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To
NBER Climate Finance Workshop Organisers

August 3, 2025

Dear Caroline and Stefano,

I am a penultimate year PhD Economics candidate at the University of Oxford (expected completion date: June 2026), working in the areas of macro-finance and environmental economics. I am very interested in the prospect of attending this workshop.

Please find attached a draft of my Job Market Paper: Climate Change, Adaptation, and Sovereign Risk. Many emerging markets face high natural disaster exposure as well as high borrowing costs due to their susceptibility to public debt crises. In this paper I consider how tight fiscal space affects their ability to adapt to climate change, and so the aggregate costs of natural disasters. The paper develops a framework to integrate climate risk, sovereign risk, and endogenous adaptation as well as a novel database of cross-country adaptation expenditure. I show that emerging market economies suffer from an 'adaptation trap': high borrowing costs restrict adaptation, leading to higher climate damages and borrowing costs in the future.

In ongoing work as part of this project I am studying how debt relief or other financial instruments could alleviate this adaptation trap. I show that default free loans can boost adaptation. I also consider the role for an 'adaptation bond' that explicitly links performance on adaptation goals to coupon reductions. I would be particularly interested in attending the workshop to receive feedback on these counterfactuals which are very much a work in progress.

In other ongoing work I consider the role of policy risk for asset pricing. I construct a new index of firm-level exposure to risks associated with climate policy uncertainty. In another project I model the impact of the Carbon Border Adjustment Mechanism on firm dynamics and environmental outcomes, taking seriously the cost of emissions reporting.

In future I plan to advance my research agenda focusing on the macroeconomic and financial implications of climate change and climate policies. In particular, I am interested in further work on adaptation. On the asset-pricing side I am interested in how the market responds to sovereign and private adaptation investments - are these protective measures priced? On the macro side I am interested in how to create the right incentives for adaptive investments and climate resilience.

My PhD advisors will be happy to provide references:
- Professor Rick van der Ploeg: rick.vanderploeg@economics.ox.ac.uk
- Professor Andrea Ferrero: andrea.ferrero@economics.ox.ac.uk

Thank you for your consideration, I look forward to hearing from you.

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Updated August 3, 2025

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Research Interests

Macroeconomics, Environmental Economics, Finance

Education

University of Oxford Oxford, UK
DPhil Economics 2022 – 2026
Supervisors: Professors Rick van der Ploeg and Andrea Ferrero

University of Oxford Oxford, UK
MPhil in Economics 2020 – 2022
Supervisor: Professor Rick van der Ploeg
Grade: Distinction.

University of Oxford Oxford, UK
BA Philosophy, Politics and Economics 2017 – 2020
Grade: First Class

Working Papers

Climate Change, Adaptation, and Sovereign Risk

Abstract: How costly are natural disasters for emerging markets? I consider this question paying special attention to the role of adaptation and financial frictions limiting fiscal space. A sovereign default model augmented with natural disasters and endogenous adaptation predicts that i) climate change increases borrowing costs, ii) adaptation reduces borrowing costs, and iii) default risk constrains adaptation. These economies suffer from an 'adaptation trap': high borrowing costs restrict adaptation, leading to higher losses from disasters and higher borrowing costs in the future. In order to test these predictions I construct a novel measure of adaptation using text analysis to identify adaptation expenditures in government budgets. Consistent with the model, I document a robust positive relationship between sovereign ratings and adaptation as well as a positive causal effect of cyclone strikes on default risk that is attenuated by adaptation. The sovereign risk- adaptation channel is quantitatively important in the calibrated model. In the Caribbean 10% of GDP losses from cyclones are due to default risk.

Climate Policy Risk: A text-based approach

Under Review.

Abstract: Shifts in climate policy stringency have heterogeneous effects on firms' profitability. Does the market price this risk? This paper provides new evidence on this question, utilising a supervised machine learning algorithm to construct a firm-level measure of climate policy risk exposure. Firms exposed to climate policy risk have negative abnormal returns on climate policy announcement days. I build a set of such dates and characterize abnormal return responses using *Risk Factors* discussions in 10-K filings. The algorithm uncovers predictors of policy risk exposure in the text which are used to construct an exposure score for each firm. This exposure score is correlated with emissions, environmental lobbying behaviour, and is predictive out of sample. Higher exposure is not associated with a premium. Green preference shifts are considered as a mechanism to rationalize this result. I find that empirically identified preference shocks can partly explain the lack of a climate policy risk premium.

Carbon Border Adjustment Mechanisms with Heterogeneous Firms and Fixed Costs
with Martin Bodenstein, Federica Di Pace, Aydan Dogan, and Marco Garofalo.
Abstract: We examine the effects of a levy on the carbon footprint of imported goods—commonly known as the Carbon Border Adjustment Mechanism (CBAM)—within an international trade model featuring heterogeneous firms, following Melitz (2003). In this framework, goods production causes undesirable emissions that firms do not internalize unless subject to a fee, such as a carbon tax or emissions price. When a country implements carbon pricing to encourage abatement, production may shift to countries without similar regulations, undermining the effectiveness of the policy. Our analysis shows that carbon leakage due to production shifting can be mitigated by imposing a goods-specific import levy that increases with the carbon footprint. Although the CBAM does not entirely prevent production relocation, it significantly reduces the carbon content of imports, as foreign firms adopt emission abatement measures to lower their CBAM-related costs. Empirical analysis of reported Scope 1 and 2 emissions indicates that abatement technologies vary across countries. Expanding our baseline model to a three-country setting, we find that a country with superior abatement technology—an environmental comparative advantage—can gain market share in a foreign country when that country introduces a CBAM.

Work in Progress

Disasters and Global Imbalances
with Andrea Ferrero

Market Neutrality and Climate Non-Neutrality
with Anna Carruthers

Honors and

David Walton Scholarship 2025

scholarships

Department of Economics Scholarship (University of Oxford) 2024
Balliol-Oxford Economics Scholarship (Balliol College) 2022
James Hall Scholarship (Balliol College) 2019

Teaching experience

College Lecturer in Economics, University of Oxford 2022-2025
Introduction to Macroeconomics, Macroeconomics, Introduction to Econometrics, Econometrics, Environmental Economics (All Undergraduate)

Presentations

2025: CEPR Climate Change and the Environment Symposium, NYU Climate Finance Workshop, Warwick PhD Conference, IM-TCD Women in Macro Workshop, DIW Women in Macro Workshop.
2024: EAERE annual conference, IEA annual conference, MMF annual conference, Bank of England
2023: Chicago Booth Machine Learning in Economics Summer Institute, HEC Economics PhD Conference, MMF PhD Conference, LSE Environment Day

Experience

PhD Research Intern: Bank of England 2024
Developed a heterogeneous firm trade model with climate policy to examine the potential macroeconomic effects of the Carbon Border Adjustment Mechanism.

Research Assistant to Prof Andrea Ferrero 2023
Provided Research Assistance on a project in international macroeconomics.

Research Intern: Ofcom 2021
Developed an economic framework to consider the effects of a climate change mandate on Ofcom's regulatory activities in the telecommunications sector.

Skills and Other

Programming
Proficient in: R, MATLAB
Familiar with: STATA, Julia

Citizenship: Irish

Peer Review: Macroeconomic Dynamics, Oxford Economic Papers

Membership: Royal Economic Society

Climate Change, Adaptation, and Sovereign Risk

Sarah Duffy*

August 2025

How costly are natural disasters for emerging markets? I consider this question paying special attention to the role of adaptation and financial frictions limiting fiscal space. A sovereign default model augmented with natural disasters and endogenous adaptation predicts that i) climate change increases borrowing costs, ii) adaptation reduces borrowing costs, and iii) default risk constrains adaptation. These economies suffer from an 'adaptation trap': high borrowing costs restrict adaptation, leading to higher losses from disasters and higher borrowing costs in the future. In order to test these predictions I construct a novel measure of adaptation using text analysis to identify adaptation expenditures in government budgets. Consistent with the model, I document a robust positive relationship between sovereign ratings and adaptation as well as a positive causal effect of cyclone strikes on default risk that is attenuated by adaptation. The sovereign risk- adaptation channel is quantitatively important in the calibrated model. In the Caribbean 10% of GDP losses from cyclones are due to default risk.

JEL Classifications: F34, F41, Q54, Q56

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*University of Oxford, Department of Economics: sarah.duffy@economics.ox.ac.uk. I am thankful to Andrea Ferrero and Rick van der Ploeg for their support and guidance. I am also grateful to Elizabeth Baldwin, Martin Bodenstein, Patrick Bolton, Andrea Chiavari, Sergio de Ferra, Carlo Galli, Sean Lavender, Enrico Mallucci, Michael McMahon, Camilla Pelosi and participants at the CEPR Climate Change and the Environment Symposium, IM-TCD Women in Macro workshop, DIW WIMFEH, NYU Climate Finance workshop, Warwick PhD conference, and University of Oxford Macroeconomics and Environmental Economics workshops for helpful comments. I acknowledge the use of the University of Oxford Advanced Research Computing (ARC) facility in carrying out this work.

1. Introduction

Climate change is projected to increase both the frequency and severity of natural disasters in many countries. Emissions abatement will not fully address the consequences of these disasters, especially in the medium term. Therefore, the attention of policymakers is turning towards adaptation: investments to limit damages from natural disasters when they occur.[1] However, adaptive investments are costly and many of the countries that are most exposed to climate damages also have limited fiscal space due to their susceptibility to public debt crises. This paper studies the interactions between climate change, adaptation, and sovereign risk and shows that default risk magnifies the costs of natural disasters via restricted adaptation.

The contribution of this paper is threefold. First, I develop a theoretical framework which integrates natural disasters, sovereign risk, and endogenous adaptation capital. Second, I construct a database of adaptation expenditures which I use to validate the predictions of the theoretical model. Third, I discipline the model with this data to derive quantitative results on the relationship between climate change, adaptation, and sovereign risk. Together, this paper provides new evidence that sovereign risk exacerbates the costs of climate change for emerging market economies.

In particular, I apply my framework to natural disaster risk in Latin America and the Caribbean. The analysis focuses on the risk of hurricanes. Hurricanes are responsible for the largest share of monetary damages of any natural disaster and are projected to increase in frequency and severity as climate change intensifies.[2] Exposure to climate change is high in this region. As a result, adaptation has been a major policy concern.

The paper proceeds in five steps. First, I set up the model. I augment a quantitative sovereign default model with natural disaster shocks and endogenous adaptation capital. Disasters reduce the endowment, but damages can be limited via investment in adaptation. The model features output costs of default and long term debt as in Hatchondo and Martinez (2009). The sovereign issues debt to support consumption and invest in adaptive capital but cannot commit to repaying. It has the option to default in each period. The price of government debt endogenously adjusts to compensate lenders for default risk which is in turn affected by climate change. This default risk will therefore shape the adaptation choices made by sovereigns. Elevated default risk tight-

[1] For example coastal protections to limit flooding from cyclones, or early warning systems to prevent wildfire casualties.

[2] IPCC AR6: https://www.ipcc.ch/assessment-report/ar6/.
In this paper I will use the terms 'cyclone', and 'hurricane' interchangeably.

ens the budget constraint, limiting the amount the sovereign can borrow. In this model default risk will increase the costs of natural disasters by generating under-investment in adaptation.

Second, in order to sharply characterize the channels at play I solve analytically for the spread in a restricted version of the model. In this simplified framework there are two periods, log utility and procyclical default costs as in Aguiar and Gopinath (2006). The model implies a spread on government debt over the risk free rate. As in Phan and Schwartzman (2024) I show that the spread is increasing in the probability of a disaster. The more likely a bad shock is in the future, the more likely the sovereign is to default. Further, I prove that the spread is declining in the level of adaptive investment. The more the sovereign invests in adaptation, the less vulnerable they are to disasters in the future, and so the less likely they are to default. The presence of this adaptation channel attenuates the effect of climate change on the spread. As climate change intensifies, the incentives to adapt also grow. Therefore the sovereign will increase its adaptive capacity with climate change, reducing the impact of climate change on borrowing costs.

I compare the model to a counterfactual with perfect financial markets. In this counterfactual the sovereign commits to always repaying its debt and so can borrow at the risk free rate. Comparing the optimal adaptation choice under sovereign risk to the choice under commitment, I show that adaptation may be either higher or lower. The responsiveness of the spread to adaptation introduces an additional incentive to adapt. Greater investment in adaptive infrastructure reduces default probabilities and borrowing costs. However, the option to default also dampens adaptive investment by constraining the sovereign. Default risk tightens the budget constraint and so increases the marginal utility of consumption today, and reduces the marginal benefit of adaptation relative to the perfect financial markets benchmark.

For low spread calibrations it is possible for adaptation to be higher with default risk than without. However, for spreads consistent with the data for emerging economies, the second channel dominates and adaptation is constrained by the default risk. Higher initial debt, lower default costs, and less patient sovereigns make the second channel more powerful. Economies with high existing debt burdens and climate change exposure are effectively 'locked-in' to low adaptation and a high likelihood of climate related defaults in the future - this is the adaptation trap. For these economies, adaptation is declining in borrowing costs.

