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Climate Change Impacts on Public Finances Around the World

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Abstract

This article reviews a rapidly growing literature on how climatic risks and events affect public finances around the world. This literature includes empirical evaluations of how past climatic events have affected fiscal outcomes, empirical and model-based assessments of how climatic risks affect public borrowing costs, and macro-fiscal-climate models that investigate the policy and welfare implications of fiscal climate risks. This article highlights five stylized facts that emerge from this literature and points to important knowledge gaps for future research. Key findings include the facts that (i) the fiscal costs of climatic risks are economically significant overall, (ii) lower-income and credit-constrained regions are especially vulnerable and poorly insured against growing climatic fiscal risks, but that (iii) fiscal policy responses to climatic risks can mitigate their economic impacts substantially.

JEL-Codes: Q540, H200, H500, H600, H700, H840.

Keywords: climate change, fiscal costs, public budgets, sovereign debt, natural disasters, climate adaptation, social cost of carbon, integrated assessment.

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1 Introduction

How will climate change affect public finances around the world? While both governments and financial markets appear increasingly concerned about climate change's impacts on public budgets, these fiscal impacts have been much less studied compared to other sectors. Indeed, a recent conference poll among finance ministry representatives revealed that many countries have not yet assessed their fiscal vulnerability to physical climate change with many citing a lack of data, empirical tools, and modeling frameworks as hindrances (CFMCA, 2024). By the same token, standard models and approaches used to quantify the social costs of carbon emissions generally do not consider fiscal effects and their broader macroeconomic consequences.[1] Climate economists' limited focus on the public sector is perhaps even more surprising in light of its economic significance, both for aggregate outcomes (with government consumption expenditure accounting for around 17% of world GDP[2]) and for inequality and the distribution of resources.

This article surveys some of the most relevant evidence on what is known about potential fiscal impacts of a changing climate. The evidence base on this topic is rapidly evolving: most of the core studies reviewed in this article have been published or posted in the past two years (2022-24). The literature we review includes four main types of studies. First, a substantial number of empirical studies have assessed how *past* climatic events have affected fiscal outcomes at both the national and sub-national levels. A second strand of literature combines such ex-post assessments with climate model output to gauge the fiscal impacts of past or future climate change. A third strand of the literature evaluates whether public borrowing costs are affected by climatic risks using both empirical and model-based frameworks. Finally, a nascent literature introduces climatic risks into quantitative macro-fiscal models to gauge the welfare impacts of both future climate change and competing policy responses thereto.[3] Before reviewing the literature in more detail, we highlight five "stylized facts" that emerge from its reading:

1. Adverse climatic events often lead to increases in public expenditures, especially in jurisdictions with high incomes and/or good access to credit. In lower-income and financially constrained areas, however, this counter-cyclical response often seems muted.

[1] For example, neither benchmark integrated assessment models such as DICE (Barrage & Nordhaus 2024) or FUND (Anthoff & Tol 2013), nor modular approaches such as GIVE (Rennert et al. 2022) model fiscal impacts and their macroeconomic feedback effects.

[2] Global average (2017-22) for general government consumption expenditure from World Bank data.

[3] A number of scholars have also produced more stylized or review-based assessments of climate change's potential fiscal impacts, including some early literature (e.g., Heipertz & Nickel 2008; Egenhofer et al. 2010; Osberghaus & Reif 2010) and some recent work such as the assessment of debt sustainability and climatic risks in the EU by Gagliardi et al. (2022).

2. Adverse climatic events are also typically associated with stagnant or declining own-source public revenues, often resulting in increased in budgetary deficits. While intergovernmental transfers *can* provide insurance and offset local costs, they do not necessarily do so, especially in lower-income regions.

3. Adverse climatic risks and events have repeatedly been shown to increase public borrowing costs, especially for regions that are poor and/or already credit-constrained. These credit market impacts may trigger a vicious cycle where regions are limited in their ability to support economic recovery after adverse events, resulting in larger output losses, which, in turn, further degrade a government's ability to borrow.

4. Fiscal actions - ranging from improved risk-sharing to efficient financing of adaptive expenditures - can substantially mitigate the welfare costs of climate change.

5. Fiscal impacts, in turn, can substantially affect both the magnitude and distribution of climate change's economic effects, and may thus constitute an important omission in traditional measures of the social cost of carbon.

Despite the value of these general findings, important knowledge gaps remain. For example, more structural work is needed to inform welfare and policy implications. That is, while the (more common) reduced-form approaches provide invaluable insights, when it comes to fiscal outcomes, the mapping to welfare can be particularly complex. For instance, a flood increasing budget deficits could reflect both a strong counter-cyclical spending response or a decline in revenues from eroded taxbases or a decline in revenues from temporary tax relief, the overall welfare effects of which would not only differ but further depend on how the deficit is financed. Assessing the fiscal impacts of slow-moving climate hazards such as sea level rise may also necessitate the development of structural dynamic models.[4] New ideas for policies that can mitigate climate change's fiscal impacts - which are urgently needed - may also require a broader set of approaches, such as structural models or field experiments, for testing and evaluation. Another limitation of the literature to date has been its geographic focus, displayed in Figure 1. Comparatively less research has considered some of the most climate change-vulnerable and fiscally constrained countries. Indeed, a Poisson regression of the number of studies per country on GDP per capita (PPP-adjusted in 2023), a sovereign bond ratings-based measure of fiscal space (from Kose et al. 2022), and climate change vulnerability (proxied by future mortality impacts from Carleton et al. 2022)

[4] Some studies relate future sea level rise to the present-day budgetary importance of property tax revenues in different locations (e.g., Shi & Varuzzo 2020). However, future housing prices are expected to change differentially between vulnerable and non-vulnerable homes (e.g., Bakkensen & Barrage 2022). Section 4 discusses CGE-model evidence from Parrado et al. (2020).

suggests that fiscally constrained countries have received signifcantly less attention in the literature to date. More (specific) work on vulnerable emerging market economies is thus needed. Finally, the fiscal impacts literature may benefit from deepening connections to the broader climate impacts literature which has documented effects on many fiscally relevant variables ranging from mortality (e.g., Carleton et al. 2022) and migration (e.g., Cruz & Rossi-Hansberg 2023) to labor supply (e.g., Somanathan et al. 2021). How these changes will ultimately affect fiscal outcomes has yet to be formalized. This literature has also increasingly documented the relevance of general fiscal programs, such as income support and public health, for households' vulnerability to climatic shocks (e.g,. Adhvaryu et al. 2024; Cohen & Dechezleprêtre 2022; Fried 2021; Mullins & White 2020). Integrating these broader feedbacks into fiscal-climate frameworks is yet another important frontier for further study.

