer less and recover faster from climate extremes suggests adaptation, knowledge gaps remain, and little is known about the efficiency of specific adaptation actions. I review various “no or low” regrets adaptation options that are recommended when uncertainties over climate change impacts are high. I discuss how governments can play an important role in adaptation by directly providing public goods to manage disaster risks or by facilitating private agents’ adaptation responses but also highlight the political economy of policy and coordination failures.

1. INTRODUCTION

The 10 warmest years in the historical record have all occurred in the past decade (2014–2023) (Lindsey & Dahlman 2024). In 2023, following the hottest June on record, July was the hottest month ever measured worldwide, with devastating heat waves in large areas of the United States, Mexico, Southern Europe, and China that broke many local high temperature records and that would have been “virtually impossible” without human-induced climate change (Zachariah et al. 2023). In August 2023, the island of Maui experienced the deadliest wildfire in the past 100 years in the United States, where in 2023 there were 25 billion-dollar weather and climate disaster events (severe storms, flooding, tropical cyclone, drought, wildfire), each with losses exceeding \$1 billion. This was the highest number of such events since the record starts in 1980 (NOAA 2023). Record-breaking extreme weather and climate events have become the new normal.

Global temperatures are expected to continue to increase and with them the frequency and intensity of extreme weather and climate events (IPCC 2023).¹ Under any realistic climate policy scenario, atmospheric greenhouse gas (GHG) concentrations will continue to grow. Even if we could quickly and drastically reduce GHG emissions (which seems unlikely in the current economic and political reality), due to the high residence time of GHGs and lagging climate response, temperatures will continue to rise from past increases in GHG emissions, making it likely that a 2°C warming cannot be avoided (Tol 2018, Pindyck 2022).²

Aggressive mitigation of GHG emissions remains the most important prescription of climate policy, especially to insure against low-probability, high-impact catastrophes (Weitzman 2009), but climate is projected to change regardless of current GHG mitigation efforts, and climate extremes are affecting societies today. The World Economic Forum’s *2023 Global Risks Report* considers the failure to mitigate climate change, failure of climate change adaptation, and natural disasters and extreme weather events to be the top three greatest risks in the next 10 years (World Econ. Forum 2023). While in the past there has been some reluctance to discuss adaptation due to concerns about moral hazard (Aldy & Zeckhauser 2020), it has become painfully evident that climate policy must include strategies to alleviate the negative impacts of climate change (Kahn 2016, Aldy & Zeckhauser 2020, Pindyck 2022). Climate adaptation has the potential to significantly reduce the damages from climate extreme events but remains one of the least explored areas of climate economics (Burke et al. 2016).

This article reviews the empirical literature on the economic impacts of climate extremes to learn how we can better manage their risks to prevent as well as prepare for, cope with, and recover from disasters when they occur. I draw from two distinct branches of literature: one examining the economic costs of natural disasters, previously reviewed by Cavallo & Noy (2011), Kellenberg & Mobarak (2011), and Botzen et al. (2019), and the other examining the economic impacts of climate change, reviewed by Dell et al. (2014), Carleton & Hsiang (2016), Tol (2018), and Auffhammer (2018). A key focus of the latter has been the study of impacts of climate on agriculture (see, e.g., Mendelsohn et al. 1994, Fisher et al. 2012, Carter et al. 2018), but similar to Kousky (2014), my focus in this review is on weather- and climate-related disasters. Climate

¹The distinction between weather and climate extremes is related to their specific time scales, but it is not precise. Extreme weather events are often short-lived (e.g., heat waves, freezes, tropical cyclones, floods). Extreme climate events persist longer and can be the accumulation of several weather events over a longer period (e.g., droughts or wildfire outbreaks) (IPCC 2012, p. 117). For simplicity and following IPCC (2012), in this review I refer to both as climate extremes.

²If GHG concentrations in the atmosphere reach 700 ppm (parts per million), a rise of temperatures between 1.5 and 4.5°C is most likely. But the distribution of possible temperature increases possesses fat tails, implying a non-negligible, 10% probability that temperatures will increase by 6°C (Wagner & Weitzman 2015).

extremes do not always result in disasters; they do when they cause widespread damage and severe alterations to the normal functioning of communities or societies (IPCC 2012). And those impacts depend on the characteristics and intensity of the extremes themselves, as well as on the exposure and vulnerability of those affected.³

The literature reviewed in Sections 2 and 3 suggests overall negative consequences of climate disasters on economies and societies, but it shows that the impacts are heterogeneous, offering insights into adaptation to climate extremes. A consistent finding is that rich countries fare better, supporting Schelling's (1992) argument that developing countries' best defense against climate change may be their own continued development. Beyond this somewhat generic, macrolevel recommendation, decision makers are faced with limited resources and a potentially large portfolio of adaptation options and need to prioritize among them.

In Section 4, I discuss the role of governments in adaptation, which in the context of climate extremes entails managing disaster risk. Among the portfolio of adaptation actions, some help reduce exposure or vulnerability to climate hazards, while others transfer risk (e.g., through insurance) or help manage the remaining residual risk. Some require the provision of public goods (e.g., early warning systems, flood-risk protection through so-called hard infrastructure, or through nature-based solutions), while others, undertaken by households or firms (e.g., protective investments, insurance purchase, relocation) can be facilitated by policies that address market failures and the cognitive biases and behavioral barriers that are typical of decisions made in contexts of deep uncertainty. In Section 4, I review several specific adaptation strategies that have been recommended as no regrets or low regrets but also discuss policy and coordination failures that may prevent optimal public adaptation responses. Section 5 concludes and highlights the many areas of promising future research, given that research on the efficiency of adaptation policies is still in its infancy.

2. IMPACTS OF CLIMATE EXTREMES ON THE ECONOMY

Human-caused climate change is affecting weather and climate extremes across the world, leading to widespread losses and damage to people and nature (IPCC 2023). **Figure 1** shows the increase in the number of weather- and climate-related disaster events worldwide and associated inflation-adjusted losses from 1980 to 2022. During this period, disasters caused by droughts, wildfires, floods, landslides, tropical cyclones, severe storms, and extreme temperatures killed almost 1.6 million people and caused damages exceeding \$4.6 trillion (in constant 2021 US dollars). Since 2010, global damage every year has exceeded US\$100 billion, with the last two years each above \$200 billion. For comparison, **Figure 1** also shows the number of geophysical disasters caused by earthquakes, tsunamis, and volcanic eruptions, for which a positive trend is not observed.

Climate-related disasters have direct, negative impacts on factors of production and ecosystems. For example, floods can kill people, destroy buildings, crops, roads, and bridges, and erode soils; heat waves increase mortality. Disasters disrupt economic activity (e.g., through business interruption), resulting in additional indirect, higher-order effects whose estimation is typically done through computational models such as input-output or computable general equilibrium models (Okuyama 2022 and Botzen et al. 2019 review these models).

Economic theory yields competing hypotheses for the trajectory of output following the initial disaster shock (Hsiang & Jina 2014, Botzen et al. 2019). In neoclassical growth models with exogenous technological progress, if the shock lowers capital-labor ratios, positive rates of growth

³In fact, observed increases in disaster damages worldwide can be mainly explained from the growth in population and economic activities in hazardous areas, although climate change is expected to increasingly contribute to that trend (Hoeppel 2016).