Third, I turn to the data to test the predictions of the model. I show that i) adaptation is declining in sovereign risk, ii) disasters cause sovereign risk to increase, and iii)

adaptation attenuates that effect. In order to do this I construct a novel measure of adaptation. A key challenge in the macro-adaptation literature is a measurement one: there is no available data on aggregate adaptation across countries. A contribution of this paper is to build such a measure, leveraging data from government budget documents. Budgets contain detailed information on the purpose of spending as well as the monetary amount allocated to each end. This data is therefore well suited to the task of measuring adaptation spending. I use a natural language processing approach: transfer learning, to identify adaptation related entries. A word embedding model pre-trained on adaptation-specific text generates a list of adaptation keywords. I search for entries containing these terms in each budget, and record the associated monetary value.

With this measure in hand I show that adaptation expenditure is increasing with sovereign rating. This result holds both across countries and for within country changes and is robust to controlling for institutional quality and natural disaster exposure. Additionally, this direct measure of aggregate adaptation can be used to document descriptive statistics some of which are useful for calibrating the model. I show that economies in Latin America and the Caribbean spend on average 0.31% of GDP on adaptation, or 1.1% of total expenditure. Consistent with the model, adaptation is also increasing in exposure to natural disasters.

In order to establish that default risk is sensitive to natural disasters I exploit data on physical incidence of cyclone shocks. To identify natural disaster events much of the existing literature has relied on the EMDAT database which has known issues with sample selection.[3] Instead, I employ a Local Projection approach using data on physical storm incidences and CDS spreads for more than 30 countries. I show that a hurricane strike increases CDS spreads by 1.5% six months after the event. The effect accumulates gradually indicating that sovereigns run up their debt in the aftermath of a hurricane. Additionally I show that a hurricane strike increases default probabilities by 3% three years after the event. Splitting the sample into high and low adaptation subsamples, I show that the effect is driven by the low adaptation group. For the set of countries with low adaptation expenditures, hurricanes cause statistically significant increases in default probabilities. For the high adaptation subsample, there is no statistically signficant increase in default probabilities. Consistent with the model this indicates that adaptation attenuates the impact of disasters on sovereign risk.

Fourth, having concluded that the predictions of the analytical model hold in the

[3] See, for example Felbermayr and Gröschl (2014)

data I use these results to calibrate the quantitative model. I estimate the endowment process for the set of Caribbean countries included in my sample. For these economies hurricanes are by far the most damaging hazard, allowing me to restrict attention to these disasters for which I have physical indicators. The process governing the effectiveness of adaptation is calibrated to match the data on adaptation investment. The model matches well the data on disaster incidence, borrowing, and default risk.

With this set up I quantify the importance of the sovereign risk - adaptation channel. Relative to a counterfactual with perfect financial markets, adaptation is substantially restricted. In the model with perfect financial markets, adaptation in the Caribbean is 13% higher than under sovereign risk. Default risk increases the GDP effects of cyclones by 10% relative to the commitment benchmark. Therefore the sovereign risk - adaptation channel is shown to be quantitatively important for the aggregate affects of natural disasters. Moreover, the amount by which sovereign risk restricts adaptation is increasing as climate change intensifies. This implies that the GDP losses from a cyclone of a given size are also diverging further from their perfect financial market counterparts as the probability of those cyclones increases. In particular, with the projected 29% increase in cyclone probabilities and a 48.5% increase in severity by the end of the century, the GDP losses from cyclones are 13% higher than they would have been in the absence of the sovereign risk - adaptation channel.

Finally, I use the model as a laboratory to test the potential for debt relief policies. These policies have the potential to be welfare improving by creating the fiscal space for adaptation. I consider three such policies: temporary suspension of debt service payments, a long term risk free loan, and voluntary restructuring. Each of these policies leads the sovereign to increase their adaptation investment, reducing the GDP losses from natural disasters and so easing their welfare burden. I find that debt relief can also be in the interest of investors. Reducing debt burdens today allows the sovereign to reduce their exposure to bad shocks tomorrow via investment in resilience. This reduces default probabilities, increasing the value of the debt for investors. [4]

Related Literature and Contribution. This paper is related to numerous strands of the literature in macroeconomics and environmental economics.

First, this paper contributes to the literature on sovereign default in the tradition of Eaton and Gersovitz (1981), Aguiar and Gopinath (2006), and Arellano (2008). Two existing papers embed natural disaster shocks into a model of sovereign default. Mal-

[4]These results are work in progress.

lucci (2022) considers the effect of these shocks on default risk and fiscal space for a sample of Caribbean countries. Phan and Schwartzman (2024) model the effect of sovereign risk on the economy's recovery from a disaster shock. Both papers consider the role for catastrophe bonds in limiting adverse effects. I contribute to this literature by embedding endogenous physical adaptation into a model of sovereign default with natural disasters. I speak to the effect of sovereign risk on ex ante investment in climate resilience. Also related to this paper is Arellano, Bai, and Mihalache (2024) which considers debt relief policies in a sovereign default model with an epidemiological model of COVID. I consider similar policies in a setting with climate shocks and costly adaptation.

Second, I contribute to a quantitative-macro literature on adaptation to climate change. Fried (2022) develops a heterogeneous-agent model to quantify adaptation to climate change to severe storms in the US. Hong, Wang, and Yang (2023) model adaptation to climate change in the presence of learning about disaster risk. Cantelmo, Melina, and Papageorgiou (2023) find that self-financed adaptation infrastructure provides limited welfare gains for disaster prone economies. Marto, Papageorgiou, and Klyuev (2018) argue for international donor support for resilience building in disaster prone states. While the latter two papers consider the role of debt sustainability they do so in a reduced form way without explicit default risk. I contribute to this literature by considering how the option to default on debt affects the adaptation motive, and by providing estimates of adaptation investment useful for disciplining the model.

Third, I contribute to the empirical literature on adaptation to climate change. On the macro level, existing data on adaptation investment does not exist. Therefore, the dominant approach in the literature has been to treat adaptation as a latent variable. If the damages from a disaster of a given size are lower in areas with higher historical exposure (or if they decrease over time), this approach concludes that adaptation has taken place. The evidence from this approach has been mixed. Hsiang and Narita (2012) find that countries with more intense tropical cyclone climates suffer lower marginal losses from a given cyclone. Barreca et al. (2016) find that the mortality impact of high temperature days has fallen over time. Gourio and Fries (2020) find that US counties with higher historical temperatures suffer less from extreme high temperature events. Bakkensen and Mendelsohn (2016) also find evidence for adaptation in most of the world. Burke et al. (2024) study a range of 21 outcomes, finding a statistically significant declining sensitivity to a changing climate in only 6. A small number of papers consider macro effects of particular adaptation strategies e.g. Molina and Rudik

(2024) which considers the value of forecasts. On the micro level, direct measures of adaptation are more common. Grover and Kahn (2024) survey the microeconomics literature studying firms' adaptation. Lane (2024) studies the role of credit market frictions in preventing farmers adaptation to extreme weather. For a review see Carleton et al. (2024). I contribute to this empirical literature by building a direct measure of adaptation investment on the country-level. This measure allows me to consider how adaptation varies with other characteristics, such as fiscal space, and to disaggregate the components of adaptive investment.

Fourth, I contribute to an empirical literature on the fiscal effects of natural disasters and climate change.[5] Noy and Nualsri (2011) use a panel VAR to estimate the effects of disasters on fiscal outcomes, finding pro-cyclical effects in developing countries. Klomp (2015) uses EM-DAT, a database of natural disasters mostly based on insurance claims or news stories, to estimate the effect of disasters on sovereign default premia. Auh et al. (2022) find substantial price effects of natural disasters on US municipal bonds. Klusak et al. (2023) train a machine learning model to predict that sovereign ratings will be negatively affected by climate change. Cappiello et al. (2025) show that a higher frequency of disasters is associated with lower credit ratings. Closest to my approach is Klomp (2017) which estimates that natural disasters significantly increase default probabilities. I contribute to this literature by using a Local Projection design and physical data on the incidence of hurricanes to estimate the effect of hurricanes on sovereign risk premia and default risk, accounting for the mediating role of adaptation.

Finally, I contribute to the literature on the relationship between disaster risk and asset prices along the lines of Barro (2009), Gourio (2012), and Nordhaus (2010). To this literature I add an additional feedback loop: adaptation can reduce the exposure of the economy to the diaster risk and so attenuate the effect on asset prices. However this adaptation investment is constrained by the value of government debt.

Outline. The rest of this paper proceeds as follows: Section 2 outlines the model and Section 3 presents the analytical results. Section 4 outlines the empirical methodology and results. Section 5 outlines the quantitative analysis, and Section 6 concludes.

[5] For a comprehensive review see Barrage (2024)

2. Model

I augment a sovereign default model with natural disaster shocks and endogenous adaptation. The model features output costs of default, long term bonds as in Hatchondo and Martinez (2009), natural disasters as in Mallucci (2022), and public adaptation capital. A sovereign in a small open economy makes borrowing, investment, and default decisions to maximize utility of the representative agent. The endowment is subject to disaster shocks which reduce the endowment. Damages from these disasters can be limited through investment in adaptive infrastructure. International investors are risk neutral.

The sovereign's lifetime value is:

$$v_0 = \sum_{t=0}^{\infty} \beta^t \mathbb{E}\left(u\left(c_t\right)\right),$$

where $u(c_t)$ is the household's utility from consumption.

The income process is given by:

$$y_t = y_{t-1}^{\rho}(1 - x_t d_t F\left(\Lambda_t\right))\, \epsilon_t^y,$$

where ρ allows for persistence in the endowment process and x_t is an indicator variable for the natural disaster shock with

$$\mathbb{P}(x_t = 1) = p_t.$$

A disaster realization ($x_t = 1$) reduces the endowment. Disaster damage is given by the continuous variable d_t which is iid distributed according to the distribution $F(d)$ with support $[0, 1)$. The endowment shock $log(\epsilon^y)$ is normally distributed with mean zero. The stock of adaptation capital is denoted by Λ_t. Adaptation reduces the damages from a disaster. The function $F(\Lambda)$ governs the process by which adaptation reduces damages. I assume that $F(\Lambda)$ satisfies the Inada conditions. It is decreasing and convex in adaptation. The marginal product of adaptation is infinite at zero adaptation. Therefore all sovereigns will find it beneficial to invest in at least a small amount of adaptation.[6] The stock of adaptation follows a law of motion given by:

[6]The data shows that adaptation investment is non-zero for all Latin American and Caribbean countries 2010-2025.

$$\Lambda_t = (1-\delta)\Lambda_{t-1} + \lambda_{t-1},$$

where λ_t is investment in adaptation.

I assume the coupon structure from Hatchondo and Martinez (2009): a bond issued in period t promises an infinite stream of coupons, which decreases at a constant rate ψ. Therefore, the duration of a bond is $\frac{1+r^*}{\psi+r^*}$.

In each period the sovereign first chooses whether or not to default on its outstanding debt. Then they decide on bond issuance (if they did not default), and investment in adaptation. If the sovereign chooses to default, it looses access to financial markets and suffers the output cost of exclusion $\phi(y_t)$. In the following period the sovereign regains access to financial markets with exogenous probability η. The resource constraint is therefore given by

$$c_t = (1-D_t)y_t + D_t\phi(y_t) + (1-D_t)q_t(b_{t+1} - (1-\psi)b_t) - (1-D_t)b_t - \lambda_t, \tag{1}$$

where q_t is the price the bond, b_t denotes the number of outstanding coupon claims, and D_t is a default indicator. $D_t = 1$ indicates that the sovereign is in the default state.

The price of the bond that gives risk neutral investors zero profit in expectation is given by:

$$q_t = \frac{1}{1+r}\mathbb{E}\left((1-D_{t+1}) + (1-\psi)(1-D_{t+1}q_{t+1})\right), \tag{2}$$

where the first term on the right hand side is the next-period coupon payment promised by a bond. The second term is the expected value for all future coupon payments, denoted as the resale value of the bond next period.

2.1. Recursive equilibrium

In equilibrium, the sovereign sets the policy for default, bond issuance, and adaptation investment to maximize welfare of the representative household, subject to the resource constraint, the constraint implied by foreign lenders' pricing of debt, and the law of motion for adaptation.

The equilibrium is formally defined by: 1) a set of value functions for the representative household: total value V, the value with market access V_{nd}, and the value in default

V_d:

$$V = \max_{D} \left\{ (1 - D)V_{nd} + DV_d \right\}, \tag{3}$$

$$V_{nd}(y, b, \Lambda) = \max_{b', \Lambda'} u(c) + \beta \mathbb{E}[V(y', b', \Lambda')], \tag{4}$$

$$V_d(y, 0, \Lambda) = \max_{\Lambda'} u(c) + \beta \mathbb{E}[(1 - \eta)V_d(y', 0, \Lambda') + \eta V(y', b', \Lambda')], \tag{5}$$

2) government policies for default D, bond issuance b, and adaptation Λ, and 3) a government debt price function q such that:

- the debt price function is consistent with optimization by foreign lenders (2),
- the value functions of the household and the policy functions of the government solve the maximization problem,
- and the resource constraint of the household (1) is satisfied.