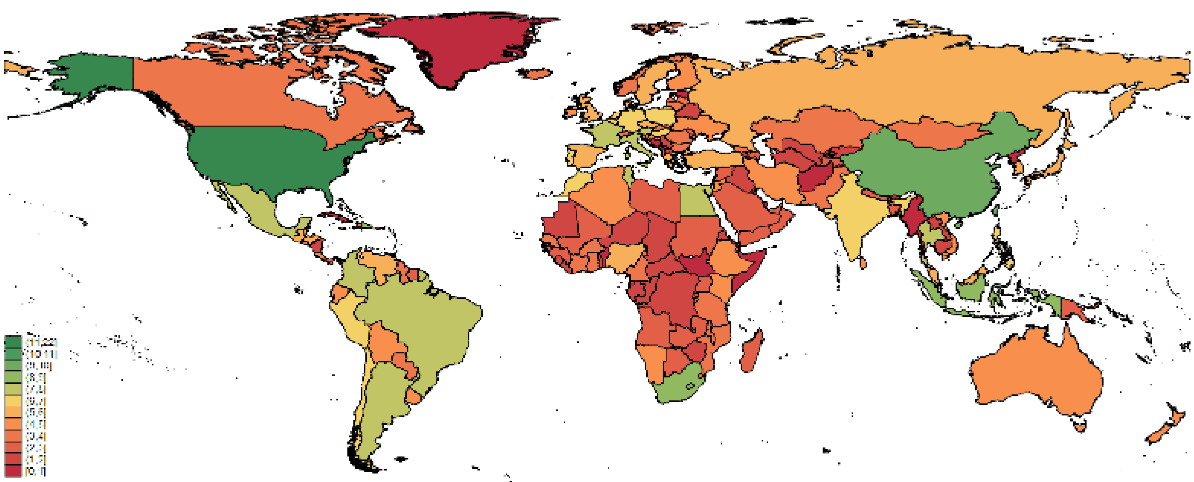

Figure 1: **Number of Studies by Country.** Figure displays number of studies surveyed in this article which include data from or focus on a given country.

The remainder of this article proceeds as follows. Section 2 describes empirical studies of how climatic events affect public expenditures, revenues, deficits, and/or program costs. This discussion is divided into cross-country studies, sub-national studies, and studies that incorporate future climate change projections. Section 3 summarizes how either past climatic events or future risks affect public borrowing costs and bond markets. Section 4 discusses some of the newer macro-fiscal-climate models, and Section 5 concludes.

2 Empirical Analyses of Climatic Events and Public Budgets

2.1 Historical Cross-Country Studies

A first generation of empirical cross-country studies provided early evidence for both the significant potential magnitudes and fundamental heterogeneity in the fiscal impacts of (climatic) natural disasters.[5] As this literature focused on natural disasters in general rather than on climate change in particular, many studies constructed broad measures of disaster exposure, often relying on the EM-DAT database of disasters around the world[6]. While there are some limitations associated with this database, as discussed below, we begin by summarizing some of this early literature.

Noy & Nualsri (2011) study the impacts of large natural disasters on select fiscal variables among 42 countries. They create an indicator for "large" disasters based on estimates of direct damages (from EM-DAT) normalized by lagged GDP, specifically based on a +2 standard deviation realization of damages. The paper's main findings are twofold. On the one hand, developed countries respond to large disasters in a counter-cyclical fashion: upon impact, revenue collection falls (by -1.27% of GDP), public spending may increase, and outstanding debt increases (by a cumulative 8% of GDP over a year and a half). On the other hand, developing countries appear to exhibit a more pro-cyclical response, with lower public spending, mixed effects on revenues, and no detectable increase in debt outstanding, though these effects are estimated with limited precision.

Next, Melecky & Raddatz (2011, 2015) use a similar research design but with a focus on 77 middle- and high-income countries and a different definition of "large" disasters.[7] Their results are nonetheless similar in that higher-middle income countries increase public expenditures in response to climatic disasters, whereas, in lower middle-income countries, the authors fail to detect an increase in public expenditures whilst public revenues fall. Importantly, they also document heterogeneity based on countries' financial market development, proxied by the average ratio of private credit to GDP. In financially developed countries ($\geqslant$75th percentile), climatic disasters result in precisely estimated increases in public expenditures and public deficits. In contrast, in financially less developed countries ($\leq$25th percentile), the authors fail to detect a significant increase in expenditures or budget deficits

[5] While the question of natural disasters' fiscal impacts is not new (Deryugina 2022), we review these studies due to their relevance and to highlight recent advances.

[6] This database is maintained by the Center for Research on the Epidemiology of Disasters (CRED).

[7] They count events that (i) affect at least 0.5% of the population, (ii) cause damages of at least 0.5% of GDP, or (iii) kill at least 1/10,000 people.

in response to disasters, potentially consistent with limited access to financial markets inhibiting public recovery expenditures.

Not all studies find such clear impacts. For example, Kose et al. (2022) also use EM-DAT data to evaluate how large disasters - defined here as those with estimated direct damages exceeding 1% of GDP - affect different measures of countries' fiscal space. They generally fail to detect significant effects. Lis & Nickel (2010) similarly find precisely estimated negative effects of "large" disasters on budget balance among some country groups but not others. There are several reasons why these types of studies may find divergent and imprecise results, however. First, studies differ in how they define "large" disasters, so that the same country-year may be assigned "treatment" status by some but included in the "control" group by others. Second, these studies typically estimate an average treatment effect across multiple disaster types (e.g., floods, wildfires, extreme temperatures) which may in reality induce very different fiscal impacts. Indeed, using EM-DAT data, Acevedo (2014) finds that storms and floods have *opposite signed* impacts on public debt-to-GDP growth rates (among 12 Caribbean countries). Finally, some general features of EM-DAT data add challenges in this context as, for example, selection into the database depends on disaster impact severity and the presence of reporting institutions, both of which may be endogenous to fiscal conditions. EM-DAT coverage also varies across countries and time. For the specific purpose of quantifying how climate change affects public finances, there is thus clearly value in complementing this literature with more precise meteorological measures of climatic events.