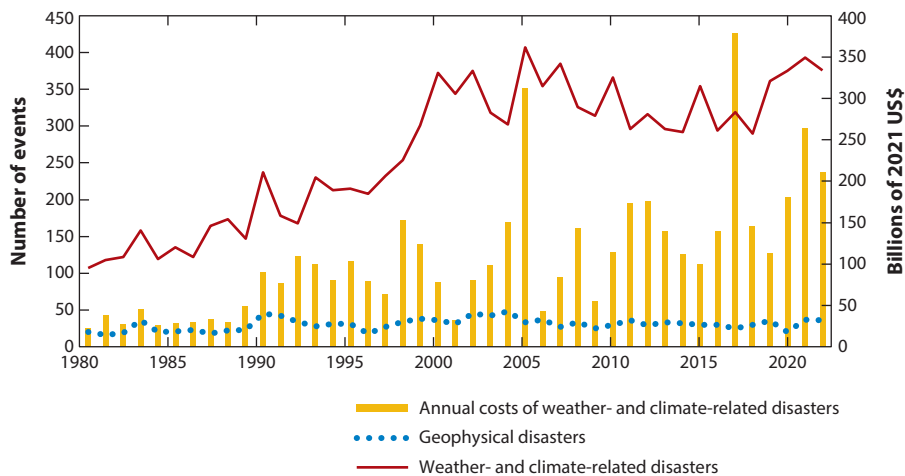


Figure 1

Evolution of weather- and climate-related disaster events worldwide: number of events and annual costs. Data are from the emergency events database EM-DAT, maintained by the Centre for Research on the Epidemiology of Disasters at the Catholic University of Louvain, Belgium (<https://www.emdat.be>). Natural disasters are recorded in EM-DAT if they fulfill one of these criteria: (a) at least 10 deaths occurred, (b) at least 100 people were reported affected, and (c) there was a declaration of a state of emergency and/or appeal for international assistance. Information is compiled from various sources (United Nations agencies, nongovernmental organizations, insurance companies, research institutes, and press agencies). Weather- and climate-related disasters are caused by droughts, wildfires, floods, landslides, tropical cyclones, severe storms, and extreme temperatures. Geophysical disasters are caused by earthquakes, tsunamis, and volcanic eruptions. Annual costs are the total estimated damages and economic losses directly or indirectly related to the disaster. In practice they typically include direct losses (e.g., damage to housing, infrastructure, and crops). Annual costs are expressed in constant 2021 US dollars.

following the shock return the economy to the steady state. This is the recovery to trend hypothesis.⁴ Endogenous growth models offer additional possibilities for postdisaster dynamics. For example, vintage capital models predict that replacement of capital after a disaster updates the technology, which, in turn, increases productivity and growth, providing the intuition for build-back-better or Schumpeterian creative-destruction hypotheses. In AK models (A denoting productivity, K capital stock), where output and output per worker depend on the level of accumulated capital, a shock that destroys capital has a lasting impact on output per worker, lowering postdisaster income permanently. This is consistent with a no recovery hypothesis. Additionally, the impact of disasters in the short run may depend on business cycle dynamics, with the shock providing a Keynesian-like stimulus during a recession but driving up inflation rather than output during a boom, when capacity is tight (Tol & Leek 1999, Hallegatte & Ghil 2008).

⁴Existing literature suggests that depreciation effects to physical capital are larger than population effects in most cases. Possible exceptions are heat waves, which cause more deaths than other climate extremes, although these concentrate on the elderly (NWS 2022) and act as a negative labor productivity shock (Bilal & Rossi-Hansberg 2023); and disasters affecting the poorest, most vulnerable countries, where the human toll tends to be disproportionately high and capital-labor ratios disproportionately low (Fankhauser & Tol 2005). An implicit assumption to return to the same steady state is that savings rates remain constant, but they may change after a disaster, e.g., if a potential drive to “enjoy life while it lasts” dominates over a precautionary tendency to self-insure, lowering savings rates (Filipski et al. 2019) or vice versa if preferences change in the opposite direction.

2.1. Econometric Methods and Data

Given conflicting theoretical predictions, the questions of whether and how climate extreme events affect economic growth have been posed as, ultimately, empirical questions (Cavallo et al. 2013, 2022). To empirically estimate their causal effect is difficult, however. It requires comparing the observed outcome to a counterfactual, unobserved outcome that would have occurred absent the shock. In practice, lacking a natural experiment to compare one population exposed to the climate extreme (i.e., treated) with an identical control population not experiencing the event, most empirical studies have estimated variants of a general specification such as Equation 1:

$$Y_{it} = \alpha D_{it} + \beta' X_{it} + \gamma' D_{it} X_{it} + \theta_i + \theta_t + \varepsilon_{it}, \quad 1.$$

where i denotes a geographical unit (e.g., a country or region) or a firm or household, and t denotes time (typically a year). Y_{it} is the outcome of interest (e.g., income, GDP per capita, or their growth rates), and D_{it} denotes contemporaneous or lagged disaster incidence. It can be a dummy for disaster occurrence, or a variable accounting for disaster frequency, intensity, or damage (e.g., wind speed of hurricanes, share of population killed or affected by a disaster). In most cases, researchers include additional controls X_{it} (e.g., indicators of education, openness, or institutional quality) that may mitigate the effect of a disaster to shed light on potential adaptation mechanisms. θ_i and θ_t are spatial and time-fixed effects, respectively, which are needed to plausibly estimate a causal effect of the disaster on the outcome of interest. In specifications such as Equation 1, the population just before an event serves as the control for itself right after the event (i.e., after being treated).

To model the temporal dynamic effects of climate shocks, researchers have used distributed lagged models or vector autoregressions, where additional lags of the disaster variable or the dependent variable are included in the right-hand side of Equation 1. In contrast, the spatial spillovers of shocks remain understudied. In a highly interconnected world, climate shocks spread across regions through trade and financial flows, flows of people (i.e., migration), and flows of resources (e.g., water). Even without shocks, the economic performance of a region is influenced by that of its neighbors. Thus, areas not directly affected by a shock may be subject to spillover effects, which would violate the stable unit treatment value assumption and threaten causal identification (Kolak & Anselin 2020). To date, few studies [Strobl (2011) and Lima & Barbosa (2019) being exceptions] explicitly incorporate spatial dependence into econometric models of disaster effects.

An important consideration of empirical studies estimating versions of Equation 1 is that in panel fixed-effects models, identification arises from within-unit year-to-year fluctuations in weather and the outcome of interest, which isolates the effects of disaster strikes, but it does not tell us much about long-run adaptation responses to disaster risk (Auffhammer 2018, Bakkensen & Barrage 2018). Cross-sectional specifications, on the other hand, allow for long-run adaptation but are subject to potential omitted variable bias, which has led most researchers to favor panel data or a combination of both approaches (Auffhammer 2018). Insights into adaptation in panel studies have typically come from specifications that include interactive terms $\gamma' D_{it} X_{it}$, as described above. A promising, novel, alternative approach feeds results from the empirical estimation of panel versions of Equation 1 to structural models of the economy to yield general equilibrium effects that allow one to directly model long-run endogenous adaptation through, for example, migration, savings, and capital investment (Bakkensen & Barrage 2018, Bilal & Rossi-Hansberg 2023).