The model is solved using state of the art techniques from the quantitative sovereign default literature. The problem is augmented with extreme value taste shocks. For details see Appendix C. I also solve a counterfactual perfect financial markets benchmark in which the default policy is set to zero in all states.

3. Analytical Characterization

In order to sharply characterize the relationship between sovereign risk, climate change, and adaptation and to derive some testable implications of the model I make a number of assumptions. First, I restrict the model to two periods such that the sovereign chooses adaptation and borrowing only in period one, and default only in period two. In period one adaptation capital is set to zero, and the endowment is normalized to one. For tractability I assume log utility:

$$u(c_t) = ln(c_t).$$

Default costs are procyclical as in Aguiar and Gopinath (2006) and Phan and Schwartz-

man (2024):

$$\phi(y_t) = \left(1 - \bar{l}e^{\psi g}\right).$$

This implies that the sovereign has more incentive to default in low-growth states. Such an assumption is common in the quantitative sovereign default literature as it helps to match cyclical movements of spreads.[7]

3.1. Commitment Benchmark

I begin by outlining a benchmark version of the model where there is full commitment. The sovereign cannot default on its debt and so repays the issued bonds in period two. This perfect financial markets benchmark will be useful for examining the effects of the default option on adaptation. In this case consumption is given by:

$$c_1 = y_1 + \frac{1}{1+r}b - \lambda, \qquad c_2 = y_1^{\rho}(1 - x_2 d_2 F(\lambda))\epsilon^{y} - b,$$

where b is bond issuance in period one. Debt is fully repaid in period two in this benchmark. As there is no default risk, the price of the bond is given by $\frac{1}{1+r}$ where r is the risk free rate. Adaptation investment λ is chosen in period one. The adaptation choice therefore trades of the costs of investment and the benefits of reducing damages next period.

PROPOSITION 1. *Adaptation is increasing in the probability of a disaster:*

$$\frac{\partial \lambda^*}{\partial p} > 0$$

FOC(λ)*:*

$$\frac{1}{c_1} = -p\beta\mathbb{E}\frac{d_2 F'(\lambda) y_1^{\rho}\epsilon^{y}}{c_2(x_2 = 1)} \tag{6}$$

where the proposition follows since $F(\lambda)$ is decreasing and convex. A higher value of p increases the likelihood of a negative shock next period. Therefore the expected benefits of adaptation are greater. This increases the sovereign's adaptation choice.

[7] I will consider kinked default costs in the quantitative model. These default costs have better quantitative properties.

3.2. Limited Commitment

Now consider the case where there is default risk. The sovereign can no longer commit to repaying the bond. In period 2 the sovereign decides whether or not to repay its debt. If the sovereign defaults, it is subject to the default cost:

$$\phi(y_2) = \left(1 - \bar{l}e^{\psi g}\right).$$

where

$$g = log(\epsilon_2^Y)$$

which has an iid normal distribution $\Phi(g)$.

Consumption in period 2 is denoted by c_R if the sovereign chooses to repay, and c_D if it defaults. The sovereign defaults if $c_D > c_R$.

$$c_R = y_1^\rho(1 - x_t d_t F(\lambda))\epsilon^y - b, \qquad c_D = \phi(y_2) y_1^\rho(1 - x_t d_t F(\lambda))\epsilon^y. \tag{7}$$

This implies that default occurs if the disaster adjusted growth rate $\tilde{g}$ is below an endogenous default threshold $\bar{g}$:

$$\underbrace{g + \frac{1}{1+\psi} ln(1 - x_t d_t F(\lambda))}_{\tilde{g}} < \underbrace{\frac{1}{1+\psi} ln(\frac{b}{\bar{l} y_1^\rho})}_{\bar{g}}, \tag{8}$$

where the endogenous default threshold is determined by the size of the default costs and the debt to GDP ratio. A higher debt to GDP ratio increases the default threshold $\bar{g}$ and so makes default more likely. Larger default costs lower the threshold and therefore make default less likely. In the absence of a disaster, the sovereign defaults if the growth rate g is below this endogenous default threshold. If a disaster hits, the growth rate falls to $\tilde{g} < g$. Therefore, a disaster makes default more likely.

Investors are risk neutral. Default risk implies that the price of the bond in period 1 will include a spread over the risk free rate. The price of the bond is given by:

$$q = \frac{1 - s}{1 + r}$$

where the spread is the probability of default:

$$
\begin{aligned}
s(b,\lambda) &= \Pr\left[\tilde{g}' < \bar{g}(b)\right] \\
&= (1-p)\Phi_g(\bar{g}) + pE_{d'}\left[\Phi_g\left(\bar{g} - \frac{1}{1+\psi} ln(1-d_t(F(\lambda_t)\right)\right]
\end{aligned} \tag{9}
$$

As in Phan and Schwartzman (2024) this implies the following two results:

PROPOSITION 2. *The spread is increasing in the probability of a disaster*

$$
\frac{\partial s}{\partial p} = -\Phi_g(\bar{g}) + E_{d'}\Phi_g\left(\bar{g} - \frac{1}{1+\psi} ln(1-d_t F(\lambda_t)\right) > 0.
$$

PROPOSITION 3. *The spread is increasing in a first order stochastic dominance sense in the distribution of the severity of the disasters*

$$
\hat{\Phi}_d \overset{fosd}{\geq} \bar{\Phi}_d \Rightarrow s(\cdot,\cdot|\hat{\Phi}_d) \geq s(\cdot,\cdot|\bar{\Phi}_d).
$$

An increase in the frequency or severity of disasters increases the likelihood of a low value for $\tilde{g}$. Therefore, in the model climate change increases default probabilities and so raises borrowing costs for the sovereign. In this model there is an additional effect through adaptation:

PROPOSITION 4. *The spread is decreasing in the level of adaptation*

$$
\frac{\partial s}{\partial \lambda} = pE_{d'}\left[\phi_g\left(\bar{g} - \frac{1}{1+\psi}\ln(1-d\cdot F(\lambda)\right)\cdot\frac{d\cdot F(\lambda)}{(1+\psi)(1-d\cdot F(\lambda))}\right] < 0
$$

Proof. Appendix B.

The more the sovereign invests in adaptation, the lower the expected damages from a disaster shock are next period. Adaptation reduces the exposure of the economy to a bad shock in the future. This increases the disaster adjusted growth rate $\tilde{g}$ in the disaster state, and so reduces the probability of default. As adaptation reduces the probability of a disaster causing the sovereign to default, it also increases the market value of the government's debt.

Additionally, allowing for endogenous adaptation makes the spread less responsive to an increase in the probability of a disaster. Adaptation reduces expected damages and so attenuates the effect of climate change on borrowing costs:

$$\frac{\partial s}{\partial p} < \left.\frac{\partial s}{\partial p}\right|_{\lambda=0}$$

The adaptation choice itself is affected by the presence of default risk. Given the bond price function derived above, the sovereign chooses b and λ in period one to maximize lifetime utility. Now:

$$c_1 = y_1 + \frac{1-s}{1+r}b - \lambda,$$

and the expected value of consumption in period two is the given by the default probability and the default and repayment values as in (7). The sovereign internalises the effect of its adaptation choice on the price of its bond. The first order condition for adaptation is therefore given by:

$$\underbrace{\frac{1}{c_1}}_{MC} = \underbrace{\beta\mathbb{E}\left(\frac{y_2'(\lambda)}{c_R} - s(\lambda)\frac{y_2'(\lambda)b}{y_2 c_R}\right)}_{\text{MB damage reduction}} + \underbrace{\beta\mathbb{E}\left(s'(\lambda)(u(c_D)-u(c_R))\right)}_{\text{MB reduced default prob}} \underbrace{-\frac{\frac{1}{1+r}s'(\lambda)b}{c_1}}_{\text{MB lower spread}} \tag{10}$$

The presence of default risk introduces two additional terms relative to the commitment case (6): the marginal benefit of a reduced default probability, and the marginal benefit of lower borrowing costs. As shown in Proposition 4, the probability of default is declining in the level of adaptive investment. As long as utility is greater in the repayment state than in the default state in expectation, higher adaptation is therefore associated with a marginal benefit of reducing the probability of default. The second additional marginal benefit arises as adaptation lowers the spread and so reduces borrowing costs for the sovereign. These two additional terms increase the incentive for the sovereign to adapt relative to the commitment case.

However, default risk also tightens the budget constraint and lessens the ability of the sovereign to consumption smooth. Therefore consumption is pushed forwards in time relative to the commitment case: c_1 is lower relative to c_R. This increases the marginal cost of adaptation, and reduces the marginal benefit of damage reduction relative to the commitment case. In this way, the presence of default risk constrains the sovereign, dampening the incentive to invest in adaptation.

The presence of default risk both introduces new benefits from adaptation through the default probability, and reduces the incentive to adapt through the budget constraint. Therefore, adaptation may be either higher or lower under default risk than

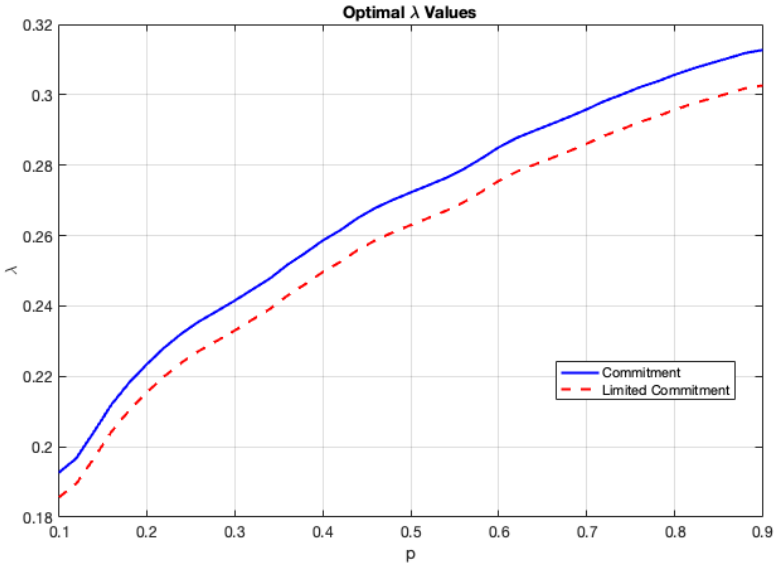


FIGURE 1. Optimal adaptation for a range of values of the probability of a disaster. The blue line shows the case with no default risk, the red dotted line shows the case with such risk. Parameter values are standard for emerging markets: $\beta = 0.9$, $\bar{l} = 0.7$, $\psi = 7$, $r = 0.01$.

commitment. Whether adaptation is higher or lower under default risk than under commitment will depend on the relative size of these two channels. This will depend on the calibration of the model.

For low spread calibrations the first channel dominates and adaptation is higher under default risk than under commitment. However, for calibrations giving reasonable spread values for emerging economies, the second channel dominates and adaptation is restricted relative to the commitment benchmark. Economic fundamentals are important for determining whether a sovereign will be enabled or restricted from investing in adaptation by the presence of default risk. Figure 1 shows a representative emerging market calibration where baseline spreads are high and adaptation is lower under default risk than commitment for all values of the probability of a disaster.

It is worth drawing out two comparisons to the related literature. First, in this model with endogenous adaptation, the effect of climate change on default risk is attenuated. Previous literature has assumed that the size of climate damages are fixed (or increasing at a deterministic rate). This implicitly assumes away the potential for endogenous adaptation. Allowing for adaptation investment which responds to the probability of a disaster, even when that adaptation is constrained by default risk, reduces damages from future events. Therefore in this model the effect of climate change on borrowing

costs will be less than in model such as Mallucci (2022) or Phan and Schwartzman (2024). In this sense the predictions of the model are optimistic relative to pre-existing conclusions.

On the other hand, the model tells us that the presence of default risk may substantially affect the adaptation decision. Therefore, relative to the literature on adaptation without this friction (for example Hong, Wang, and Yang (2023)) the model is pessimistic. From this exercise we learn that even when adaptation is very effective, and would therefore also be effective in reducing borrowing costs tomorrow, the presence of the constraint today may prevent the sovereign from accessing these benefits. This opens the door to the potential for debt relief policies to improve climate resilience.

4. Data

The model predicts that i) adaptation is declining in sovereign risk, ii) natural disasters increase default probabilities, and iii) adaptation attenuates that effect. I validate these predictions in the data.

4.1. A Novel measure of Adaptation

The claim that more fiscally constrained economies are less able to invest in protecting themselves against future climate damages is a key pillar of the argument for debt relief for climate resilience. Does this relationship hold in practice? One obstacle to testing it is the lack of data on adaptation investments by country.

The literature on economy-wide adaptation to natural disasters has thus far employed a latent variable approach to test for the existence of adaptation using weather shocks. If the damages from a disaster of a given size are lower in areas with higher historical exposure (or if they decrease over time), this method infers that adaptation has taken place. Identification in this latent variable approach comes from panel variation and suffers from low power. Therefore it is not possible to directly test how the amount of adaptation varies across countries. It is also not possible to understand how exactly countries are adapting to climate change.[8] I build a direct measure of adaptation which can be used to understand how investment varies across countries, and its components.