An early such study by Ouattara & Strobl (2013) investigates the impacts of hurricanes on fiscal outcomes in Caribbean countries. Their disaster exposure measure - a hurricane wind damage index - is based on meteorological observations and a wind field model. They find that hurricane strikes (of Saffir-Simpson Scale 3 and above) (i) increase government spending economically and statistically significantly (by +4.2% on impact), (ii) do not appear to affect public revenues significantly (with point estimates close to zero), and (iii) decrease budget balance significantly. Outtara et al. (2018) revisit this question with higher frequency data and an updated hurricane measure. Here they find that fiscal revenues fall contemporaneously with the storm - specifically by 8 cents per 1 dollar of estimated hurricane damages. The authors also note that the sample frequency of hurricane strikes may not capture the hurricane risk a location faces. Fitting probability distributions to estimate country-specific risks, they again document substantial potential effects (e.g., with a 20-year return period, Anguilla may expect fiscal revenue losses of 9% from storms).

Some recent literature has also moved beyond conventional measures of disasters to consider broader climatic outcomes such as temperature anomalies. Kunawotor et al. (2022) find that, in a sample of 30 African countries, a +1°C increase in annual temperatures above the long-term mean is associated with a 1.1 percentage point decrease in budget balance (in % of GDP).[8] Giovanis & Ozdamar (2022) similarly find that warmer temperatures significantly decrease budget balance and increase debt-to-GDP ratios in a sample of 17 middle eastern and north African (MENA) countries (with a +1°C increase associated with around a +2 percentage point increase in debt-to-GDP ratios). Fuje et al. (2023) similarly estimate that exposure to a drought during the crop-growing season decreases government revenues by 0.5 percent of GDP on average in a sample of 164 countries. This effect appears to be driven by emerging markets where revenue losses amount to 0.7 percent of GDP.[9]

A very recent study by Akyapi et al. (2024) illustrates how far the literature has come in connecting to climatic data. Akyapi et al. (2024) investigate the fiscal and GDP impacts of weather shocks in an analysis that considers more than 164 weather variables - measured at the grid-cell level from reanalysis data - and uses machine-learning (LASSO) methods to select the most relevant among them. For explaining GDP growth, the chosen variables are (i) the population-weighted share of grid-days with harsh drought conditions, (ii) the population-weighted share of grid-days with maximum daily temperatures exceeding 35°C, and (iii) the share of grid-days with average temperatures between 9-12°C. For the analysis of fiscal outcomes, they add the first additional variable selected for each fiscal outcome by LASSO. These include a lagged measure of cold waves (for revenues) and a measure of precipitation (in wet days and the driest month). The results overall point again to a counter-cyclical fiscal response to adverse weather conditions (on average across countries). For example, increases in harsh drought conditions are associated with significant increases in public expenditures, whereas increases in hot days or decrease in mild temperature days are associated with declines in public revenue collections not solely driven by the associated declines in GDP. The results also suggest that, on average, public expenditures and debt-to-GDP ratios increase as a result of lower precipitation. Whether and how these responses differ across countries remains, however, an open question.

2.2 Historical Within-Country Studies

While cross-country studies offer broad global coverage, their high level of aggregation may obfuscate important local impacts, and data availability may also limit the set of fiscal outcomes that can be analyzed. A susbtantial literature has thus studied the impacts of climatic events on fiscal outcomes across sub-national regions. This section summarizes

[8] For reference, they also consider meteorological and climatic disaster indicators from EM-DAT, and find that "large" disasters (defined as in Lis & Nickel 2010) are on average associated with a smaller impact on budget balances (-0.44 percentage points) than temperature anomalies.

[9] The authors fail to detect a significant effect of droughts on expenditures. They also consider floods and storms based on EM-DAT data, but generally find smaller and less precisely estimated impacts.

some of these studies, organized by region.

2.2.1 Americas

The United States is arguably the most widely studied country when it comes to fiscal impacts of climatic events (see Figure 1). A pioneering analysis by Deryugina (2017) studies the impacts of hurricanes - measured based on meteorological hurricane track data and estimated maximum wind speed radius - on total government transfer flows across U.S. counties. She finds that hurricane strikes trigger not only disbursements of disaster assistance but also substantial increases in general social safety net transfers (e.g., unemployment insurance), which are estimated to increase by 1.3-3.9 percent in the 10 years following a storm. Increases in public health benefits ($300-600 per capita in present value terms, $2013) account for the largest share of the estimated total transfer increases ($780 - $1,150 per capita). These social safety net transfers notably also vastly exceed the value of direct disaster assistance ($180 per capita on average). In a similarily structured analysis focused on the effects of temperature extremes, Barrage (2024) finds that even just one additional very hot day (with average temperatures $\geq 32°C$) per year increases U.S. counties' total annual public health expenditures by up to +0.3%.

Another strand of the literature considers climatic event impacts on local fiscal aggregates. Miao et al. (2018) investgiate the effects of natural disasters at the U.S. state level, where disasters are measured based on estimated economic losses from the SHELDUS database. Similar to EM-DAT, this database has the advantage of providing estimated losses for many types of disasters, but also some well-known limitations in terms of coverage (Gallagher 2023). They find a significant increase in state-level public spending, specifically a cumulative 5-year effect of +0.2% of gross state product (GSP) per +1 percentage point increase in disaster damages relative to GSP. They also find an increase in federal-to-state transfers that exceeds the estimated spending increases, suggesting effective insurance on average.[10]

A subsequent analysis by Miao et al. (2022) reveals that high- and low-income U.S. counties respond very differently to floods and hurricanes (measured based on Presidential Disaster Declarations): High-income counties increase expenditures, receive increased intergovernmental transfers, and do not experience declines in tax revenues. Low-income counties, in contrast, fail to exhibit significant increases in expenditures or, somewhat shockingly, intergovernmental transfers,[11] but suffer significant declines in tax revenues. In line with this evidence, the authors find that long-term debt levels increase in low-income counties but

[10] Miao et al. (2018) fail to detect significant impacts on debt issuance and overall tax revenues.

[11] The point estimates and standard errors are such that a substantial economic effect can be ruled out with reasonable precision for intergovernmental transfers but not for expenditures.

decrease in high-income counties, as might be expected if low-income counties receive fewer transfers and must thus rely more on borrowing to meet post-disaster needs.