Most studies estimate Equation 1 using ordinary least squares (OLS), which imposes a linear relationship between the intensity of the shock and the dependent variable, an assumption that may be inappropriate for fat-tailed damage distributions. Coronese et al. (2019) show that while their OLS estimates of disaster impacts over time are small and statistically insignificant, quantile-regression estimates increase exponentially with disaster intensity.

Regarding data, most multicountry studies have used the publicly available EM-DAT global data set to construct the disaster variables in Equation 1 (<https://www.emdat.be>; see Figure 1). Alternative data sets maintained by reinsurance companies (Swiss Re's Sigma and Munich Re's NatCatSERVICE) provide a shorter time coverage and limited access and have been used less frequently. Disaster variables in these three data sets may not be exogenous, however. Because monetary damages of disasters are larger in richer economies, damage-based disaster intensity measures are correlated with GDP per capita. Felbermayr & Gröschl (2014) show that the likelihood of a disaster being reported in EM-DAT, conditional on its physical magnitude, depends strongly on the affected country's GDP per capita.⁵

In contrast, indicators of the intensity of the underlying hazard events are plausibly exogenous to the economic variables of interest (at least in the short run) and have been used directly or as instruments of disaster intensity. Early examples are Hsiang (2010) and Strobl (2011, 2012), who use tropical cyclone track data and wind field models to reconstruct local exposure to tropical cyclones.⁶ As for data sources, some countries maintain publicly accessible databases for natural hazards and disasters. For example, the US National Centers for Environmental Information maintains a billion-dollar weather and climate disasters database for disasters exceeding \$1 billion in damages within US borders, as well as several databases for natural hazards, some of them global in scope, like the International Best Track Archive for Climate Stewardship for tropical cyclones (<https://www.ncei.noaa.gov/products/natural-hazards>). Academic-driven publicly available global data sets with granular spatial and temporal resolutions include the Standardized Precipitation-Evapotranspiration Index (SPEI) database for droughts, or the Dartmouth Flood Observatory for floods.⁷ A wider and growing availability of geospatially referenced climate and hazard data offers much promise by expanding the range of data that can be tailored to specific research questions.

2.2. Effects of Disasters on GDP and GDP Growth in Multicountry Studies

The consensus is that disasters, especially those most severe or affecting developing countries have, on average, negative impacts on GDP and GDP growth in the short run.⁸ In their meta-analysis of more than 750 estimates from 22 primary studies, Klomp & Valckx (2014) report a negative genuine effect of natural disasters on economic growth, with climate disasters in developing countries having the most adverse impacts. However, they also report much variation in the estimates, with an important fraction being not significant or positive (38%), and note a publication bias in the reporting of negative estimates. The heterogeneity in the estimates suggests that the type and characteristics of the disaster as well as the responses across countries and economic sectors are important determinants of their impacts (Loayza et al. 2012), but there may also be sample composition effects (Bakkensen & Barrage 2018). In addition, Felbermayr & Gröschl (2014) find

⁵Kousky (2014) highlights two additional drawbacks of damage-based disaster indicators: (a) small events are not recorded although their frequent occurrence can be costly; (b) potentially highly destructive hazards with low impact (e.g., due to preexisting effective adaptation strategies) are not recorded either, although they would be very informative to assess which risk-management strategies drive the low impact.

⁶Felbermayr & Gröschl (2014) developed and used a global disaster events database (ifo GAME; <https://www.ifo.de/en/ifo-game-geological-and-meteorological-events-database>) with primary information on the physical strength of the hazards associated with disasters (e.g., hurricane track data, wind speed, precipitation) for the period 1979–2010.

⁷More details at <https://spei.csic.es/database.html> and <https://floodobservatory.colorado.edu/>, respectively.

⁸The short run is defined as 1–5 years postdisaster. Most studies using conventional panel fixed-effects model specifications estimate immediate (next year) impacts.

nonlinearities with the worst 5-percent disaster years reducing GDP per capita by 0.46% and those in the top 1-percentile by at least 6.8%.

Of the estimates reviewed by Klomp & Valckx (2014), less than 10% explain the long-run impact of disasters (after 5 years), reflecting a paucity of studies concerned with this question, partly because of the difficulty for causal identification. An early, influential study by Skidmore & Toya (2002) reports positive correlations between climate disasters and average annual growth rates of GDP and total factor productivity between 1960 and 1989. Their result has been interpreted as evidence for Schumpeterian creative destruction dynamics, although Cuaresma et al. (2008) found that the relationship between technology absorption and disasters that would support this argument only held for high-GDP countries. Cuaresma (2022) revisits Skidmore & Toya's (2002) basic specifications with updated data and Bayesian model averaging techniques and finds that disasters are not robust predictors of long-run economic growth.

Cross-sectional approaches like those of Skidmore & Toya (2002) provide long-run estimates that allow for adaptation but have the caveat of potential omitted variables. Using synthetic control methods to build a counterfactual for affected countries, Cavallo et al. (2013) report that even extremely severe disasters do not significantly affect short- or long-run economic growth.⁹ In contrast, Hsiang & Jina (2014), using a panel distributed lag model, estimate a negative effect of tropical cyclones on GDP growth that persists 15–20 years following an event, arising from a small but persistent suppression of annual growth rates.

2.3. Subnational Analyses of Economic Disaster Impacts

To date, the unit of analysis in studies of disaster impacts on economic growth has typically been the country. This level of aggregation may mask significant impacts at a subnational level, particularly in large countries, missing potentially important regional distributional effects. In addition, national macroeconomic aggregates do not account well for the detrimental effects of climate extremes on the poor, who have fewer assets to lose and may participate more in the informal economy, which misses additional distributional effects of climate extremes within countries (Hallegatte & Rozenberg 2017). Equation 1 can still be used to estimate the effects of climate extremes on spatial units other than the country. Moving beyond country-level analyses, however, requires systematic collection of statistical information at the subnational level, which may be challenging, especially for low-income countries.

For coastal counties in the United States, Strobl (2011) finds that an average hurricane lowers a county's annual economic growth by 0.45 percentage points the year it strikes but that this effect does not manifest at the state or national levels, highlighting the importance of a disaggregated level of analysis. In the longer run (8 years out) and for all US counties, Roth Tran & Wilson (2023) find that disasters increase income per capita by 0.6% in counties affected, with offsetting negative effects on other counties within the region. In one of the few studies to explicitly model spatial spillovers of climate extremes, Lima & Barbosa (2019) show that per capita GDP declined an average of 7.6% in Brazilian municipalities affected by a flash flood, while those affected indirectly also experienced a decline of approximately 0.54–1.98%.