[8] See Carleton et al. (2024) for a review of the empirical literature on adaptation to climate change.

4.1.1. Data and Methodology

Sample. I leverage data from government budgets. These documents contain detailed descriptions of spending by purpose and associated monetary allocations. Budgets are available on government websites in PDF format. I focus on Latin America and the Caribbean. Economies in this region are subject to the dual challenges of natural disaster exposure and elevated sovereign risk.

The key challenge is to generate a measure that is sufficiently complete and comparable. Adaptation encompasses many strategies including: early warning systems, physical infrastructure, ecological adaptations, and relocation or behavioral measures. In the context of the Caribbean in particular, governments have heavily invested in coastal protection infrastructure including sea walls, artificial reefs, and drainage systems. Nature-based solutions are also common. These strategies include planting of mangroves and reef management.[9] Governments may describe their investments in each of the strands of adaptation in different ways in their respective budgets as reporting is not standardized. I therefore build a general measure of adaptation utilising text analysis methods to flexibily account for a range of adaptation strategies. I show that my results are robust to i) including country fixed effects to account for differences in budgetary processes across sovereigns, and ii) using narrower measures of adaptation: meteorological services expenditure or disaster preparedness expenditure.

Methodology. I use tools from natural language processing to identify line items in government budgets that correspond to a broad notion of adaptation. This measure will be less sensitive to exactly how budgets categorize their spending than pre-specifying narrow subcategories of adaptation. The procedure for constructing this total adaptation measure follows six steps:

First, I supply a list of initial keywords which unambiguously describe adaptation. I draw this list of initial keywords from two sources: table 17.1 from chapter 17 of the IPCC AR6, and table SPM.4 from the IPCC AR4 summary for policymakers. Both of these tables list common ways by which countries adapt to climate risk. The set of initial keywords is listed in Appendix A.1. Second, I build a large corpus of text discussing adaptation. This allows me to train a model to recognize the niche language that is often used in discussing adaptation. This text comes from a number of sources listed in Appendix A.2, including UN adaptation reports and scientific literature. Third, I pre-process this raw text to obtain a set of terms, including bigrams and trigrams. After

[9] See IPCC AR6 for a review.

pre-processing there are $V = 15,971$ unique terms that appear a total of 43 million times in the corpus. Details of the text pre-processing are described in Appendix A.3.

Fourth, I construct word embeddings in this corpus using the GloVe model from the Stanford NLP group.[10] GloVe is an unsupervised machine learning model used for obtaining vector representations of words. The model uses co-occurrences of words to map them into a meaningful space where the distance between words relates to how similar they are semantically. The context of a term $w_{d,n}$ in a vocabulary V is defined as a window of terms surrounding that term:

$$C\left(w_{d,n}\right) = \left(w_{d,n-L}, \ldots, w_{d,n-1}, w_{d,n+1}, w_{d,n+L}\right). \tag{11}$$

Co-occurrences are defined by a VxV matrix where an entry $W_{i,j}$ is the number of times that term i appears within the context of j, and vice versa. As is standard, I chose the context window $L = 10$. Each term is associated with a vector $\boldsymbol{\rho}_v$ in $\mathbb{R}^K$ by the model. These vectors are chosen to solve:

$$\min_{\boldsymbol{\rho}_v} \sum_{i,j} f\left(W_{i,j}\right)\left(\boldsymbol{\rho}_i^T \boldsymbol{\rho}_j - \log\left(W_{i,j}\right)\right)^2 \tag{12}$$

where $f(\cdot)$ is a non-negative, increasing, and concave weighting function, such that rare word pairs count less in the objective. This minimizes the squared difference between the dot product of the word vectors, $\boldsymbol{\rho}_i^T \boldsymbol{\rho}_j$, and the empirical co-occurrence, $\log\left(W_{ij}\right)$. Terms that regularly co-occur tend to have vectors with a high dot product. The fitted vectors $\hat{\boldsymbol{\rho}}_v$ are the embeddings. These give similar representations to words that appear in similar corpus contexts and can be used to represent and compare vocabulary terms.

Fifth, I identify terms with a high semantic similarity to at least one of the initial keywords. I use the standard distance measure to compare vectors in text analysis: cosine similarity. This value is higher when the angle between the vectors is smaller i.e. when they share similar directions in the vector space. I select terms which have a cosine similarity of at least 0.7 with at least one of the initial keywords. The initial keywords plus these semantically similar terms comprises my final set of keywords.[11]

[10] For an overview of word embeddings, along with other text algorithms and their application in economics see Ash and Hansen (2023)

[11] For the final set of keywords see Appendix A.

Finally, I search for instances of the keywords in the budgets. I record the *monetary value* associated with each entry containing at least one of these keywords. The final measure of adaptation is the sum of monetary values associated with each of the flagged entries. In this final step I hand read all flagged entries to ensure there is no double counting. In this final step I also hand-prune a small number of false positive entries from the analysis.[12]

As well as this total measure of adaptation I consider two narrower measures. From hand reading all entries flagged by the algorithm I find that each document contains some entry related to 'disaster preparedness' expenditure. While budgets contain entries related to many specific projects to do with adaptation such as building a new sea wall or maintaining an existing dyke, governments also budget for a general disaster preparedness fund. This allows them to mobilize resources when a disaster is forecast. I take the value allocated to this end as my second measure of adaptation. This measure has the advantage of being included in every budget, of agreed meaning, and so is comparable across my sample.

Second, all countries also budget for their meteorological services. Early warning and forecasting of natural disasters is considered one of the key ways in which economies can adapt to the increasing frequency and severity of these disasters. Therefore I take the amount of meteorological service spending in each country as my final measure of adaptation.

As a measure of sovereign risk I take the average of the sovereign's previous three years of sovereign ratings form the World Bank Group cross-country database of fiscal space (Kose et al. 2022). This results in an unbalanced panel of 19 countries in Latin America and the Caribbean with a sovereign rating from 2014-2025. [13]

4.1.2. Results

I find that adaptation expenditure is 0.31% of GDP on average for economies in this sample. This corresponds to 1.1% of total expenditure. Disaster preparedness expenditure is 0.11% of GDP on average. Summary statistics are reported in Table 1.

These results imply that on average adaptation investment is about a tenth of health expenditure, or a fifth of agricultural spending.[14] The closest existing statistic of adapta-

[12]This pruning removes < 2% of the included line items.

[13]Mexico, Argentina, Uruguay, Honduras, Guatemala, Colombia, Peru, Chile, Ecuador, Costa Rica, Dominican Republic, Grenada, Belize, Jamaica, Barbados, Bahamas, Turks and Caicos, St Vincent and the Grenadines, Panama. For details of sample construction see Appendix A

[14]Source: Economic Commission for Latin America (ELAC)

TABLE 1. Summary Statistics

	N	Mean	St. Dev.	Min	Max
Adaptation Total / GDP	163	0.31%	0.0031	0.001	0.0187
Adaptation Total / Expenditure	163	1.1%	0.0100	0.0038	0.0538
Disaster Preparedness / GDP	163	0.11%	0.0024	0.0001	0.0122
Meteorological / GDP	163	0.03%	0.0007	0.000	0.0009

tion is from Hong, Wang, and Yang (2023). They compute average flood control spending for a sample of countries in Australasia, finding it to be around 0.3% of GDP. I find that total adaptation spending in Latin America and the Caribbean is of a similar magnitude to flood control spending in Australasia.

In order to validate the measures of adaptation I investigate how it varies with exposure to natural hazards. The existing literature on adaptation infers its presence from a negative relationship between historical exposure to natural disasters and damages from disasters of a given size. I can test for this relationship using my measures. Figure A1 shows this relationship. As cyclones are the most damaging disaster in this region I take average historical wind speeds scaled by land area as a measure of natural disaster exposure. Countries with higher historical exposure to storms tend to invest more in adaptation. I find the same positive relationship between exposure to natural disasters and adaptation using a number of other measures of exposure. For details see Appendix A.9.1. This positive relationship between historical exposure to disasters and adaptation indicates that governments respond to their climactic conditions by investing in measures to build resilience.

With the measure of total adaptation spending I can also investigate the components of adaptation. The machine learning approach to building a measure of adaptation picks out budget entries that include at least one term from the key word dictionary. I process all of the text from each of these entries to understand the components of adaptation. The left panel of figure 2 shows a word cloud representing the most frequently used terms in adaptation related budget entries. Disaster response and flood protection are important components of adaptation. For the Caribbean subsample cyclones are the most salient risk and coastal protection stands out further as an important channel of adaptation as show in figure A7. To further investigate the components of adaptation I categorize the search terms and construct count variables for each component. The right panel of figure 2 documents the most common components of adaptation. After disaster preparedness and meteorological expenditure, agricultural, water supply, and

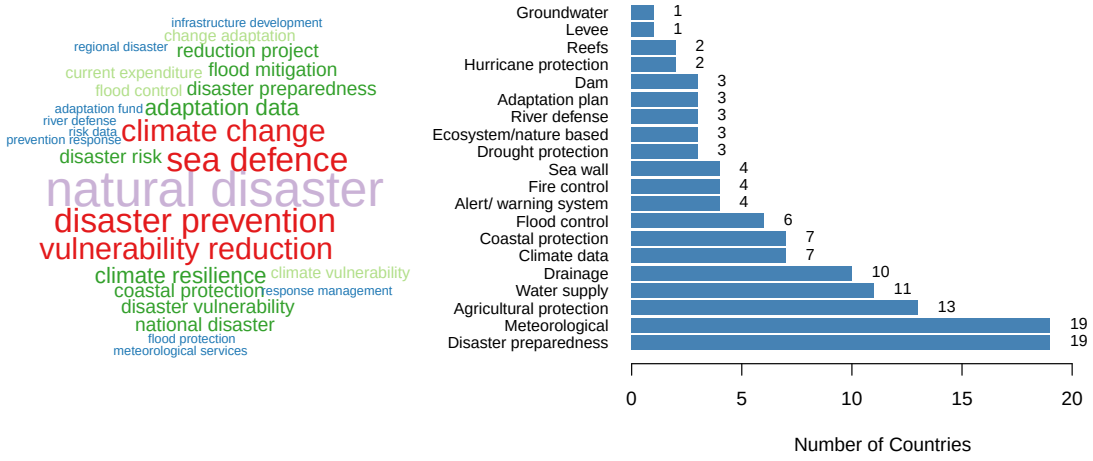


FIGURE 2. Adaptation is disaggregated by subtype. The left panel shows the most frequently used terms in budget entries flagged by the algorithm. The right panel shows the most common categories of adaptation by country in 2022.

coastal protection are the most common forms of adaptation.

I now use the validated adaptation measure to investigate how adaptation spending varies across countries' characteristics. In particular, I find a positive and significant relationship between sovereign ratings and adaptation spending. Figure 3 shows this relationship. The binned scatter plot shows that country-year observations with higher sovereign ratings are associated with higher adaptation expenditures. The result is robust to leaving out one observation at a time and is significant at the 10% level. It also holds for the two narrower measures of adaptation as shown in figure 4. To further examine the relationship I run the following regression:

$$\text{Adaptation}_{i,t} = \beta_0 + \beta_1 \text{sovrate}_{i,t} + \Gamma X_{i,t} + \mu_t + \varepsilon_{i,t}, \tag{13}$$

where *Adaptation* is the a measure of adaptation as constructed above measured in US dollars and *sovrate* is the average of the sovereign's ratings over the previous three years on a scale from 0-21 from the World Bank fiscal space database (Kose et al. 2022). X is a vector of controls that includes GDP, a measure of exposure to natural hazards: average maximum historical wind speed, and an index of regulatory quality from the World Bank. Table 2 shows the results of this estimation. The first column controls

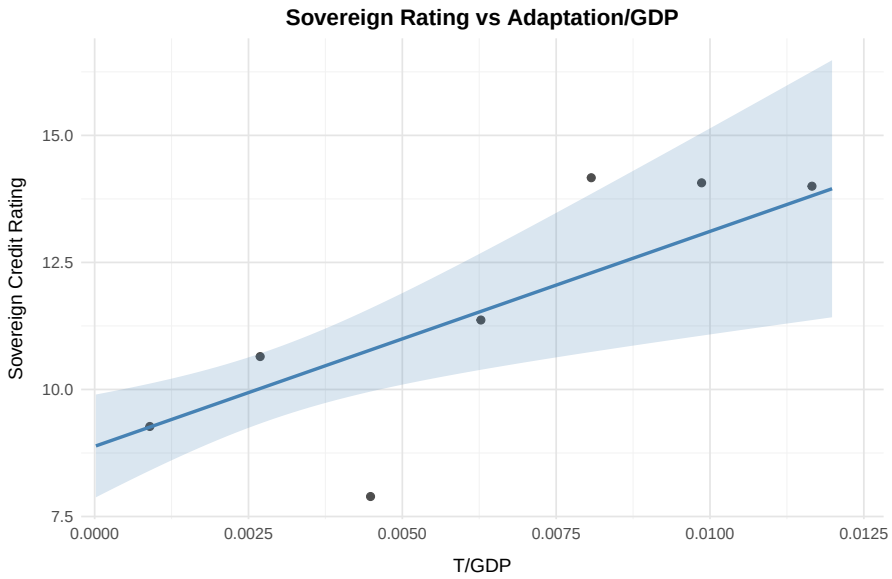


FIGURE 3. Adaptation Investment and Sovereign Ratings. Sovereign ratings are an average of the previous three years, on a scale from 0-21 from the World Bank fiscal space database (Kose et al. 2022). The adaptation measure is total adaptation spending as derived from the computational linguistics measure, shown as a proportion of GDP and in 8 bins. The shaded region shows standard errors at the 90% level.

for exposure and regulatory quality, the second column instead includes a country fixed effect. In both cases there is a significant positive relationship between adaptation expenditure and sovereign rating. In particular, a one point increase in sovereign rating is associated with an increase in adaptation spending of approximately $52 million according to the first specification, and $31 million according to the second.