Jerch et al. (2023) add further evidence on both the overall relevance and the regressivity of adverse weather events' fiscal costs. They evaluate the effects of hurricane strikes - measured based on wind speeds - on municipal budgets. Their results imply an approximately 2% decline in municipalities' own-source revenues on average (per 1 standard deviation increase in their hurricane wind speed measure in the 6-10 years after the storm), but that these declines are 1.5 to 2.6 times larger in low socio-economic status municipalities. For expenditure impacts, the results are mixed. Jerch et al. (2023) also document significant and heterogeneous impacts on bond markets as described in Section 3.

As a final example of the U.S. literture, Liao & Kousky (2022) consider the effects of wildfires on municipal budgets in California. They find large increases in expenditures (+17.6% on average over 5 years after a wildfire affecting at least 10% of the local population) driven by spending categories such as public safety and community development. Surprisingly, they also document a sizable increase in municipal tax revenues overall (10.5% in 5 years after a fire) and property taxes in particular (+21.2%). The authors note that this result may be driven by a unique aspect of California law, which delays property tax reassessments until they are sold. As wildfires increase housing market turnover, they may thus increase the property tax base. On net, however, the increase in expenditures dominates, and Liao & Kousky (2022) find that wildfires increase the probability of a municipal budget deficit by 25 percentage points. It is not clear, however, to what extent these results would generalize outside of California.[12]

2.2.2 Asia

Despite its importance both with regards to global population share and climate change vulnerability, comparatively fewer studies have investigated fiscal climate impacts in Asia. This emerging new literature has, however, already derived several important insights. Miao et al. (2020) investigate the impacts of tropical storms, floods, and droughts on province-level fiscal outcomes in China. Each of these climatic hazards is found to significantly increase both public spending (e.g., +5.4 percentage points of the province's GDP in 5 years after severe tropical storms) and central government transfers (e.g., +4.5 percentage points), whereas estimated impacts on provincial tax revenues are small and imprecisely estimated. Strikingly, the authors also find that both expenditure and intergovernmental transfer impacts are larger

[12] Other U.S. studies with a more regional-local focus include Fannin et al. (2012), who investigate fiscal hurricane impacts on northern Gulf coast counties and parishes, and Chen (2020), who studies natural disasters within New York state.

in higher-income provinces, echoing results from the United States (Miao et al. 2022).

Two other recent studies focused on China highlight the relevance of temperatures for local fiscal outcomes. At the county level, Qi et al. (2024) find that extreme temperatures increase public per capita expenditures, with mixed or only imprecisely estimated impacts on revenues, potentially resulting in a worsening of budget balance. For example, just one more day with average temperatures $>32°C$ increases annual per capita public expenditures by $+0.3\%$ (relative to a day with average temperatures betwee 4-10$°C$) and significantly decreases local budget balance. These effects are larger in agricultural counties, where public revenues also decrease significantly in response to heat. The estimated expenditure increases are also large for areas with larger shares of the population aged over 60, potentially consistent with other evidence suggesting health expenditures to be an important impact channel. Qi et al. (2024) also project future warming impacts as dicussed in Section 2.3. At the municipality level, Chen et al. (2024) similarily find that exteme temperatures are associated with significant increases in budget deficits, and that this effect appears to be driven primarily by extreme heat.

In India, evidence on fiscal impacts has also started to emerge. Panwar & Sen (2020) analyze the effects of floods across 24 states, where exposure is measured based on a damages index. The results indicate that floods lead to increases in both public expenditures and intergovernmental transfers. However, these transfers are not sufficient to cover expenditure increases (on average). Given that own-source revenues also appear to decline after flood events, states thus see significant declines in budget balance and increases in debt. A more recent analysis by Suresh et al. (2024) asses how cyclones and floods affect public finances across 25 Indian states using meteorological measures for both events. Their findings again indicate positive impacts of disasters on public expenditures and budget deficits.

Finally, empirical evidence has begun to emerge from other countries as well. For example, Wiyanti & Halimatussadiah (2021) study the impacts of natural disasters on both district and province-level public finances in Indonesia. Their measures of disaster exposure are based on realized damages, such as the number of damaged buildings or length of damaged roads, as recorded by the National Agency for Disaster Management. The main finding is that most natural disaster impacts decrease budget solvency at the district level. At the province level, the estimated impacts are noisier, though there are again clear negative budgetary impacts from climatically sensitive outcomes such as fire damages to forests.

2.2.3 Africa

While there is perhaps the least dedicated work on fiscal climate risks in the African continent, the work that has been done demonstrates the high value of country-specific analyses that consider the local policy context. Notably, Sanoh (2015) documents significant negative impacts of adverse rainfall shocks on municipal fiscal outcomes in Mali. That is, by decreasing agricultural incomes, reductions in rainfall are associated with declines in municipal tax revenues (except in urban areas). Somewhat shockingly, these local revenue losses are also associated with decreases in central government transfers. This result is driven by the fact that the Malian central government in the time period of study (2000-2008) allocated resources to municipalities based on a rule that rewarded higher local revenue collection, ceteris paribus. Sanoh (2015) argues that this was based on a desire to balance equity with incentives for higher local revenue collection, but also the difficulty that this pro-cyclicality of transfers creates for communities that are significantly more likely to suffer consequences such as food insecurity as a result of adverse rainfall shocks.

2.2.4 Europe

While the discussion so far has focused mostly on adverse climatic events, there are of course also parts of the world where climate change is expected to yield benefits such as reduced mortality rates (e.g., Carleton et al. 2022) and lower energy consumption (Rode et al. 2021). Leppänen et al. (2017) provide early empirical evidence that Russia may also experience fiscal savings from warmer temperatures. Using weather station and fiscal data from 78 regions in Russia, they estimate that warmer annual average temperatures are associated with significant declines in public expenditures, especially in colder areas. The population-weighted national average effect implies a 2.6% regional government spending decline per $+1°C$ increase in annual average temperature. The authors also use climate model output to gauage potential overall spending reductions due to warming from 2000 to the mid 2020s as discussed in Section 2.3. Of couse, a caveat to the interpretation of these results is that it is not clear ex ante whether the estimated expenditure reductions represent a reduced need for public spending or a reduced ability to provide public services due to adverse economic effects of warmer temperatures on regions' fiscal space. While triangulation with the broader climate literature would suggest that the former is more likely, these questions illustrate again the challenges that can arise in mapping reduced-form fiscal outcomes into welfare.