Studies at a micro, firm level have shed light on postdisaster reconstruction dynamics. Leiter et al. (2009) find evidence that, in the short run, companies in regions hit by a flood grow physical capital and labor at a higher rate than firms in unaffected regions, but that this increase does not translate into higher productivity. This contrasts with Cole et al. (2019), who find that, conditional

⁹This is after controlling for two events where radical political revolutions followed the disaster. (The causality of this link is not assessed.)

on firm survival of the 1995 Kobe earthquake in Japan, firms experienced a temporary increase in productivity consistent with build back better effects. Consistent with a cleansing hypothesis, Basker & Miranda (2018) find that less-productive firms exited in the aftermath of Hurricane Katrina in the US Gulf region, and that even after controlling for productivity, small, credit-constrained firms were disproportionately affected. In Sri Lanka, De Mel et al. (2012) show that following the 2004 tsunami a lack of access to capital inhibited the recovery process, with firms that received randomly allocated grants recovering profit levels almost two years before other damaged firms.

Weather risk is an important source of income volatility for the rural poor and the subject of a vast literature within development economics. This literature offers insights into adaptation by investigating households' ability and strategies to prepare for and cope with climate extremes including risk sharing and self-insurance via savings (often in the form of grain or cattle assets), or adoption of lower-risk, often lower-return technologies (see, e.g., Kazianga & Udry 2006, Dercon & Christiaensen 2011, and Castells-Quintana et al. 2018 for a review). Few studies, however, examine the effect of climate extremes on income or consumption growth in developing countries using microlevel household data, largely because suitable panel data sets have not been available. One early exception is Dercon (2004) who, using data from the Ethiopia Rural Household Survey, shows that rainfall shocks had a substantial negative impact on consumption growth in the period 1989–1997, which persisted for many years.

The lack of socioeconomic data at a subnational level is a chronic constraint to studying the impacts of climate extremes on regional, local, or individual household outcomes in poorer countries, where this information is arguably most needed. The average interval between nationally representative economic surveys in half of the African nations is more than 6.5 years, compared to a subannual frequency in most wealthy countries (Burke et al. 2021). The long intervals between surveys make it difficult to link climate extremes to changes in economic and social outcomes. High-frequency household surveys and systematic postdisaster surveys with anonymized geo-referenced data to assess hazard exposure are expensive and time-consuming and may require deploying enumerators to remote and dangerous locations, but they are needed to better assess the role of climate shocks in development and poverty reduction (Hallegatte & Rozenberg 2017, Burke et al. 2021).

To overcome the paucity of survey-based, spatially disaggregated socioeconomic data, satellite images of nighttime light intensity have been used as a proxy for local economic activity (Bertinelli & Strobl 2013, Elliott et al. 2015, Klomp 2016). Recent advances in satellite-based methods combine nighttime light data with high-resolution daytime satellite images (both publicly available) for a more accurate approximation to household consumption and wealth (Yeh et al. 2020). These new approaches offer the promise to complement and enhance primary data collection. They can also assist with quick preliminary damage estimation that would take much longer with conventional damage and loss assessments.

2.4. Effects of Disasters on Other Economic and Social Outcomes

An important limitation of the focus of empirical research on GDP and its growth is that GDP measures the monetary value of economic output, not welfare. Evaluating the efficiency of adaptation measures necessitates a full accounting of all the impacts of climate extremes on welfare, including those that are difficult to monetize (e.g., fatalities, morbidity, psychological damage, or biodiversity loss) and that markets do not capture well. In addition, Bakkensen & Barrage (2018) argue that because economic growth in macroeconomic climate-economy models is endogenous, empirical research should quantify disaster impacts on the structural determinants of

growth: human capital, physical capital, and productivity, and not just on growth itself to account for macroeconomic adaptation through endogenous adjustments in savings and investment. For example, Bilal & Rossi-Hansberg (2023) use reduced-form estimates of the impacts of severe storms and heat waves on wages, employment, population, and investment to calibrate a general equilibrium model of the US economy, which they use to quantify long-term adaptation responses through migration and investment mobility.

2.4.1. Effects on human capital. Climate extremes affect human capital in multiple ways. First, they kill and injure people. Excess mortality and morbidity can occur immediately, through drowning or injuries—as with tropical cyclones, severe storms, or floods—or with a lag, through malnutrition or disease including pathogenic disease (Mora et al. 2022)—as with floods or droughts. In addition to physical health, climate extremes can have significant negative consequences for mental health (Obradovich et al. 2018).

Studies explaining disaster fatalities have estimated versions of Equation 1, finding generally that countries with higher incomes and better institutions suffer fewer deaths from disasters (Kahn 2005, Noy 2009, Fankhauser & McDermott 2014). More frequent exposure to tropical cyclones reduces fatalities (Hsiang & Narita 2012), which suggests adaptation. However, the intensity of the storms as well as the timing of the exposure may matter for the extent of adaptation. Bakkensen & Mendelsohn (2016) find similar results but only for strong storms. For floods, Miao (2019) finds that it is recent past floods that reduce fatalities of current events. Heat waves are among the most lethal climate extremes (NWS 2022), and here there is also evidence of adaptation. Barreca et al. (2016) show that, in the United States, mortality on days with mean temperature exceeding 80°F is lower in hot climates than in cooler climates. They further document a 75% decline in heat-related mortality over the twentieth century due to the adoption of residential air conditioning. Climate control can also mitigate the effects of extreme heat on workers' productivity (Somanathan et al. 2021).

Monetization of mortality risks has relied on empirical estimates of the value of a statistical life (VSL) and the value of a life year, but studies tailored to climate extremes and developing countries have not been forthcoming. This contrasts with the large magnitude of the potential losses. The central VSL-based estimate of excess mortality from heat waves in France between 2015 and 2019 is €23.2 billion (Adélaïde et al. 2022). Globally, Carleton et al. (2022) estimate the mean increase in mortality risk from extreme temperatures under a high-emissions scenario at 3.2% of global GDP in 2100—but as high as 27.5% and 18.5% of GDP in Pakistan and Bangladesh, respectively.

Additional, complementary estimates of the welfare costs of climate extremes are provided by studies directly estimating their effect on measures of subjective well-being (e.g., self-reported life satisfaction) that are used as proxies for experienced utility. Luechinger & Raschky (2009) and Ahmadiani & Ferreira (2021) report impacts of floods on life satisfaction that are sizeable and that yield monetary estimates comparable to price discounts in housing markets. Their findings also suggest that risk transfer mechanisms, disaster relief, and social support reduce the adverse effects of flood disasters.

Climate extremes can affect human capital accumulation in other important ways. For example, the 2010 Pakistan floods lowered literacy and increased school dropout rates. Khan & Hussain (2022) show that in addition to destroying nearly 11,000 schools, the floods lowered employment and incomes of many households that self-insured by sending children to work. Similar disinvestments in human capital are observed following typhoons in the Philippines, especially for girls (Anttila-Hughes & Hsiang 2013, Deuchert & Felfe 2015). Maccini & Yang (2009) show that rainfall shocks—even if experienced well before schooling age, e.g., around the time of birth—can have persistent, long-term impacts on adult socioeconomic status and suggest that these shocks

operate through effects on infant health and educational attainment. They are only significant for women, which is consistent with gender bias in the allocation of resources in response to environmental shocks.¹⁰ Even before birth, the fetal origins hypothesis applied to economic outcomes posits that shocks in utero can impact later-life health, educational attainment, and income (Currie & Rossin-Slater 2013, Sotomayor 2013). Further, shocks can transmit intergenerationally, with children of women exposed to disasters exhibiting lower education (Caruso 2017).