TABLE 2. Regression Results

	adapt	
sovrate	51,554,921***	30,964,525***
	(16,647,312)	(9,241,031)
gdp	0.0022***	0.0069***
	(0.0002)	(0.0018)
exposure	7,464,182**	
	(2,946,190)	
regulatory quality	1,419,732,592***	
	(2,415,672)	
Country Fixed Effects	No	Yes
Year Fixed Effects	Yes	Yes
Observations	98	105
R-squared	0.95	0.84

Notes: * p < 0.10, ** p < 0.05, *** p < 0.01

This upward sloping relationship between adaptation and sovereign ratings is consistent with the prediction of the model. The positive relationship may include components both from sovereign rating to adaptation and in the reverse, also consistent with the model.

The evidence is also consistent with narratives prevalent in ratings agency and development bank reports. For example, Fitch has noted that while a large natural disaster shock could lead to a downgrade for Jamaica, evidence of enhanced resilience to such shocks could lead to an upgrade. At the same time, investment in resilience building is constrained by a 'lack of meaningful fiscal space'.[15]

[15]https://www.fitchratings.com/research/sovereigns/fitch-upgrades-jamaica-to-bb-outlook-positive-05-03-2024. For additional narrative evidence see Appendix A

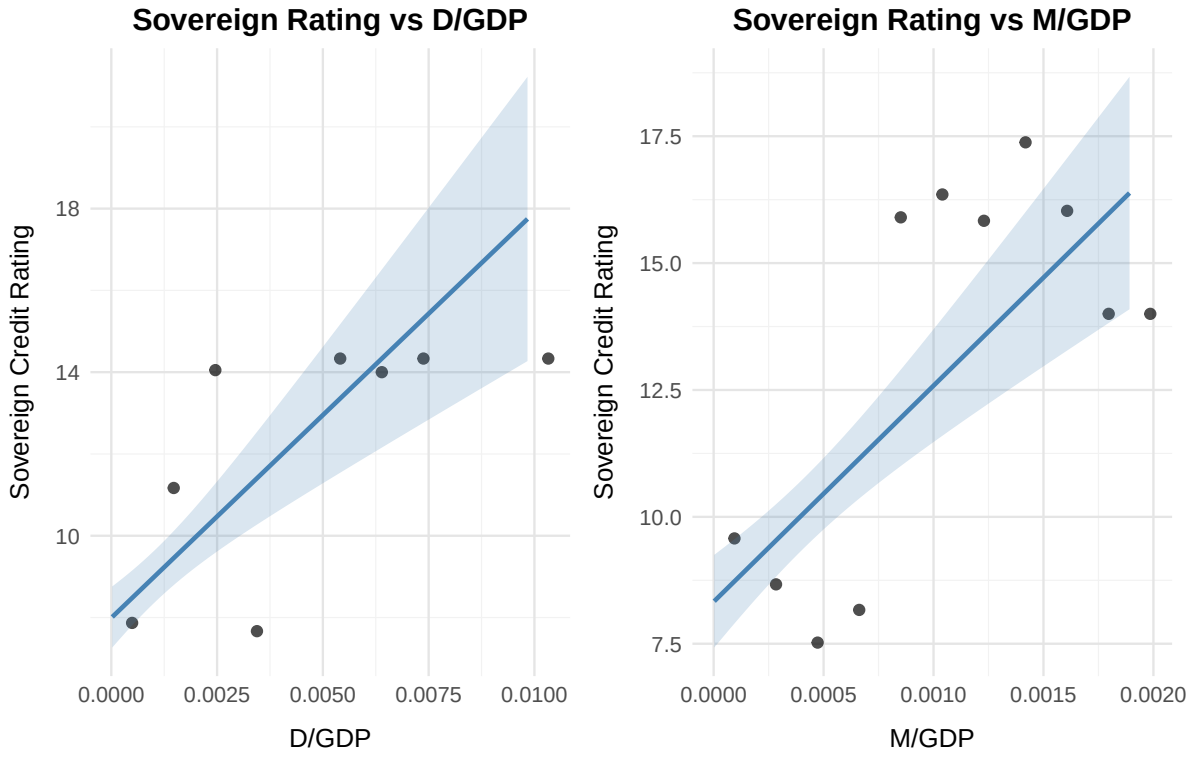


FIGURE 4. Adaptation Investment and Sovereign Ratings. Sovereign ratings are an average of the previous three years, on a scale from 0-21 from the World Bank fiscal space database (Kose et al. 2022). The adaptation measures are disaster preparedness expenditure and meteorological services expenditure, both scaled by GDP.

4.2. Natural disasters and sovereign risk

Having validated that adaptation is declining in sovereign risk I investigate the additional predictions of the model. How does climate change affect sovereign risk? How is this relationship mediated by adaptation? I provide a causal estimate of the effect of a hurricane strike on sovereign risk premia and default probabilities, and show that the response differs with adaptation expenditure.

Much of the existing literature examining the macroeconomic effects of natural disasters uses data from EM-DAT. The EM-DAT database collates damages from natural disasters using insurance claims and news articles as its source.[16] Felbermayr and Gröschl (2014), show that the use of such data leads to estimation bias when estimating growth effects of disasters as selection correlates with GDP. In advanced economies disasters are more likely to be covered in the news and/or result in insurance pay-outs. As a result disasters in these countries are more likely to be recorded in EM-DAT then those in emerging economies. Felbermayr and Gröschl (2014) find that using physically collected data on disaster strikes flips the result on the growth effect of natural disasters from marginally positive to large, negative, and statistically significant.

Similarly, selection into EM-DAT correlates with sovereign risk premia, as advanced economies tend to be perceived as less risky. Therefore, the use of EM-DAT would also bias existing estimates of the effect of disasters on risk premia. The contribution of this section is to provide causal estimates of *physically identified* hurricane strikes on sovereign risk.

4.2.1. Data

The data for physical storm incidence comes from the *International Best Track Archive for Climate Stewardship* (IBTrACS). This data is provided by the *National Climatic Data Center of the National Oceanic and Atmospheric Administration* (NOAA) which records data of individual storms along with their location and intensity at six hourly intervals. This information is collated from a variety of sources including satellites, ships, and aircraft. The hurricane track data provides no information on the countries affected. Therefore I map the data to countries using longitude and latitude, accounting for the fact that hurricanes that do not make landfall but pass close to coastlines can also cause significant destruction. I create an indicator D_{it} that is equal to one if country i experiences a storm of at least category one hurricane force in time t. A storm is

[16] www.embdat.be

counted if it achieves a maximum sustained windspeed of at least 74 mph.

The sample runs from 1980-2025, extending earlier datasets linking IBTrACS to the country level which finish in 2010 (Felbermayr and Gröschl 2014), (Hsiang and Jina 2014). Summary statistics for countries which experience at least one such storm are presented in Appendix A.13. On average in this sample of cyclone exposed economies, a country experiences a storm of at least 74 mph once every five years.

As dependent variables I use sovereign credit default swap (CDS) spreads, as well as a dummy for a sovereign debt crisis. Sovereign CDS are credit protection contracts, similar to insurance for a holder of a sovereign bond against possibility of default. [17] The owner of the CDS makes periodic payments to the seller and receives a payoff if the underlying sovereign bond undergoes a credit event. The premium on the CDS therefore depends on the credit risk of the government issuing the underlying bond. Therefore, the CDS spread reflects the market assessment of the sovereign's riskiness. I obtain monthly data on 5-year CDS spreads from Bloomberg from 2000 to 2025 and match it with the cyclone data. This results in a sample of 36 countries who experience at least one hurricane and for which CDS data are available. Summary statistics are presented in Appendix A.13.

Additionally I employ data from the Global Macro Database (Müller et al. 2025). This dataset includes a dummy variable for a country experiencing a sovereign debt crisis, as well as data on government budget deficits at annual frequency. The coverage of this dataset is larger. When matched with the hurricane data I obtain a sample of 80 economies.

4.2.2. Estimation

My goal is to study the dynamic causal effect of cyclones on sovereign risk and how this might vary with adaptation. For this purpose I follow the local projection method proposed by Jordà (2005) to estimate impulse response functions. I proceed in two steps. First I estimate the unconditional effect of a cyclone on sovereign risk using the following specification:

$$y_{i,t+h} - y_{i,t-1} = \alpha_i + \alpha_t + \beta_h D_{i,t} + \epsilon_{i,t+h}, \tag{14}$$

where $h = 0, ...H$ is the horizon, y is the dependent variable of interest - here either

[17] The difference being that one can own a sovereign CDS without also owning the underlying bond.

$log(CDS)$ or *SovCrisis* - and D is the cyclone indicator variable. Equation 14 is estimated using OLS for the sample described above.[18] Impulse response functions (IRFs) are obtained by plotting the estimated β_h coefficients for with 90 percent confidence bands computed using robust standard errors allowing for two way clustering over countries and dates.

The timing, location and intensity of hurricane exposure is unpredictable and stochastic across years, conditional on each country's average climate and trends in climate, whose effects are absorbed by country fixed effects and year effects. Following Hsiang and Jina (2014) this allows us to assume that D is exogenous and uncorrelated with other unobserved factors that influence sovereign risk, permitting the causal effect of hurricanes on sovereign risk at horizon h to be identified by the coefficient β_h.

Second, in order to investigate the role of adaptation in mediating the response of sovereign risk to cyclones, I split the sample and re-estimate equation 14. In the 'High Adaptation' sample I include countries for which their average adaptation investment as a proportion of GDP is greater than the median, and in the 'Low Adaptation' sample I include the remaining countries.

4.2.3. Results

Figure 5 presents the IRF for a cyclone shock to CDS spreads. There is an increase of CDS spreads on impact which cumulates over time. Six months after the cyclone shock, CDS spreads are around 1.5% higher. In sample this is approximately a 4 basis point increase. The increasing effect over time is consistent with sovereigns increasing borrowing in the process of recovery to the shock. It is also consistent with the prediction of the model that cyclones increase default probabilities.[19]

Cyclones increase sovereign risk. How is this affected by adaptation? It is not possible to answer this question using the CDS data, as the overlap between countries for whom CDS data is available, and that are included in my Latin American and Caribbean adaptation sample is too small.[20] Therefore, in order to consider the role of adaptation in the relationship between cyclones and sovereign risk I instead use a dependent variable for which there is better coverage: the *SovCrisis* dummy variable from the Global Macro Database.

[18] This approach follows that of Gilchrist et al. (2022).

[19] For the table summarizing these results see Appendix A.14

[20] However, the result presented in Figure 5 that cyclones cause CDS spreads to increase does still hold in the restricted sample of countries also included in the adaptation sample.

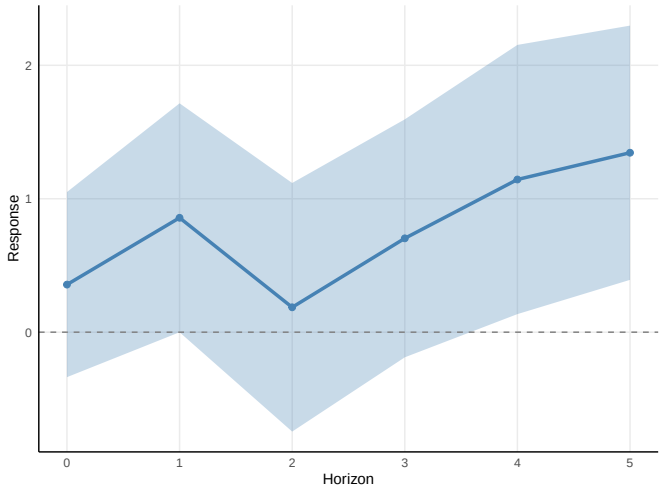


FIGURE 5. Impulse Response Function of CDS spreads to a cyclone shock over a horizon of six months. 90% confidence bands are shaded in blue.

Figure 6 plots the IRF estimates from equation 14 with the Sovereign Crisis dummy as the dependent variable. This dummy is available at *yearly* frequency. The probability of a sovereign debt crisis increases slightly on impact. It reaches it's peak elevation two years after the cyclone hits. In this period an affected sovereign is about 2.5% more likely to enter a debt crisis. This delayed impact of the storm on sovereign risk is also consistent with the story whereby sovereigns increase borrowing in response to the shock.