Other sub-national studies in Europe include several papers on flooding, which generally find results in line with the broader literature. For example, Unterberger (2017) analyzes how flood (and other hazard) damages to public infrastructure affect municipal budget outcomes in Upper Austria. He finds that damages to public infrastructure significantly reduce contemporaneous municipal budget balance both gross (-0.22% per +1% increase in damages) and net (-0.04% per +1% increase in damages) of transfers.[13]

[13] Lodi et al. (2023) likewise investigate the budgetary impacts of flooding in select municipalities in Italy.

2.3 Climate Change Impact Projections

Most of the papers described so far demonstrate that climatic events can have significant impacts on public finances. Most of these studies do not, however, attempt to quantify the effects of changes in the probability distribution of those events under global warming. Three core challenge arise in moving from retrospective empirical analyses to climate change impact quantification.

The first is the availability of projections of how the risk of a given outcome may change under a different climate. For some outcomes, such as daily average temperatures, there is a wealth of downscaled climate model output available, facilitating such projections. For example, both Giovanis & Ozdamar (2022) and Qi et al. (2024) combine their estimates of how temperatures affect fiscal outcomes (in MENA countries and Chinese counties, respectively) with temperature change projections under different future emissions scenarios to quantify their budgetary impacts. For other climatic risks, such estimates may not be as readily accessible, though the availability of climate risk data is generally increasing. In some cases, the relevant estimates can also be generated through additional processing of climate model output. For example, Bakkensen & Barrage (2021) conduct Monte Carlo simulations of synthetic cyclone tracks under current and future climate from Emanuel et al. (2008) to estimate country-specific Weibull distribution parameters of annual maximum wind speeds under current and future climate, which Barrage (2024) uses to map Deryugina's (2017) estimates of hurricanes' fiscal impacts in the United States into future costs.

A second challenge is accounting for adaptation and other fundamental economic changes that may cause future fiscal vulnerability to climatic events to differ from what is observed in the past. This is a challenge that affects the broader climate impacts literature as well. A third challenge is interpretability. As previously noted, this can be a challenge especially in the fiscal realm, which may be compounded in the context of future projections.

The emerging literature on fiscal climate impact projections has dealt with these challenges in different ways. With regards to adaptation, some studies avoid making long-run projections and seek to align the time horizon over which empirical estimates are made to the one over which climate change is considered. For example, Diffenbaugh et al. (2021) quantify the impacts of *past* climate change from 1991-2017 on payouts of the U.S. crop insurance program, where they infer counterfactual temperatures without anthropogenic warming from climate model output. Leppänen et al. (2017) similarily project the effects of temperature change on regional public expenditures in Russia only from 2000 to the 2020s. Others have borrowed approaches from the broader climate impacts literature to quantify

Their measure of flood exposure is based on receipt of reconstruction funds from the central government, which they find to be associated with increases in municipalities' expenditures.

future adaptation in making longer run projections. For example, Barrage (2024) uses the heterogeneous marginal effects approach of Carleton et al. (2022) to quantify the extent to which the marginal impact of hot temperatures on public health expenditures may decline as U.S. counties adapt to continued warming.

The interpretation challenge has likewise been addressed in different ways. On the one hand, there are a number of studies that project changes in future public expenditures for a given public program or service. To the extent that said program provides a constant level of service, empirically observed changes in program expenditures can be interpreted as changes in the *c*ost of providing a given level of public goods, which have a clearer welfare interpretation than overall changes in public expenditures. For example, Moore et al. (2022) estimate how climate change will alter the fiscal costs of the U.S. Endangered Species Act. The U.S. government in particular has produced numerous careful estimates of how a changing climate may affect the costs of providing public services ranging from hurricane relief (CBO 2016) and urban drainage (EPA 2017) to fire suppression (OMB 2022). Another approach to clarifying interpretation and mapping to welfare has been the integration of empirical estimates into structural models, as dicussed in Section 4. Finally, the next section describes a growing literature that considers climate risk impacts on another specific public sector cost: the cost of public borrowing.

3 Climate Risks and Public Borrowing Costs

A growing literature documents that both past climatic events and future climate risks can increase public borrowing costs. Intuitively, there are several core mechanisms at work. One is that climate-related disasters have been linked to sovereign default episodes both directly (such as in the case of Hurricane Ivan and Grenada's default in 2004, Mallucci 2022) and statistically (e.g., Klomp 2017). As bond yields increase in the probability of default, higher default risk should thus also increase bond spreads (over the risk-free rate). Another mechanism emphasized by Goldsmith-Pinkham et al. (2023) is that climate-induced uncertainty over future economic conditions may also contribute to increases in public bond spreads. Table 1 summarizes some of the key findings of this literature, which showcase the economic significance of climate risks at both the sub-national and national levels. Beyond these overall impact estimates, two sets of "stylized facts" emerge.

First, the capitalization of climatic risks into public bonds is highly heterogeneous across markets. In particular, climatic risks seem to have significantly bigger impacts on public borrowing costs in areas with lower levels of income (e.g., Klomp 2017; Cevik & Jalles 2022, Beirne et al. 2021), lower baseline credit ratings/access (Painter 2020; Acharya 2022;

Klomp 2017), and more disadvantaged populations (Jerch et al. 2023; Jeon et al. 2024). The capitalization of climate risks also apperas signficantly larger for longer maturity bonds (Painter 2020; Acharya et al. 2022). In the municipal context, capitalization also appears higher for bonds backed by less diversified revenue sources (e.g,. Auh et al. 2022; Acharya et al. 2022) as well as in areas that rely more heavily on local property taxes (Goldsmith-Pinkham et al. 2023; Jeon et al. 2024).

Second, the capitalization of future climate risks into U.S. municipal bonds has been increasing over time. Figure 2 showcases how the capitalization of future sea level rise (from Goldsmith-Pinkham et al. 2023), heat stress (from Acharya et al. 2022), and wildfire risk increases (from Jeon et al. 2024) into U.S. municipal bonds has changed over time. Despite being estimated on different samples of U.S. municipalities and measuring risks with very different spatial distributions, all three studies find remarkably similar increases in municipal bond spread responses to future climate risks since around 2014.