Fast-onset extreme weather events such as hurricanes or floods can displace people suddenly and involuntarily, often temporarily and over short distances.¹¹ If these events cause permanent migration, it is likely to be internal, within a country's borders. Slow-onset events such as droughts can also result in migration but one that is perceived as voluntary and economically driven (Cattaneo et al. 2019). Clement et al. (2021) project that the number of internal climate migrants by 2050 will be more than 216 million, an increase of 73 million over similar estimates just three years earlier (Rigaud et al. 2018). Much of that migration will occur from rural to urban areas where, if unplanned, it could overwhelm a city's ability to cope with the inflow of residents and increase risks of, for example, extreme heat or flooding (Dodman et al. 2022). International migration is costlier and less common than internal migration and may exacerbate brain drain in developing countries by involving the migration of highly skilled people (Drabo & Mbaye 2015). Sheldon & Zhan (2022) find that in response to hurricanes, floods, and coastal storms in the United States, high-income households are more likely to (mostly internally) emigrate than are low-income households who are in some cases less likely to emigrate than they would have been in the absence of the shock. This highlights that although climate shocks create an incentive to move, moving costs act as a significant barrier that may become unsurmountable after experiencing a disaster and can trap vulnerable populations in riskier areas (Cattaneo et al. 2019, Kaczan & Orgill-Meyer 2020).

2.4.2. Effects on physical and financial capital, competitiveness, and innovation. Disasters destroy and damage physical, human-made capital, including residential, commercial, and government buildings and their contents, vehicles, public infrastructure, and agricultural assets. As in the case of fatalities, studies estimating Equation 1 with natural disaster damages on the left-hand side generally find that countries with higher incomes and better institutions suffer fewer losses from disasters (Kahn 2005, Noy 2009, Fankhauser & McDermott 2014), which again suggests adaptation as income increases.

Recovery and reconstruction in the aftermath of climate disasters require potentially large flows of financial capital, but climate disasters can destabilize financial markets. Climate change risk is systemic and not hedgeable with standard financial instruments (Bolton et al. 2021). The financial sector itself is exposed to climate risks through the effect of disasters on the solvency of borrowers as well as their effect on the value of real estate assets used as collateral for bank loans (Hernández de Cos 2021).

Existing evidence suggests that both public finances and private capital flows are negatively affected by disasters. Major disasters often increase government debt by increasing public spending—in disaster relief response and in the repair and reconstruction of damaged public infrastructure, while lowering tax revenues (Lis & Nickel 2010, Melecky & Raddatz 2015, Deryugina 2022). In the United States, hurricanes increase nondisaster government transfers such as employment insurance and public medical payments in affected counties in the decade after the hurricane (Deryugina 2017). At the same time, climate risk vulnerability and climatological disasters increase

¹⁰See also Neumayer & Plümper (2007).

¹¹In 2022, a record 32.6 million people were displaced by disasters, mostly by floods (IDMC 2023).

the cost of government debt financing, especially for local governments (Jerch et al. 2023) and in developing countries (Cevik & Jalles 2022, Fisera et al. 2023), and increase the probability of a sovereign debt default (Klomp 2017). Credit ratings are already lower in developing countries, and updating beliefs about climate threats (due to, e.g., more frequent climate extreme events) could lead to capital flight from most vulnerable countries (Ferriani et al. 2023). Yang (2008) shows that only two forms of international financial flows to poor countries increase after they experience hurricanes: foreign aid and migrants' remittances, although David (2011) does not corroborate the findings for aid flows following climatic disasters. Moreover, humanitarian aid is typically a small fraction of the magnitude of the destruction (Becerra et al. 2014), and sometimes is reallocated from aid that had already been committed to other sectors of the affected country (Becerra et al. 2015).

Large disasters that destroy production capabilities may reduce competitiveness. Although the effects on imports are ambiguous, the consensus is that exports decrease (Osberghaus 2019). The response of the export sector (and the overall recovery) is bigger and faster in flexible exchange rate regimes (Ramcharan 2007). Pelli & Tschopp (2017) show that exporting sectors are affected differentially across the spectrum of comparative advantage, reminiscent of a Schumpeterian process of creative destruction of shifting resources toward higher comparative advantage industries. Miao & Popp (2014) ask whether disasters spur "risk-mitigating innovation" that facilitates coping with and building resilience to future shocks (e.g., new techniques for flood control or new drought-resistant crops). They find that patents increase following domestic disasters and foreign floods, suggesting (reactive) adaptation by the private sector.

3. LESSONS FOR ADAPTATION

Climate adaptation is the process of adjustment to the effects of actual or expected climate to moderate harm or exploit beneficial opportunities (IPCC 2012, p. 556). In the context of climate extremes, it entails disaster risk management, as defined in the Sendai Framework for Disaster Risk Reduction. This includes actions to prevent new disaster risk, reduce existing risk and, acknowledging that not all disaster risk can be eliminated, manage residual risk (UNDRR 2015). **Figure 2** characterizes the range of adaptation options for reducing disaster losses and strengthening resilience.¹²

The empirical literature reviewed in Section 2 does not explicitly measure adaptation activity. Adaptation is inferred from how the response to climate extremes varies according to exposure and to a series of economic, social, and political characteristics that explain vulnerability (captured by X_{it} in Equation 1). One such key factor is the level of economic development. In Fankhauser & McDermott's (2014) model of adaptation, demand for adaptation increases with income per capita. On the supply side, economic development strongly correlates with the capacity to handle climate risks financially (e.g., through access to credit and insurance), institutionally (e.g., through effective planning regulations and building codes, good public services), and technically (e.g., by providing hazard information and early warning systems). Richer countries with better institutions tend to suffer lower human and economic losses from climate disasters (Kahn 2005, Noy 2009, Felbermayr & Gröschl 2014). At a micro level, poor people are disproportionately adversely affected by natural disasters (Hallegatte et al. 2020). Beyond the generic recommendation of getting

¹²Note that the risk management and hazard literatures use the term mitigation, rather than adaptation, to describe reduction of climate risks. In the climate literature, mitigation is the reduction of GHG emissions. Resilience is defined as the ability to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner (IPCC 2012).