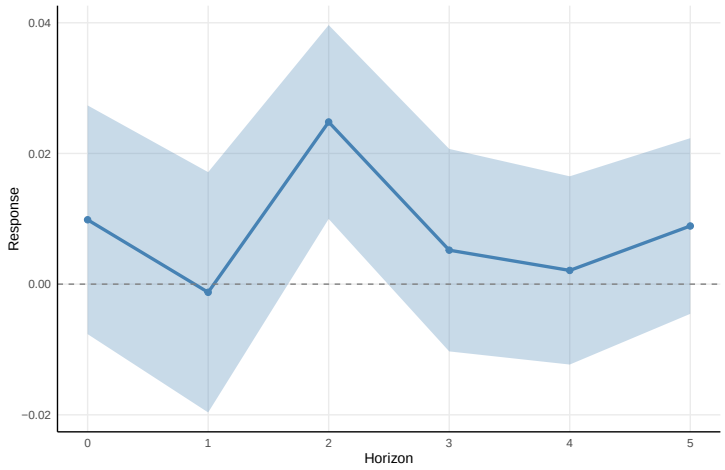


FIGURE 6. Impulse Response Function of Sovereign Crisis dummy to a cyclone shock over a horizon of six months. 90% confidence bands are shaded in blue.

Figure 7 shows how this response varies across the two subsamples. The figure shows

that the increase in sovereign risk after a cyclone is driven by countries with low levels of adaptation. For countries with higher levels of adaptation there is no statistically significant increase in crisis probabilities. In fact, the probability of a debt crisis actually decreases one year after the shock. However, for countries with low levels of adaptation default probabilities increase on impact and remain elevated. This is consistent with the prediction from the model that adaptation attenuates the effect of natural disaster shocks on default probabilities.

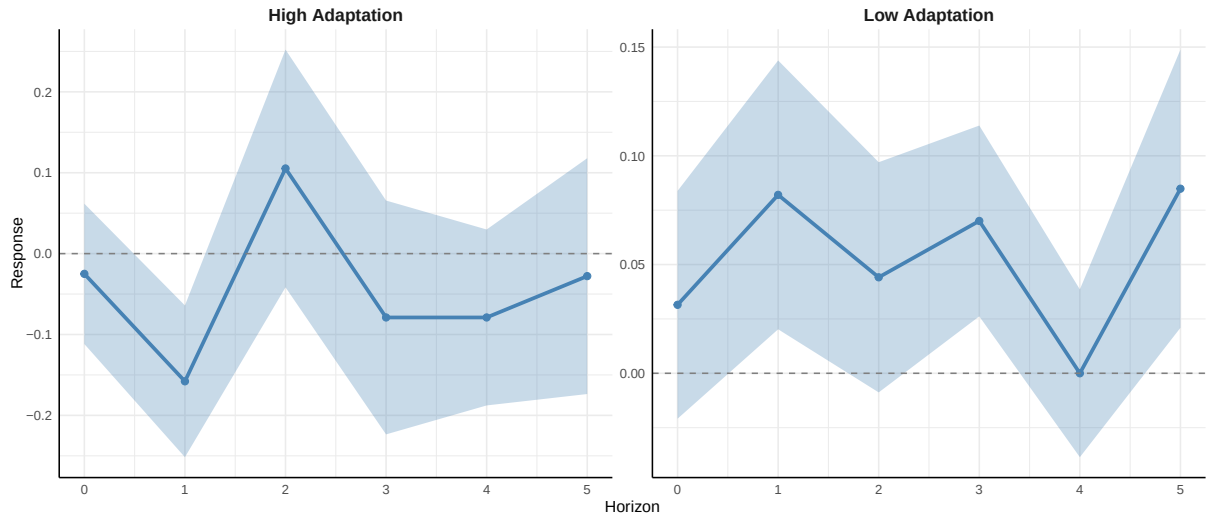


FIGURE 7. Impulse Response Function of Sovereign Crisis dummy to a cyclone shock over a horizon of six months. 90% confidence bands are shaded in blue. Left panel shows IRF for the subsample of countries with above the median level of adaptation investment as a proportion of GDP. The right panel shows the IRF for the subsample with below the median level of adaptation.

5. Quantitative Analysis

I leverage the model to examine the quantitative importance of the sovereign risk - adaptation channel. Additionally the model is used to simulate counterfactuals: outcomes under climate change, and under debt relief scenarios.

5.1. Quantification

Output costs of default are given by the function $\phi(y_t)$. As in Arellano (2008) output costs of default are asymmetric and increasing in the endowment realization in a piecewise-linear fashion:

$$\phi(y) = \left\{ \begin{array}{ll} \hat{y} & \text{if} \quad y > \hat{y} \\ y & \text{if} \quad y \leq \hat{y} \end{array} \right\},$$

where

$$\hat{y} = \omega \mathbb{E}(y).$$

Asymmetric output costs allow the quantitative model to deliver empirically observed historical default probabilities. Output contractions after default are also consistent with empirical observation that sovereign default disrupts the functioning of the private financial market and the assumption that such private credit is an important input to production.

Households' utility takes the standard constant relative risk aversion (CRRA) form:

$$U(c) = \frac{c^{1-\gamma}}{1-\gamma},$$

where the parameter γ determines the degree of risk aversion.

The adaptation function $F(\Lambda)$ takes the following form as in Fried (2022):

$$f(\lambda_t) = exp\left(-\alpha \lambda_t^{1/\alpha}\right),$$

where the parameter $\alpha > 1$ determines how effective adaptive capital is at reducing damages from a disaster shock. The marginal benefit of adaptive capital is increasing in α. Crucially, the data on adaptation expenditures will allow me to pin down this parameter.

The model is calibrated at annual frequency. For the baseline calibration I restrict

attention to Caribbean economies included in my adaptation expenditure dataset. For these economies, cyclones are by far the most frequent and severe natural disaster, allowing me to calibrate the endowment process using physical data on cyclones. Three parameters are set to standard values from the literature, five are calibrated externally from the data, and four are estimated internally to match a set of population weighted target moments. Table 3 summarizes the calibration.

Parameter		Value	Source/Target statistic
Parameters set Externally:			
Relative risk aversion	γ	2	Standard
Readmission probability	η	0.33	Richmond and Dias (2009)
Depreciation	δ	0.1	Standard
Parameters Estimated Externally:			
Risk free rate	r	0.0451	US T-Bill
Duration	ψ	0.0564	Average Maturity
Hurricane Frequency	p	0.103	NOAA
Endowment autocorr	ρ	0.95	Data
Endowment st dev	σ_ϵ	0.021	Data
Disaster st dev	σ_d	0.031	Data
Parameters Set Internally:			
Discount factor	β	0.903	Debt/GDP
Output cost	κ	0.671	Mean Spread
Hurricane intensity	μ_d	0.096	Mean hurricane loss
Adaptation benefit	α	2.496	Adaptation investment/ GDP

TABLE 3. Calibrated Parameters: Caribbean.

Externally Set Parameters. The coefficient of relative risk aversion γ is set to a standard value of 2. The readmission probability η is set to 0.33, consistent with the average re-entry rate as estimated by Richmond and Dias (2009). I set the depreciation of adaptation capital δ to 0.1. An additional five parameters are externally calibrated to the data. The risk free rate r is set to the average annual T-Bill rate from 1980 to 2025. The duration ψ is set to match a population weighted average maturity of the countries in my sample. I set the probability of a disaster to the empirical frequency of cyclone strikes of at

least category 1 speed between 1980 and 2025. I estimate the endowment process by regressing logged and de-trended GDP for each country on its lag and a cyclone indicator:

$$log(y_t) = \rho log(y_{t-1}) - \beta_1 * x + \epsilon_y.$$

This specification is equivalent to the endowment process in the model with

$$\beta_1 = E[d \cdot F(\lambda)].$$

Therefore, the estimate for β will combine the physical intensity of the disaster, d, and the extent of adaptation, $F(\lambda)$. From this regression I take a population weighted estimate for ρ from the coefficient on lagged de-trended GDP, σ_y from the standard deviation of the residual ϵ_y, and σ_d from the standard deviation of the damages β_1.

Internally set parameters:. I set the remaining parameters to jointly target a set of moments. The innovation of the calibration strategy is to pin down the mean disaster losses and adaptation effects separately using the dataset on adaptation expenditures. The most informative moment for α, the parameter governing the effectiveness of adaptation, is the share of adaptation investment in GDP computed from the dataset on adaptation expenditures. Given a level of adaptation investment, the observed losses from a hurricane, β_1 as estimated above, is pinned down by the physical strength of the shock. Therefore the mean hurricane intensity, μ_d is calibrated to match the mean hurricane loss.

The discount factor, β, and the output loss of default, κ, are set to match the debt to GDP ratio and the mean spread. Data on these variables are obtained from the Global Macro Database and the JP Morgan EMBI. All moments are weighted by population.

5.2. Model Performance

Model fit is shown in Table A9. The first section of the table shows the targeted moments. The second section shows untargeted moments for which data counterparts are available. The third section shows untargeted moments for which empirical counterparts are not readily available. The model matches well the empirical observations of natural disasters, adaptation, and fiscal conditions. Welfare is 5.1% lower than it would be in the absence of hurricanes. [21]

[21] See Appendix C.2 for the simulated moments for the economy without hurricane risk.

	Model	Data
Targeted		
Adaptation Investment/GDP	0.003	0.003
Debt/GDP	0.410	0.414
GDP loss | Cyclone	0.052	0.050
Mean Spread	502	526
Untargeted		
Default Frequency	0.048	0.051
Untargeted		
Adaptation Capital/GDP	0.029	
Percent Damages Avoided	0.45	
Market Value Debt/GDP	0.37	
Median Spread	121	
Welfare Loss		
	5.1%	

TABLE 4. Simulated Moments: Model Fit
The table presents selected moments of the baseline model and corresponding moments from the data. The model is simulated for 9, 000 periods. Welfare loss is the consumption equivalent welfare change compared to a counterfactual with no hurricanes.

Additionally, the mechanisms linking climate change, adaptation, and sovereign risk outlined in section 3 are visible in the full model. Figure 8 shows that the bond price is increasing in the level of adaptation. Adaptation protects the sovereign against hurricane strikes. The price of a bond is lower in states where the bad shock occurs, but the gap between the bond price in the no-hurricane state and the hurricane-state is increasing in the level of adaptation. As adaptation increases the bond price in the hurricane state converges to that in the non-hurricane state, as the hurricane no longer affects the endowment. The price of the bond in the non-hurricane state is also increasing in adaptation. This is because adaptation reduces future default probabilities. At high levels of debt, default probabilities are already high regardless of adaptation choices and hurricane strikes. Therefore the gap between the bond price curves is smaller.

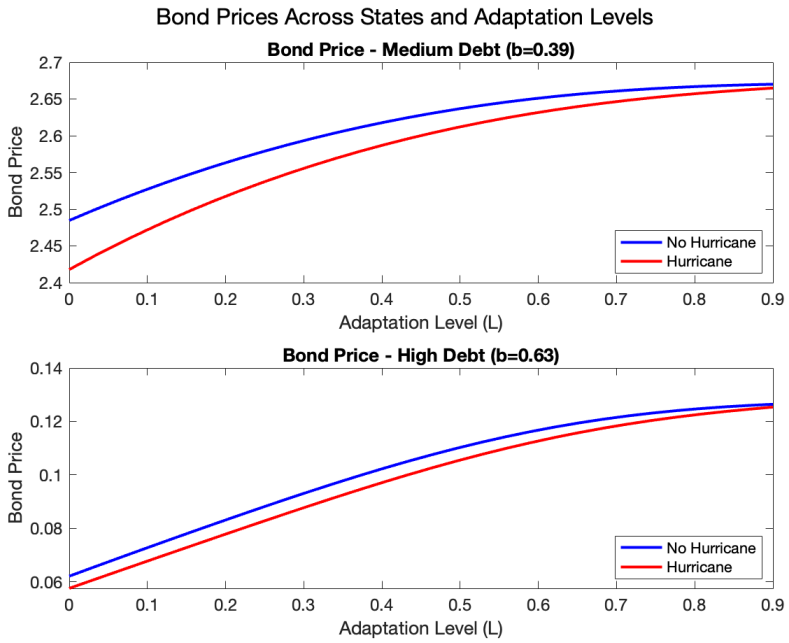


FIGURE 8. Sovereign Bond prices for different levels of adaptation. The panes show results for different levels of debt.

5.3. Counterfactuals

5.3.1. Perfect Financial Markets

How does sovereign risk affect adaptation and the welfare costs of natural disasters? I compare the model outcomes to those of a counterfactual where the default policy is set to zero in all periods. In this counterfactual the sovereign can fully commit to repaying debt and so borrows at the risk free rate.

Table 5 shows the counterfactual moments. Welfare gains are computed in terms of the consumption equivalent welfare changes and correspond to the percentage increases in consumption that an agent in the baseline economy should receive in any period and in any state of the world to achieve the same utility as in the economy without cyclones.