Table 1: Climate Risks and Public Borrowing Costs

Study	Geography	Climate Risk	Risk Measure	Impact
1.	31 countries	Past windstorms	Windstorm disaster in EM-DAT (=1)	↑ Emerging markets bond index spread +40%
2.	115 countries	Past storms, floods, droughts	Count of top 10% wind speed, flood, drought events (norm. by country area)	↑ Prob. of debt crisis: storms +4%; ⇝ mixed/insig. for drought, floods
3.	103 countries	Past disasters	Natural disaster in EM-DAT with direct damages at least 1% of GDP (=1)	⇝ Fail to detect significant impcat on sovereign debt rating index
4.	U.S. muni's	Past hurricane strikes	+1 std. dev. hurricane wind speed	↑ Share of bonds rated "high risk" +10-12%
5.	U.S. counties	Past disasters	Meteorological disaster of at least $3 /capita costs in SHELDUS data (=1)	↓ Bond returns -0.31% (4 month avg.)
6.	U.S. counties	Future sea-level rise exposure	+1% GDP loss (from 40cm)	↑ Issuance costs +23.4 bps
7.	U.S. muni's	Future sea-level rise exposure	+1 std. dev. in fraction of homes exposed to 6 ft. sea-level rise	↑ Spreads +5.3 bps (in 2015)
8.	U.S. counties	Future heat stress	+1% GDP loss (by 2080-99) +1 hot day (max temp>37.8°C, by 2080-99)	↑ Spreads +17.2 bps (in 2019) ↑ Spreads +0.29 bps (in 2019)
9.	U.S. muni's	Future wildfire risk increase	+1 std. dev. future wildfire housing stock exposure increase	↑ Spreads +23 bps (avg. 2014-20)
10.	7 Caribbean countries	Future hurricane risk increases	Frequency +29.2%; damages +48.5%	↑ Spreads +95 bps on avg. ↓ Welfare -6.81% to -1.12%
11.	Mexico	Future hurricane risk increases	Intensity +10% (scale parameter of Weibull distribution)	↓ Welfare -0.95%
12.-14	Cross-country	Climate vulnerability, resilience index from ND-GAIN	+1 p.p. vulnerability index +1 p.p. resilience index	↑ Spreads ↓ Spreads

1. Borensztein et al. (2009), 2. Klomp (2017), 3. Kose et al. (2022), 4. Jerch et al. (2023), 5. Auh et al. (2022), 6. Painter (2020), 7. Goldsmith-Pinkham et al. (2023), 8. Acharya et al. (2022), 9. Jeon et al. (2024), 10. Mallucci (2022), 11. Phan and Schwartzmann (2024), 12. Cevik and Jalles (2022) 13. Berine et al. (2021, whose resilience index is from FTSE Russel not ND-GAIN), 14. Kling et al. (2018)

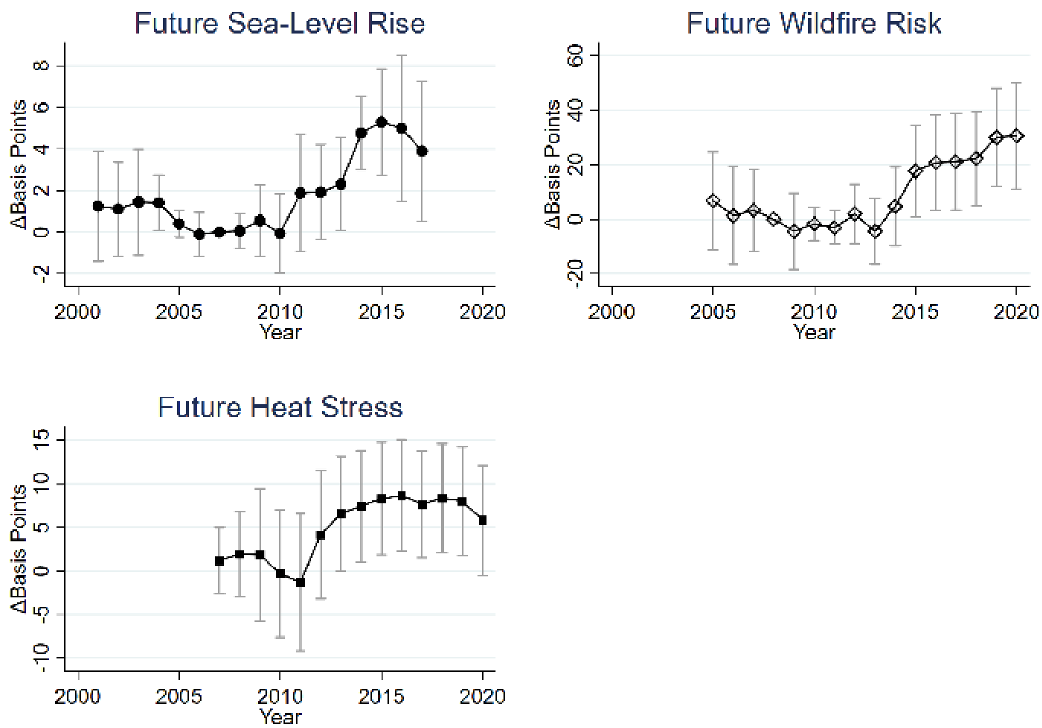

Figure 2: **Literature Estimates of the Capitalization of Future Climate Risks into U.S. Municipal Bond Spreads over Time.** Figure displays estimated coefficients (black markers) and 95% confidence intervals (grey bars) representing the impacts of future climate risks on U.S. municipal bond spreads over time. Sea-level rise estimates are from Goldsmith-Pinkham et al. (2023, Table 2 Col. 3) and repesent the effect of a +1 standard deviation increase in the fraction of homes in a school district exposed to 6 feet of sea-level rise. Wildfire risk estimates are from Jeon et al. (2024, Table 2 Col. 3) and represent the effect of a +1 standard deviation increase in the fraction of homes in a school district at the wildland-urban-interface who will be additionally exposed to future wildfire risk. Heat Stress estimates are from Acharya et al. (2022, Table 3 Col. 4) and represent the effect of a +1 standard deviation increase in a proprietary heat stress index.

The results described so far mainly demonstrate the quantitative importance of climatic risks in affecting public borrowing costs. The next section describes some of the structural modeling studies that consider policy responses to these effects and their potential to mitigate the welfare costs of increasing climate risks.

4 Macro-Fiscal Models with Climate Risk

This section describes a nascent literature that integrates fiscal climate impacts into three types of frameworks: sovereign default models, computable general equilibrium (CGE) models, and dynamic growth models.