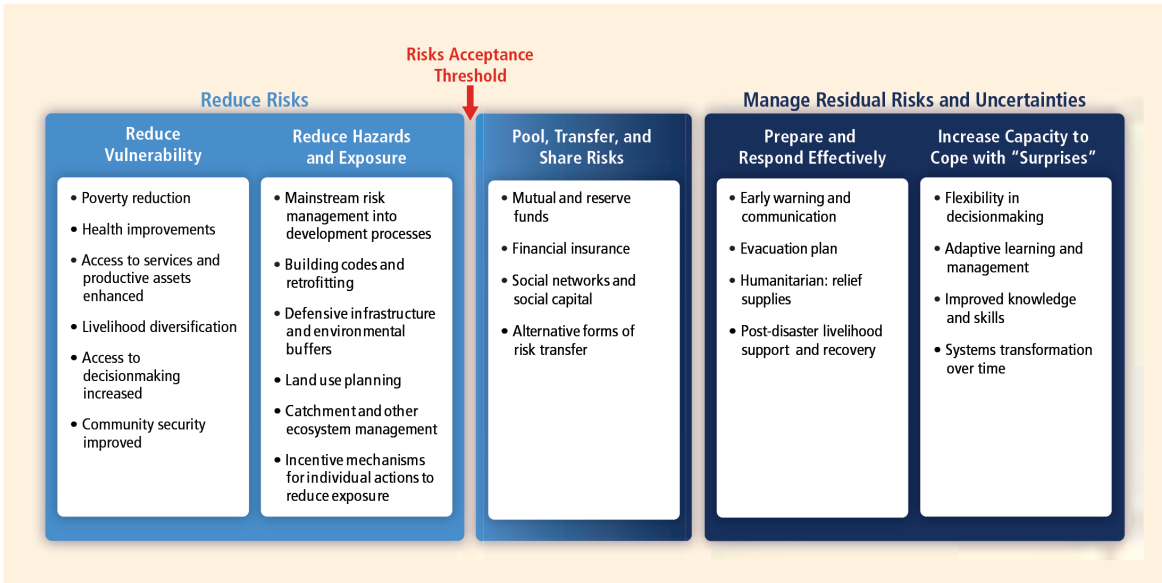


Figure 2
Risk management and adaptation options. Complementary response measures for observed and projected disaster risks supported by respective institutional and individual capacity for making informed decisions. Reproduced with permission from IPPC (2012, p. 361, figure 6.3).

richer and better governed, some studies have started to identify more specific factors and interventions that mitigate adverse disaster impacts and speed up recovery, offering practical lessons for adaptation.

3.1. Postdisaster Support and Risk Transfer

Richer countries fare better partly because, financially, they can mobilize significant resources for reconstruction (Cavallo & Noy 2011). Countries with more developed debt and insurance markets experience lower output declines from disasters (Melecky & Raddatz 2015). Moreover, they tend to follow counter-cyclical fiscal policy in the aftermath of disasters in contrast to developing countries whose procyclical behavior exacerbates adverse macroeconomic outcomes (Noy & Nualsri 2011). Availability of disaster relief funds facilitates the rapid deployment of postdisaster liquidity. For example, FONDEN, Mexico’s indexed Natural Disaster Fund, financed the reconstruction of federal infrastructure, which accelerated recovery (Del Valle et al. 2020) and, by restoring access to health services, mitigated mortality impacts of disasters, with a benefit-cost ratio above 3.2 (Del Valle 2024).

Overall financial development helps coping with disasters—in the case of insurance without increasing the fiscal burden (Melecky & Raddatz 2015). von Peter et al. (2024) show that the uninsured losses drive the macroeconomic costs of disasters. Timely insurance payments help speed up recovery at both macro and micro (household and firm) levels (Kousky 2019, Nguyen & Noy 2020). The role of insurance in promoting risk mitigation is, however, less clear. First, the costs of insurance may be high, preventing adoption (Kousky 2019). Second, government-sponsored programs that encourage adoption through subsidized premiums could create moral hazard (Annan & Schlenker 2015). Similarly, expectations of disaster aid might discourage ex ante

risk management (including purchasing insurance). In the United States, Deryugina & Kirwan (2018) show that farmers reduce crop insurance coverage in anticipation of government disaster relief. In contrast, Kousky et al. (2018) find only a small reduction in the quantity of flood insurance purchased in Florida after receipt of Federal Emergency Management Agency (FEMA) individual assistance grants and no impact on take-up rates, likely because there is a requirement that disaster aid recipients purchase insurance. Using a macro model calibrated with data on US storms, disaster aid, and cyclone wind speed, Fried (2022) finds that disaster aid reduces adaptation, but that federal subsidies for adaptation more than offset this moral hazard effect.

In developing countries, provision of crop insurance allows farmers to invest more in production activities that yield higher expected returns but are also riskier, e.g., more sensitive to deficient rainfall (Cole et al. 2017). It is often assumed that insurance premiums can incentivize risk reduction and location choice; e.g., for flood insurance, premium discounts for hazard mitigation activities can reduce risks, and aligning premiums with actual flood risks can deter floodplain development. However, empirical work in this area is scarce, limited by data availability and a lack of exogenous changes to allow causal identification (Kousky 2019).

In developing countries, where resources to self-insure are few and risk transfer mechanisms remain uncommon (Surminski 2022), foreign aid and migrants' remittances can lessen the impacts of disasters (Hochrainer 2009). Remittances can help with both recovery and preparedness (e.g., by financing stronger houses and access to communication equipment) (Mohapatra et al. 2012). At an international level, sovereign states highly exposed to climate extremes have created disaster insurance pools, such as the Caribbean Catastrophe Risk Insurance Facility, the African Risk Capacity, or the Pacific Catastrophe Risk Assessment and Financing Initiative. International risk pools would be even more effective if implemented globally instead of regionally (Ciullo et al. 2023).

3.2. Institutions and Accountability

Democratic countries with better institutions experience fewer deaths and damages and recover more quickly from natural disasters (Kahn 2005, Noy 2009). Felbermayr & Gröschl (2014) hypothesize that safer property rights in democracies encourage foreign and domestic investment, which speeds up recovery after a disaster, and Kellenberg & Mobarak (2011) that governments in democracies are more accountable for disaster preparations and postdisaster assistance. Besley & Burgess (2002) show that (democratic) state governments in India are more responsive to extreme rainfall conditions where newspaper circulation, political competition, and electoral accountability are larger. In Section 4.3, I return to other aspects of the political economy of government adaptation policy.

4. GOVERNMENT ADAPTATION POLICY: PUBLIC VERSUS PRIVATE ADAPTATION

Economic development is not a sufficient condition for climate resiliency. **As economies grow, exposure to climate extremes might increase if people and economic activity move to poorly planned urban centers in vulnerable coastlines (Glavovic et al. 2022).** Effective adaptation is not automatic, either; it requires knowledge of the risks and potential mitigating actions, resources for implementation, coordinated planning, and foresight (Fankhauser 2017).

The Sendai Framework for Disaster Risk Reduction recognizes that the state has a primary role in reducing disaster risk, but that responsibility should be shared with local government, the private sector, and other stakeholders (UNDRR 2015). Moreover, given the international transmission of disaster impacts and responses, adaptation can be conceptualized as a multilevel public

good with domestic, transboundary, and global dimensions (Banda 2018, Persson 2019, Carter et al. 2021).

National governments are critical to providing public goods related to risk management (e.g., flood risk protection through infrastructure, early warning systems) and are responsible for much of the public infrastructure and assets at risk (e.g., bridges, roads). They control budgetary allocations, and through disaster relief they are often the insurer of last resort (Priest 1996). Through institutional arrangements, policies, and regulations they create the environment in which other stakeholders make decisions (Lal et al. 2012). An important role of public policy in this regard is to facilitate effective private adaptation by incentivizing the right actions and removing potential distortions (Fankhauser 2017).