Under commitment adaptation/ GDP is 13% higher than under default risk. The sovereign is able to borrow more cheaply. Its budget constraint slackens and it chooses to invest more in adaptation. This translates to a larger stock of adaptation capital. As a result cyclones are less costly. In the counterfactual without default risk, cyclones are 10% less damaging. These results imply that the sovereign risk-adaptation channel is responsible for a quantitatively important share of total losses from natural disasters.

	Model	Commitment
Adaptation		
Adaptation Investment/GDP	0.003	0.0034
Adaptation Capital/GDP	0.029	0.032
Cyclones		
GDP loss per Cyclone	0.05	0.045
Percent damages avoided	0.45	0.53

TABLE 5. Simulated Moments: Perfect Financial Markets Counterfactual.
The first column presents simulated moments from the baseline model. The second column presents moments from a perfect financial markets counterfactual. In this counterfactual the default policy is set to zero in all periods.

5.3.2. Climate Change

Climate change is projected to increase the frequency and severity of cyclones. How will this affect the adaptation motive under sovereign risk versus under commitment? I show that climate change increases the wedge between adaptation investments in these two scenarios.

Following Mallucci (2022) I consider projected increases in frequency and severity of cyclones by the end of the century drawing on the scientific literature. In particular I consider a 29.2% increase in frequency, and a 48.5% increase in severity.[22] Table 6 presents select simulated moments from these climate change scenarios.

The table shows that climate change increases adaptive investments. Climate change increases the expected benefits from adaptation, increasing the incentives for the sovereign to adapt. The sovereign therefore accumulates a larger stock of adaptive capital. This is the case both when only the probability or severity of a cyclone increases, and when both increase together. As climate change leads to greater adaptation, the fraction of damages avoided under climate change grows. However, this increase in adaptation is not sufficient to offset the increase in the hazard. Therefore, the climate change scenarios are associated with welfare losses.

As well as the direct effect of climate change on cyclone strikes and associated losses, there are indirect effects that operate through the value of debt and default probabilities. Climate change increases default probabilities. This lowers the value of government

[22]The frequency projection comes from Bhatia et al. (2018). The severity projection is the mean from Mejia (2016).

debt, increasing spreads and tightening the budget constraint. Debt to GDP ratios are therefore also lower under climate change.

The final column presents simulated moments for the model under climate change without default risk. In this commitment counterfactual adaptation investment/GDP is 31% higher. The wedge between adaptation investment under commitment vs default risk is therefore higher as hazard exposure increases. Under perfect financial markets the sovereign is able to respond to the greater threat of cyclones by investing much more in adaptation. Under default risk the sovereign is constrained and under-invests. Due to diminishing returns from adaptation investment, the wedge between GDP losses from cyclones increases by less. GDP losses from cyclones are 13% greater due to the sovereign risk-adaptation channel under the climate change scenario.

	Baseline	Frequency $1.292 \cdot p$	Severity $1.485 \cdot \mu_d$	Both	Perfect Markets
Adaptation					
Adaptation Investment/GDP	0.003	0.0036	0.0039	0.0045	0.0059
Adaptation Capital/GDP	0.029	0.035	0.037	0.044	0.056
Cyclones					
Frequency	0.1	0.1292	0.1	0.1292	0.1292
GDP loss | Cyclone	0.052	0.051	0.076	0.071	0.063
Percent Damages Avoided	0.45	0.47	0.47	0.50	0.56
Debt					
Debt/GDP	0.41	0.40	0.38	0.38	1.65
Market Value Debt/GDP	0.37	0.33	0.31	0.31	1.65
Mean Spread	502	549	640	646	
Median Spread	121	156	173	181	
Default Frequency	0.048	0.049	0.05	0.05	

TABLE 6. Simulated Moments: Climate Change.
This table presents select simulated moments for the baseline model and climate change counterfactuals. In the first column, moments are for the baseline calibration. The second column considers a scenario whereby the probability of a cyclone increases by 29.2%. In the third column mean losses from cyclones are 48.5% larger than in the baseline. The fourth column presents the integrated climate change scenario in which both the frequency and severity of the cyclone shock is elevated. The final column presents results from the scenario with climate change but without default risk.

5.4. Debt Relief: *Work In Progress*

Sovereign risk tightens government budget constraints, limiting investment in adaptation, and so increasing the costs of climate change. Emerging market economies have called for debt relief policies to increase fiscal space for adaptation. Could such policies be effective? At what cost? I consider a number of such proposals: debt forgiveness, an interest free loan, and coupon suspension. As in Arellano, Bai, and Mihalache (2024) I find that such policies can be effective.

5.4.1. Interest Free Loan

I model a loan program by introducing an official lender who offers a default free loan of a fixed size to the sovereign.[23] The International Monetary Fund established the Resilience and Sustainability Trust (RST) in 2022. This new lending facility was earmarked to provide long term funding to bolster countries' capacity to address climate change and their pandemic preparedness. The loan program considered in this section is motivated by this facility. I consider the role of a financial assistance entity for easing financial constraints and so increasing adaptation to climate change. As the IMF is the most senior lender very few of its loans are in arrears (Schlegl, Trebesch, and Wright 2019). Therefore I consider such a loan to be default free.

In this counterfactual the sovereign gets F as a lump-sum in period $t = t^*$[24]. A grace period follows in which the sovereign does not have to repay the loan. After g periods of grace, repayment begins. The sovereign repays $\tilde{F}$ each following period in perpetuity. The official lender breaks even at the risk free rate. Therefore the terms of the loan are such that:

$$\tilde{F} = r(1+r)^g F.$$

I evaluate a loan with a size of 10% of pre-loan output, with a grace period of 3 years. Table 7 presents the outcomes under this loan program. The first column shows simulated moments for the economy in the case where there is no such loan i.e. the baseline results. The second column presents moments for the loan program counterfactual.

The loan program generates substantial benefits. The sovereign primarily uses the loan to increase adaptive investments. In particular, adaptation investment as a

[23] This experiment follows Arellano, Bai, and Mihalache (2024).

[24] In the simulations I first simulate the baseline economy for 5000 periods. i.e. this lump sum loan occurs in period 5001. The simulation runs for 10, 000 periods total.

	Baseline	Loan Program
Adaptation		
Adaptation Investment/GDP	0.003	0.0031
Adaptation Capital/GDP	0.029	0.030
Cyclones		
GDP loss per Cyclone	0.05	0.048
Percent damages avoided	0.45	0.48

TABLE 7. Simulated Moments: Loan Program Counterfactual.
The first column presents simulated moments from the baseline model. The second column presents moments from the interest free loan counterfactual. The loan program consists of a long-term, default-free loan equivalent to 10% of output. The baseline model is simulated for 5000 periods. The loan is introduces in period 5001. Simulated moments are the average over periods 5001 to 10000.

proportion of GDP rises by almost 5%. This is 38% of the gap between adaptation under default risk versus under perfect financial markets. As a result of greater adaptation investment, the stock of adaptive capital increases, reducing the losses from hurricanes. Hurricanes are 4% less costly due to this larger stock of protective capital. The interest free loan therefore reduces hurricane losses by 40% of the total potential reduction from completely frictionless financial markets.

5.4.2. Voluntary Restructuring

5.4.3. An Adaptation Bond

6. Conclusion

I have studied the costs of climate change for emerging markets in an environment with financial frictions and endogenous adaptation. These economies are subject to the joint challenges of high natural disaster exposure and tight fiscal space. I have shown empirically, theoretically, and quantitatively that the financial friction leading to elevated borrowing costs restricts the ability of emerging markets to adapt to climate change. Comparing my model to an otherwise identical one without the risk of default, I have shown that sovereign risk is responsible for 10% of the GDP losses from cyclones in the Caribbean, with this rising to 13% with climate change. This adaptation trap

dynamic is likely to be of concern to policymakers and opens the door to debt relief policies. Ongoing work examines the potential for debt relief policies to induce these sovereigns to invest more in adaptation, reducing the likelihood of disastrous cyclone damages and climate related credit events in the future.

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Appendix A. Data

A.1. Adaptation Measure: Initial Keywords

- adaptation
- climate_adaptation
- coastal_protection
- seawall
- shoreline_management
- coral_reef_restoration
- stormwater_management
- mangrove_plantation
- coastal_management
- urban_green_area
- air_conditioning_system
- shading
- drainage
- flood_insurance
- agricultural_insurance
- early_warning_system
- irrigation
- water_management
- natural_disaster_management
- national_disaster_management
- drought_management
- flood_management
- hazard_mapping
- cyclone_shelter
- storm_management
- wastewater_management
- managed_retreat
- ecosystem_restoration
- watershed_management
- wetlands_management

A.2. Adaptation Corpus

Adaptation discussions comprise of niche language. This generates problems for NLP models trained on general corpora of text. Therefore I train a model on a corpus of adaptation specific text. This enables me to generate more reliable word embeddings and discover adaptation specific keywords related to my initial set of keywords.

Adaptation specific text comes from a number of sources:

- Adaptation sections of Nationally Determined Contributions, as submitted to the UN
- National Adaptation Plans, as submitted to the UN
- UNEP Adaptation Gap Reports
- UNFCCC Adaptation related reports
- Adaptation Communications, as submitted to the UN
- Country Climate and Development Reports, from the World Bank
- Reports from the Global Commission on Climate Adaptation
- Adaptation specific reports from the World Bank and Asian Development Bank

Each of these sources comprise of discussion of adaptation to climate change using specific language.

A.3. Text Pre-Processing

I find and replace meaningful phrases in the corpus of adaptation related text with a single term. These phrases are constructed as follows:

a. Initial phrases from the initial set of keywords
b. Additional unigrams and multiword phrases. To identify these I tag all of the words in the corpus using a part-of-speech tagger from the Stanford NLP group. I then tabulate patterns that are likely to correspond to meaningful sequences. The final set of phrases is the resulting unigrams, bigrams and trigrams that appear more than 20 times in the corpus.

I then follow the standard steps to complete the pre-processing:

a. Lowercase all text
b. Tokenize text by breaking it into individual terms
c. Drop common words from a standard stopword list

A.4. Final Set of Keywords

coastal_adaptation	waterfront_protection	water_conservation
coastal_protection	gullies	water_storage
coastal_retreat	shore_nourishment	water_saving
coastal_management	shoreline_management	rainwater_harvesting
coastal_infrastructure	integrated_shoreline	water_supply
coastal_protection	coral_reef_restoration	water_quality_management
coastal_restoration	reef_restoration	groundwater
coastal_resilience	coral_reef	aquifers
coastal_degradation	reef_protection	renewable_water
coastal_risk	reef_system	water_levels
coastal_zone_protection	vegetation_restoration	water_efficiency
terrain_raise	sedimentation	water_tank
sea_level	soil_management	water_investment
sea_surge	soil_erosion	water_harvesting
sea_grass	salinization	water_resource_management
salt_marsh	erosion_control	surface_water
sea_defense	sludge_management	watershed_area_management
groyne	storm_surge_protection	adaptation
sea_wall	stormwater_management	climate_adaptation
wetlands_restore	risk_mapping	disaster_risk
wetlands	hazard_risk	disaster_preparedness
wetlands_management	environmental_hazards	post_disaster
wetland_protection	hazard_information	disaster_recovery
mangroves	hazard_data	disaster_prevention
mangrove_conservation	bush_fire	disaster_relief
mangrove_protection	fire_management	disaster_resilience
mangrove_reefs	forest_fire	emergency_management
mangrove_restoration	wildfire	emergency_preparedness
mangrove_planting	shading	national_emergency
mangrove_forests	shade	emergency_shelter

TABLE A1. List of Final Keywords (Part 1)

river_restoration	agroecology	drought
river_defense	agroecological	drought_management
river_basin_management	agroforestry	drought_preparedness
river_training	retreat	drought_index
basin_management	evacuation	flood
green_space	soil_conservation	flood_management
green_areas	forest_management	flood_mitigation
green_infrastructure	vulnerability_assessment	flood_defense
green_building	remote_sensing	flood_prevention
green_resilience	climate_services	flood_control
air_conditioning	forecasting	flood_infrastructure
cooling	weather_data	weather_observation
cooling_system	weather_forecast	hydrometeorological
evaporative_cooling	meteorological	climate_information
thermal_system	climate_vulnerability	emergency_communication
drainage	climate_assessment	climatological
drainage_infrastructure	disaster_management	green_climate_fund
flood_drainage	hydrological	gcf
urban_drainage	gef	unfccc
storm	flood_forecast	climate_resilience
hurricane	flood_model	resilient_infrastructure
cyclone	flood_risk	climate_response
breakwater	flood_resilience	mitigation_infrastructure
revetment	flood_preparedness	natural_disaster
levee	flood_protection	climate_disaster
culvert	fluvial_flood	disaster_response
beach_nourishment	hazard_mapping	disaster_management
seawall	storm_management	disaster_adaptation
tidal_barrier	stormwater	adaptation_plan
dune_restoration	tropical_storm	climate_resilience

TABLE A2. List of Final Keywords (Part 2)

A.5. Keyword discovery example

	Initial Term: sea wall
Output Term	**Cosine Similarity**
sea defense	0.89
groyne	0.86
tidal barrier	0.81
dune restor	0.79
waterfront protec	0.78
gullies	0.72
breakwater	0.71

A.6. Sample Construction

I include country-year observations that have the following characteristics

- In Latin America or the Caribbean
- Budgets in English or Spanish
- Budget is machine readable
- Sovereign is rated in that year

Latin America contains 18 sovereigns, the Caribbean contains 13 sovereigns. I restrict attention to the time frame 2014-2025. I lose observations for the following reasons

a. Due to language I lose two countries: Haiti and Brazil
b. Due to lack of ratings I lose three countries: Saint Lucia, Angtigua and Barbuda, Dominica
c. Due to lack of availability of machine readable budgets I lose seven countries: Trinidad and Tobago, Cuba, Bolivia, El Salvador, Nicaragua, Paraguay, Venezuela
d. I lose a further 74 country-year observations due to lack of budget availability

This leaves a final sample which is an unbalanced panel of 19 economies from 2014-2025. I have 163 country-year observations.