4.1 Debt Sustainability and Sovereign Default

Several papers have developed quantitative models of sovereign bond markets and how they might be affected by a changing climate. First, an early analysis by Borenzstein et al. (2009) introduces hurricanes and their estimated fiscal impacts into a simple debt sustainability model calibrated to Belize. They estimate that present-day hurricane risks increase the cone of uncertainty around Belize's future debt-to-GDP ratio. Specifically hurricane risks increase the "worst case" debt-to-GDP ratio in 2020 from 110% to 170%. Importantly, the authors also model the impacts of different levels of insurance such as under the Caribbean Catastrophe Risk Insurance Facility (CCRIF), a cross-country insurance pool. They find that Belize's participation in this insurance (for the optimal coverage limit) reduces the worst-case debt-to-GDP ratio from 170% to 150% in the benchmark case.

Some of the subsequent literature takes a more structural approach in the context of sovereign default models building on Arellano (2008). In these frameworks, which focus on the macroeconomy of borrower countries, the government seeks to maximize household welfare and decides how much to borrow and whether to default on its debt each period depending on stochastic realizations of GDP and, in this new literature, climatic shocks. Governments' costs of borrowing on international markets depend on their probabilities of defaulting on their debt, which, in turn, may increase if a changing climate increases the probability of adverse GDP shocks such as from hurricanes.

Mallucci (2022) quantifies these effects in a study focused on seven Carribbean countries. He introduces hurricane risk into an otherwise standard sovereign default model with long-term bonds. The main results are as follows. First, present day hurricane risk is already estimated to be adversely affecting vulnerable countries' borrowing terms: Without hurricane risks, average Carribbean bond spreads would be 105 basis points lower, and debt-to-GDP ratios would be 15 percentage higher. Second, a stylized climate change scenario (assuming a roughly 30% increase in hurricane frequencies and 50% increase in storm damages) leads to a substantial further deterioration of borrowing terms: On average, spreads increase by 95 basis points, debt-to-GDP ratios decline by 10 percentage points, and default frequencies increase by 0.6 percentage points. The welfare impacts of this climate change scenario range from -1.12% to -6.81%. Interestingly, the distribution of the estimated welfare impacts highlights the importance of fiscal feedbacks: Belize suffers larger welfare losses from climate change (-6.81%) compared to, say, Antigua (-4.05%) even though Antigua faces both a higher hurricane probability and suffers larger GDP losses conditional on a storm. This is because Belize has a higher debt-to-GDP ratio (with and without climate change), so that the increase in borrowing costs constitute an additional impact channel which disproportionately affects Belize. Finally, Mallucci models the potential impacts of two financial innovations: hurricane disaster clauses which either (i) suspend coupon payments for some time - as adopted by Grenada and other countries in recent years - or (ii) provide a debt reduction in case of a storm. These hurricane clauses appear remarkably effective, mitigating the adverse impacts of climate change on countries' ability to borrow and ultimately welfare (by 15% for coupon suspension and 47% for debt reduction clauses, respectively).

Phan & Schwartzmann (2024) revisit these questions in a framework with capital accumulation, an important aspect of macroeconomic dynamics missing in Mallucci (2022) who considers an endowment econoy. They document the risk of a "doom loop" whereby vulnerable countries hit by a climatic disaster may see their sovereign bond spreads increase, reducing the government's ability to borrow exactly at the time when additional capital would be needed for reconstruction, thus exacerbating the GDP losses of the storm, which, in turn, results in further declines in the countries' borrowing terms. In a quantitative application to Mexico, they estimate that these dynamics can delay the country's recovery from a storm by many years, in line with empirical evidence for emerging markets (e.g., Hsiang and Jina 2024) but in contrast to what would be expected in a standard, frictionless Ramsey growth model. Phan & Schartzmann (2024) model the impacts of future climate change through an assumed 10% increase in cyclone intensity (motivated by Atlantic basin predictions by Emanuel et al. 2008). The estimated welfare impacts of this cyclone risk increase amount to a permanent consumption loss of 0.95%. While the authors estimate that actuarially fair (and thus fully adopted) disaster insurance could potentially reduce these welfare losses by 20%, they find a much smaller potential gain associated with catastrophe bonds that would reduce debt outstanding in case of a sufficiently large disaster. The contrast between their result and Mallucci's more optimstic assessment highlight the importance of further work on the potential value of financial innovation and disaster indexing in public debt instruments.

4.2 CGE Models

Several studies have begun to incorporate physical climate change impacts into CGE models with fiscal policy. The examples reviewed below are both "recursive" models, which, in this context, means that even though investment and capital accumulation are modeled, households are not making forward-looking investment decisions. That is, households are assumed to save at an exogenous rate. While this assumption limits models' ability to capture the full dynamic effects of changes in governments' budget balance or capital tax rates, it permits consideration of complexity along other dimensions, such as sectoral disaggregation.

Bachner & Bednar-Friedl (2018) present an innovative integration of 10 climate change impact fields into such a CGE model of the Austrian economy. These impact fields include changes in productivity, costs, and/or demand in sectors such as agriculture, tourism, and electricity generation, but also include changes in government expenditure requirements from natural disaster relief, public park maintenance, and forest management. The authors assume a mid-range climate change scenario with associated mean temperature increase in Austria of around $2°C$ by 2050 over 1981-2010 levels. With tax and debt levels held constant, climate change impacts lower government revenues by -0.3% (through lower production and labor tax revenues) and increases government expenditure requirements (through increased disaster relief and unemployment benefits) by around 1% by 2050. Balancing the budget thus requires either cuts in other public goods and services, increases in other taxes, or increases in debt (which are assumed to be carried forward permanently). The welfare effects of climate change depend critically on this fiscal response, ranging from -0.5% in a transfer payment reduction or capital tax[14] increase scenario to -1.7% in a labor tax increase scenario. That is, the welfare costs of the same climate change scenario vary by more than a factor of three depending on the fiscal response, and, conversely, public budgets are affected non-trivially by even moderate levels of future climate change.

Parrado et al. (2020) integrate sea level rise and the need for publicly financed adaptation thereto into a global CGE model with fiscal policy (ICES-XPS). They specifically assume that both the construction and maintenance of protection against sea level rise is financed through increased regional government borrowing which, in turn, reduces the amount of savings available for private investment and thus capital accumulation. Perhaps surprisingly, however, the main finding is that public investment in sea level rise adaptation is a net gain to public budgets. That is, even though adaptation has to be financed with debt, in the long run government debt levels are lowered by such investments because they protect land, capital, and populations from sea level rise. This protection, in turn, helps avoid output losses that would otherwise have added to public debt levels by decreasing tax revenue collections. While this analysis assumes constant and exogenous interest rates on government debt, accounting further for the fact that higher debt levels may require higher interest payments

[14] The finding of a relatively lower efficiency costs from capital vs. labor tax adjustments contrasts with results in Barrage (2024), who finds the opposite. We conjecture that this is due to Bachner & Bednar-Friedl assuming exogenous household savings rates, whereas Barrage (2024) models households as forward-looking agents whose savings rates respond to capital income tax rates.

would presumably only strengthen the projected value of public adaptation investments that lower long-run fiscal stress, especially in emerging markets. Indeed, Parrado et al. (2020) estmate that the fiscal threat from unadapted sea level rise is highest in China and South Asia.