Most countries in the world have established adaptation plans, strategies, laws, and policies to implement actions such as those depicted in **Figure 2**. However, the financing of adaptation actions in developing countries is 5–10 times below the estimated need, and the adaptation gap is widening (UNEP 2022). Prioritizing adaptation actions becomes necessary, but it is difficult. First, their efficacy is hard to assess because adaptation responses are frequently motivated by both climatic and nonclimatic drivers simultaneously, and they interact with other socioeconomic processes (e.g., urbanization, economic growth) that also affect risk (O'Neill et al. 2022). Measuring adaptation is difficult, as there are no common reporting systems, and many actions that reduce climate risk may not be labeled as climate adaptation (Lempert et al. 2018). Second, adaptation decisions are made in a context of ambiguity or deep uncertainty, as the scientific uncertainty in climate models is particularly acute for spatially and temporally localized climate extremes. In this context, the expected utility framework may be of limited use (for an overview of alternative decision frameworks, see Heal & Millner 2014 and Fankhauser 2017).

4.1. Provision of No or Low Regrets Adaptation Public Goods

No regrets and low regrets adaptation options are recommended when uncertainties over future climate change directions and impacts are high. Although they may not be optimal for every future scenario, they provide benefits under any range of climate change scenarios (Lal et al. 2012). Prominent among them, ecosystem-based adaptation harnesses nature-based solutions (NbS) and ecosystem services to protect communities from climate extremes.

One example of NbS is mangrove forests, which protect 3.5 million people and GDP worth roughly US\$400 million (Blankespoor et al. 2017). The 1999 super cyclone that struck Orissa, India caused fewer fatalities in villages with wider remaining mangroves than in villages with narrower or no mangroves, even though all villages benefited from early warnings (Das & Vincent 2009). Another NbS, coastal wetlands, reduced the property damage caused by 88 tropical storms and hurricanes between 1996 and 2016 in the United States by an average \$1.8 million/km² per year and a median value of \$91,000/km² (Sun & Carson 2020). Across the entire continental United States, each hectare (0.01 km²) of wetlands provided flood-protective services on the order of \$1,840 per year between 2001 and 2016 and more than \$8,000 in developed areas (Taylor & Druckenmiller 2022). In the Gulf of Mexico, three NbS (restoration of wetlands, barrier islands, and oyster reefs) would reduce flood risk cost-effectively, yielding average benefit-cost ratios above 3.5, with the combination of NbS and conventional (also known as gray) infrastructure being most cost-effective (Reguero et al. 2018). Tree canopy in cities reduces daytime urban air temperature (Edmondson et al. 2016), which in turn can reduce heat-related mortality (Kalkstein et al. 2022).

In addition to disaster risk reduction, NbS provide benefits such as carbon sequestration, air and water purification, soil erosion prevention, and recreation, and it is often argued that NbS could outperform defensive gray infrastructure (such as levees) if all their benefits were considered. Few

studies, however, provide full economic or social evaluations of NbS, and analyses that explicitly compare NbS to conventional, gray measures are rare (Nelson et al. 2020).

A second example of a no regrets or low regrets adaptation strategy by national governments is early warning systems. They facilitate emergency preparedness to forecastable and actionable hazards, benefiting more than 5 billion people worldwide (New et al. 2022). Two recent studies suggest that the benefit-cost ratio of improving weather forecasts is well above one. Molina & Rudik (2022) report that improvements in short-term hurricane forecasts in the United States over the period 2007–2020 reduced damages by 19%, approximately \$5 billion per hurricane. Shrader et al. (2023) show that, in the United States in the period 2005–2017, improving the accuracy of routine weather forecasts by 50% would reduce mortality from temperature by 2,200 lives, thus generating a net value of \$2.9 billion per year, of which \$0.8 billion reflects adaptation to climate change. Although most of this value comes from warm and cool days that are much more common than extreme heat or cold days, mortality risk responds to forecast errors most strongly on extreme heat days (either because adaptation is more responsive or more consequential for mortality in extreme heat).

4.2. Facilitating Effective Private Adaptation

Early warning systems can reduce mortality and other damages only if people respond to them, for example, by predeploying emergency power generation or evacuating. In fact, effective climate risk management cannot happen without household-level adaptation (Van Valkengoed & Steg 2019). Here, public policy can facilitate private adaptation by addressing market failures and behavioral barriers in a context in which individuals make decisions under risk and uncertainty. Insurance is a prime example.

It is well known that because damages from climate disasters are fat tailed and spatially correlated, climate risks cannot be pooled and are difficult to hedge, prompting governments to intervene in disaster insurance markets to guarantee availability and/or affordability of insurance coverage (Kousky 2022). In 2022, the global protection gap (i.e., the disaster losses not covered by insurance) was approximately \$151 billion (Banerjee et al. 2023). As damages from climate disasters increase, there is some evidence that private insurers are retreating from areas of high wildfire and hurricane risk (Dixon et al. 2018, Botros 2023), a trend that will accentuate governments' participation in insurance markets or as the insurer of last resort.

Government interventions can lessen the financial and economic repercussions of disasters but should be carefully designed so that financial markets correctly price climate-related risks to encourage ex ante risk management (Bolton et al. 2021). For example, an increase in insurance premiums to reflect increasing climate risks could be complemented with means-tested voucher programs coupled with loan programs for investments in hazard mitigation to address affordability (Kousky & Kunreuther 2014). In addition, smart policy should acknowledge the heuristics and biases that guide individuals' decision making regarding low-probability/high-impact climate risks (Kunreuther & Botzen 2022). Meyer & Kunreuther (2017) recommend using the principles of choice architecture in the design of measures that accept these biases as part of the choice process (e.g., bundling several low-probability risks into a single insurance policy, expressing disaster probabilities over longer time horizons, or using default options). Implementation of this type of choice architecture measures remains limited, however, and studying their effectiveness is an open area of future research.

Relocation often emerges as an alternative when other forms of adaptation are insufficient (Cattaneo et al. 2019) but also as a forward-looking adaptation strategy that substantially reduces the spatial variance in the welfare impacts of climate change (Bilal & Rossi-Hansberg 2023). As

discussed in Section 2.4.1, vulnerable populations may be involuntarily trapped in hazardous areas and require government interventions to continue living in exposed locations or to remove obstacles to a safe and orderly migration (Cissé et al. 2022). The effects of natural disasters on migration, and particularly of how government interventions can facilitate successful migration outcomes, are promising areas of research.

The empirical study of individuals' optimal adaptation is complicated by the endogeneity of risk perceptions, risk preferences, and disaster risk itself: Decisions regarding where to live, whether to purchase insurance, and other concurrent adaptive actions are influenced by risk perceptions and risk preferences, with implications for climate risk capitalization in housing markets. Hedonic pricing studies report much variability on the effect of flood risk on house prices (Beltrán et al. 2018). Hino & Burke (2021) find that in the United States flood risk information is not fully capitalized into property values—more sophisticated commercial buyers and risk-aware buyers respond more to flood risk information—which suggests that better risk communication could improve the efficiency of market outcomes. The prices of properties at risk have been found to fall after flood events, suggesting that floods provide new information that updates flood risk perceptions, but the effect is short-lived, consistent with an availability heuristic (Atreya et al. 2013, Bin & Landry 2013). In addition to the availability of information, differences in the degree of capitalization of climate risks reflect heterogeneity in beliefs about long-run climate change risks (Baldauf et al. 2020). Underestimation of such risks and sorting based on risk perceptions and amenity values can result in a significant overvaluation of vulnerable coastal properties (Bakkensen & Barrage 2022).

Risk perceptions and preferences not only are difficult to measure but, along with time preferences and prosocial behavior, can be affected by disasters (Brown et al. 2018, Schildberg-Hörisch 2018). This is an active and contested area of research,¹³ with important practical policy implications, as the findings that risk perceptions and preferences may not be stable suggest that, after a disaster, there may be a window of opportunity to encourage adaptation behaviors, including the support of adaptation and GHG mitigation policies (Bakkensen & Conte 2022).

In a meta-analysis of factors motivating individual climate adaptation, Van Valkengoed & Steg (2019) report that experiencing a natural hazard is moderately, positively associated with adaptation behaviors, which include preparatory action (e.g., buying an emergency kit), evacuation, buying insurance, information seeking, and policy support. But the authors also show a large heterogeneity between studies, highlighting that the effects of climate proximity on individual adaptation are more complex than commonly assumed (Brügger et al. 2015). In addition, the window of opportunity may be closing more rapidly as climate disasters become more commonplace. Temperatures initially considered remarkable become unremarkable (as captured by social media posts) with repeated exposure over roughly a 5-year time scale, suggesting a social normalization of extremes, but not adaptation, as disasters continue to induce negative sentiments (Moore et al. 2019).

4.3. Preventing Policy Failure

Existing (limited) evidence on the net benefits of specific adaptation measures suggests that they are efficient, with benefit-cost ratios of about four (Mechler 2016). The even scarcer evidence comparing the effectiveness of ex ante hazard mitigation and ex post public assistance programs suggests that the marginal return per dollar invested in ex ante mitigation programs is larger than

¹³Chuang & Schechter (2015) review research on the effect of natural disasters on risk and time preferences and prosocial behavior and report conflicting results along every dimension of preferences.

that of investing in recovery; Davlasheridze et al. (2017) find it to be double, which contrasts with a much lower allocation of federal monies to hazard mitigation (on the order of 1-to-4). A political economy explanation is that voters are myopic: They hold elected officials accountable for actions taken after a disaster but not for preparedness. Benefits of relief spending are highly salient, immediate, and attributable to the incumbent, but benefits of preparedness are difficult to observe and not immediate, which leads to public underinvestment in risk reduction (Healy & Malhotra 2009).

Investments in disaster relief and mitigation may not reach those who most need it (Noy et al. 2021) and may respond to additional political considerations. Garrett & Sobel (2003) show that in the United States, politically important (so-called battleground) states and those with greater representation in committees overseeing FEMA had more disasters declared between 1991 and 1999. Following floods in India, Parida (2020) shows that fatalities are lower in states whose governments are politically aligned with the central government and in election years.

Because adaptation responses often involve agents at different decision levels (local, regional, national, and even international), coordination is required to avoid incentive misalignment and moral hazard across jurisdictions. Such misalignment could happen, e.g., when a local government implements a policy designed for short-term economic growth by encouraging development in hazardous areas without fully internalizing the risks, as it can rely on federal aid if a disaster strikes (Bagstad et al. 2007). Liao & Kousky (2022), for example, show that California municipalities are insulated from the costs of wildfires. For a review of the politics of climate change adaptation, see Dolšák & Prakash (2018).

5. CONCLUSIONS

Record-breaking disasters caused by extreme weather and climatic events have become the new normal. Research on the economic costs of past disasters and on the factors that mitigate those damages can help to better prepare for and cope with current and future climate extremes. Much of this research has relied on country-level analysis of global disaster data sets and has generally found that disasters have a negative effect on economic growth in the short term. Few studies have analyzed long-term impacts, spatial spillovers, the cumulative impacts of multiple smaller climate extreme events, or the implications of relaxing the linearity assumption implicit in OLS estimations, and these remain open areas for future research. Incorporating the results from reduced-form empirical models of disaster impacts into structural general equilibrium models of the economy is another promising area of research.

Wider availability of high-resolution hazards data and advances in remote sensing have improved how we model exposure and, to some extent, vulnerability to natural hazards. However, more systematic collection of spatially referenced high-frequency household (and firm) surveys that include questions specific to the impacts of climate extremes would enable further study of their distributional implications (across space, economic sectors, and income groups) and, especially, their impacts on the poor, which are underrepresented in macroeconomic indicators such as GDP per capita.

Past studies consistently show that recovery from disasters is faster and fatalities and damages smaller in countries with higher incomes and better governance, indicating a strong link between adaptation and economic development. Adaptation, which in the context of climate extremes involves effective disaster risk management, does not happen automatically, however. Governments play an important role through the provision of public goods, such as defensive (conventional or nature-based) infrastructure or early warning systems, and through the implementation of public policy that, ideally, facilitates effective private adaptation.

The opportunities for future research on the valuation and assessment of disaster risk-management options are enormous. Existing benefit-cost analyses suggest that the benefits outweigh the costs, particularly in the case of ex ante risk mitigation programs, but the evaluation of adaptation actions is notoriously difficult for at least the three following reasons that represent avenues of future research.

First, causal identification is hindered by data availability and endogeneity. Adaptation actions are not randomly distributed; they depend on the underlying hazards, on exposure and vulnerability, and on individual and societal preferences, all of which may in turn be affected by climate disasters and risks in ways that are not yet well understood. Longitudinal research designs that study actual adaptation actions and research designs with granular spatial data that exploit exogenous variation in adaptation actions, e.g., across administrative boundaries, would be helpful.

Second, evaluation of the efficiency of adaptation actions requires a comprehensive assessment of their costs and benefits. Most studies on the economic costs of climate extremes focus on the effects on income or aggregate output. More attention should be paid to the quantification and monetization of all the effects of disasters on welfare, notably those on human life and suffering and ecological services. A full accounting of net benefits of adaptation actions extends to their so-called cobenefits or ancillary benefits, which can be considerable in the case of ecosystem-based adaptation or nature-based solutions.

Third, decisions about adaptation to climate extremes are made in a context of deep uncertainty under which conventional decision-making approaches such as benefit-cost analysis are inadequate. At a micro level, individuals' decisions with respect to low-probability, high-impact events are plagued with cognitive biases and behavioral failures that tend to preclude optimal adaptation. Governments can facilitate effective private adaptation by designing policies that correct market failure and cater to individuals' biases and heuristics. The adaptation by individuals and how public policy can incentivize optimal adaptation are other promising areas of research.

This review must end with a disclaimer and on a cautionary tone. The empirical literature covered here analyzes the impacts of climate extremes observed in the last four or five decades, but the worst may be yet to come, particularly if global warming triggers climate tipping points. Moreover, the literature reviewed here estimates marginal impacts of observed disasters using statistical methods that assume linearity, and in drawing lessons from its findings, it implicitly assumes stationarity of socioeconomic and climatic systems. In a world of increasing climate extremes and fat-tailed distributions of damages, economic research that relaxes these assumptions is important and urgent.

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