4.3 Growth Models

Finally, an emerging literature integrates fiscal-climate feedbacks into macroeconomic growth models.[15] Several of these studies (re)consider the question of the dynamic fiscal impacts of publicly financed investments in adaptation. For example, Catalano et al. (2020) set up a small open economy overlapping generations model with fiscal policy and climate change impacts on capital depreciation rates that can be mitigated by publicly financed adaptation. Their main finding is that early public investments in climate adaptation pay off in the long run. That is, while they raise the debt-to-GDP ratio initially, early public adaptation investments increase output and lower public debt in the longer run, in line with the findigns of Parrado et al. (2020). Other new studies in this literature consider climate-induced disaster risks in dynamic stochastic general equilibrium models with fiscal policy. For example, Cantelmo et al. (2023) set up a small open economy model of a country that is vulnerable to disasters which damage capital and productivity. The government can invest in public capital - which enters aggregate production and can also be made resilient to disasters at an extra cost - and finances other expenditures by taxing domestic consumption and by issuing debt to overseas lenders. The authors calibrate the model to an average disaster-prone emerging market using EM-DAT data. The results suggest that climate-related disasters already increase public debt levels and have adverse effects on macroeconomic performance and welfare. A stylized "climate change" scenario yields large additional welfare losses and public debt increases. Finally, the fiscal costs of having to self-finance investments in resilient public capital substantially undercut their welfare gains. That is, the welfare gains from investments in resilient public capital are concave and flatten outquickly if these investments have to be financed with distortionary domestic taxes. In contrast, if such investments are provided even just partly with international grants, they can substantially mitigate the welfare losses from increasing risks of climatic disasters. Subsequent work in this direction, such as Corugendo et al. (2023), have added model richness in dimensions such as tax instruments and financial frictions, and confirm again the economic significance of climatic disaster risk

[15] While a related literature has long used dynamic growth models to study interactions between climate *policy* and other taxes (see, e.g., Bovenberg and Goulder 2002; Goulder Hafstead 2017; Barron et al. 2018), this literature has generally treated climate change impacts as separable utility losses, thus abstracting from their potential fiscal and macroeconomic effects.

for tax revenues and other fiscal and macroeconomic outcomes.

The aforementioned studies focus on small economies, taking the climate and interest rates as given. They also abstract from climate change impacts on the broader set of public expenditure obligations, such as healthcare, that have been documented to exceed the costs of direct disaster assistance and recovery (e.g., Deryugina 2017). A final strand of the literature integrates fiscal policy and impacts into integrated assessment models (IAMs) which fully capture climate-economy feedbacks in large economies. Barrage (2020a) first incorporated fiscal policy into an IAM based on William Nordhaus' seminal DICE framework. Her analysis considered climate change impacts on productivity in final goods production and thus indirectly also tax revenue collections, though this was not the focus of the paper. Douenne et al. (2022) capture this same mechanism in a framework with heterogeneous households, but again, do not focus on fiscal impacts of a changing climate. Barrage (2024), however, develops a fiscal-climate-economy growth model with a rich set of fiscal impact channels, including climate change effects on public health expenditures, other government consumption (e.g,. fire suppression), transfer payments to households, tax revenues via both aggregate productivity and capital depreciation rate impacts, and the possibility of government investment in adaptation to mitigate the effects of sea level rise.[16] The model is emprically quantified for the U.S. economy, and allows the government the choice over a broad set of tools to improve welfare, including carbon pricing to reduce the severity of climate change. The main results are threefold: First, the fiscal costs of climate change appear substantial, with annual costs to U.S. taxpayers already estimated to be around $88 billion per year today (as of 2026). Second, fiscal costs add substantially to the social cost of carbon emissions (around +25-33%), highlighting the quantitative importance of this traditionally omitted impact channel.[17] Finally, consideration of fiscal interactions can substantially increase the estimated welfare benefits of climate policy, by +20-300% depending on the fiscal scenario. This last result echoes the findings of Bachner & Bednar-Friedl (2018) and others that the fiscal response to climate change is a first-order determinant of its welfare costs.

5 Conclusion

Climate change has economically significant but understudied implications for public finances around the world. A rapidly growing empirical literature has repeatedly shown that adverse climatic events, such as windstorms, floods, extreme heat, and insufficient rainfall, can induce

[16] Barrage (2020b) considers direct impacts of climate change on public expenditures as well but with a more stylized framework and quantification.

[17] Subsequent work has begun to confirm this finding in other settings (e.g., Forni & Kiarsi 2023).

substantial increases in government expenditure requirements and potentially also lower revenue collections. While governments on average appear to be able to meet these revenue needs through deficit financing, credit-constrained and lower-income regions often appear less able to do so and thus engage in less consumption-smoothing recovery spending. This dynamic appears exacerbated by the effects of climatic risks and events on public borrowing costs, which appear to be economically significant, increasing, and larger in economically disadvantaged regions. Consequently, the literature has identified the risk of a "vicious cycle" whereby the economic damages of adverse climatic events are exacerbated by their negative feedback effect on public finances. On the bright side, however, this emerging literature also points to the potential power of fiscal policy responses and risk-sharing innovations to substantially mitigate the welfare costs of climate change, though much more research is needed on this topic. Indeed, some governments have begun to engage in enhanced risk-sharing such as through re-insurance of climate-sensitive liabilities (e.g., the U.S. Flood Insurance Program) and the issuance of hurricane-indexed sovereign bonds, but the value of these activities for both current and prospective future users remains an open question. The literature to date has also often focused on the fiscal impacts of events that offer identifying variation econometrically. Fundamental questions remain, however, about how longer-term climate impacts - ranging from sea level rise to migration - affect public finances and thus ultimately welfare. Humanity has looked to government and collective organization for responding to climatic risks going back at least to ancient Mesopotamia. How one of the largest sectors of the mordern global economy - the public sector - is affected by the physical climate risks of the 21st Century should thus be an area for much future study.

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