A.7. Line Item Descriptive Statistics

I provide descriptive statistics on the number of line items identified by the transfer learning procedure in government budgets.

	N	Mean	St. Dev.	Min	Max
No. Line Items (country x year)	163	17.7	23.3	3	126
No. Line Items (country average)	19	20.33	23.4	4.9	75.4

	N	Corr	p-value
(Line Items, T/GDP)	163	-0.0967	0.2489
(avg Line Items, avg T/GDP)	19	-0.131	0.589

There is no satistically significant correlation between the number of line items identified in a budget and the dollar amount of adaptation expenditure listed.

A.8. Adaptation and Exposure

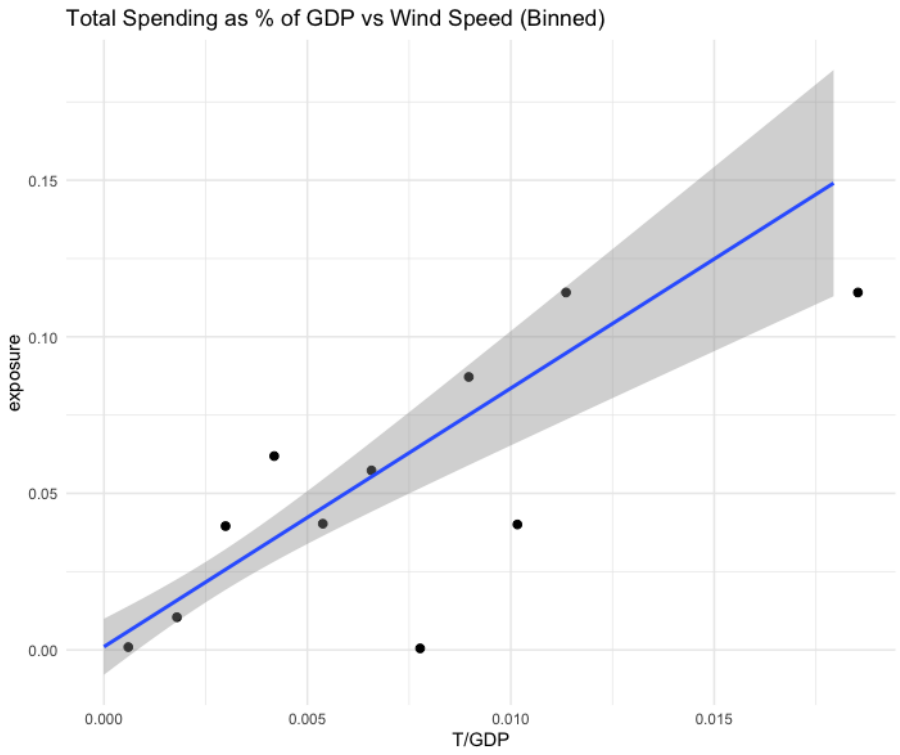


FIGURE A1. Relationship between adaptation expenditure and natural disaster exposure. The exposure measure is historical average maximum wind speeds scaled by land area. Windspeed data comes from the GeoMet database (Felbermayr and Gröschl 2014)

A.9. Adaptation: Cross Sectional Results

This section considers the analysis of the adaptation measure in terms of cross-country differences. In particular I present results for adaptation expenditure across the 19 countries in my sample for the year 2023. I show that similar patterns to those presented in the main text obtain for cross-country comparisons.

I find that adaptation expenditure is 0.43% of GDP on average in this year. Disaster preparedness expenditure is 0.11% of GDP on average. Summary statistics are reported in Table A3. On average countries in my sample have a government expenditure to GDP ratio of 25% meaning that adaptation comprises 0.92% of government expenditure.

TABLE A3. Summary Statistics

Statistic	N	Mean	St. Dev.	Min	Max
Adaptation Total / GDP	19	0.43%	0.0024	0.0001	0.0082
Disaster Preparedness / GDP	19	0.11%	0.0022	0.0001	0.0098
Meteorological Services / GDP	19	0.03%	0.0005	0.0000	0.0009

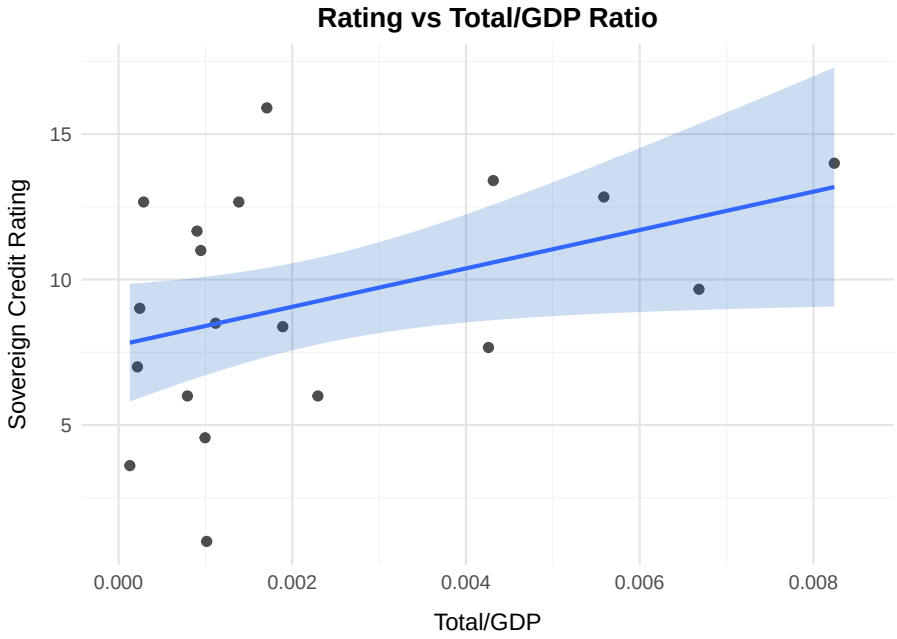


FIGURE A2. Adaptation Investment and Sovereign Ratings. Sovereign ratings are an average of the previous three years, on a scale from 0-21 from the World Bank fiscal space database (Kose et al. 2022). The adaptation measure is total adaptation spending as derived from the computational linguistics measure, shown as a proportion of GDP. The shaded region shows standard errors at the 90% level. The plot includes one observation for each country in the year 2023.

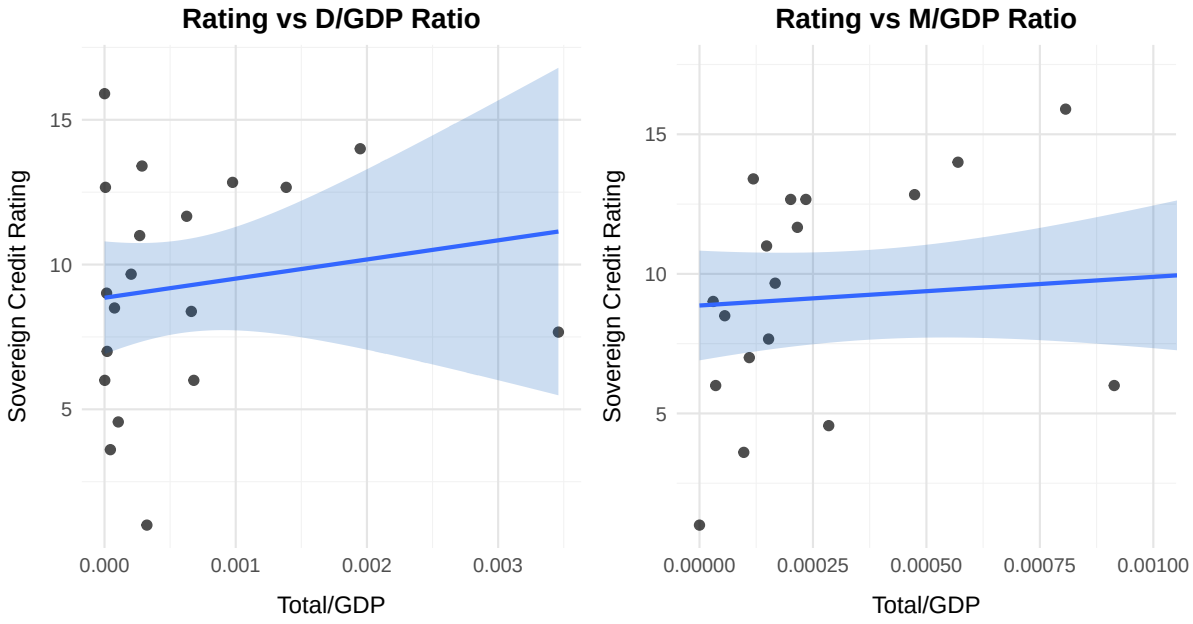


FIGURE A3. Adaptation Investment and Sovereign Ratings. Sovereign ratings are an average of the previous three years, on a scale from 0-21 from the World Bank fiscal space database (Kose et al. 2022). The adaptation measures are disaster preparedness and meteorological services spending, shown as a proportion of GDP.

	Adaptation Measure:		
	Total Adaptation	Disaster Preparedness	Meteorological Services
sovrate	3,900,370*	1,500,120	477,907
	(2,481,275)	(1,832,566)	(512,430)
GDP	0.003*	0.003*	0.0009
	(0.001)	(0.0007)	(0.002)
exposure	11,156,417	79,546,311	10,276,532
	(109,646,099)	(38,546,311)	(22,646,099)
Constant	–17,813,367	–10,673,342	–1,812,367
	(19,134,130)	(13,883,027)	(3,951,130)
Observations	19	19	19
R^2	0.909	0.939	0.382
Adjusted R^2	0.774	0.848	0.103
Residual Std. Error	12,408,556 (df = 2)	9,002,000 (df = 2)	2,562,000 (df = 2)

Note: *p<0.1; **p<0.05; ***p<0.01

TABLE A4. The first column uses the text based measure of adaptation as the independent variable. The second column uses disaster preparedness expenditure, and the third uses meteorological expenditure. All values are reported in US $

A.9.1. Adaptation Measure Validation

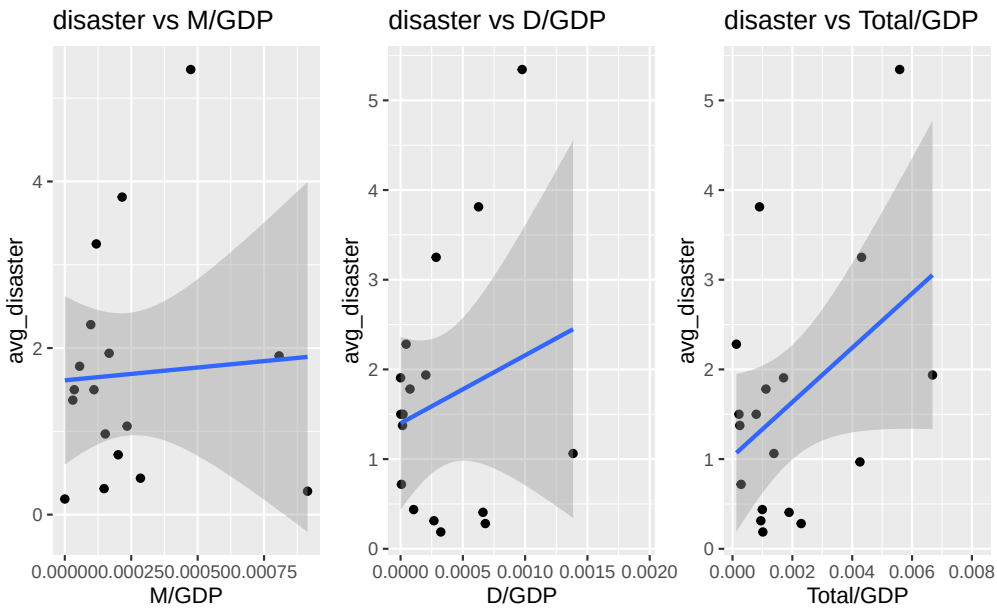


FIGURE A4. Adaptation Investment and Historical Exposure to storms. Each plot shows the relationship between one measure of adaptation and the historical average number of natural disasters per year from the EMDAT database 1980-2010.The leftmost panel has meteorological spending as a proportion of GDP, the middle panel disaster preparedness spending as a proportion of GDP, and the rightmost panel total adaptation spending as derived from the computational linguistics measure as a proportion of GDP.

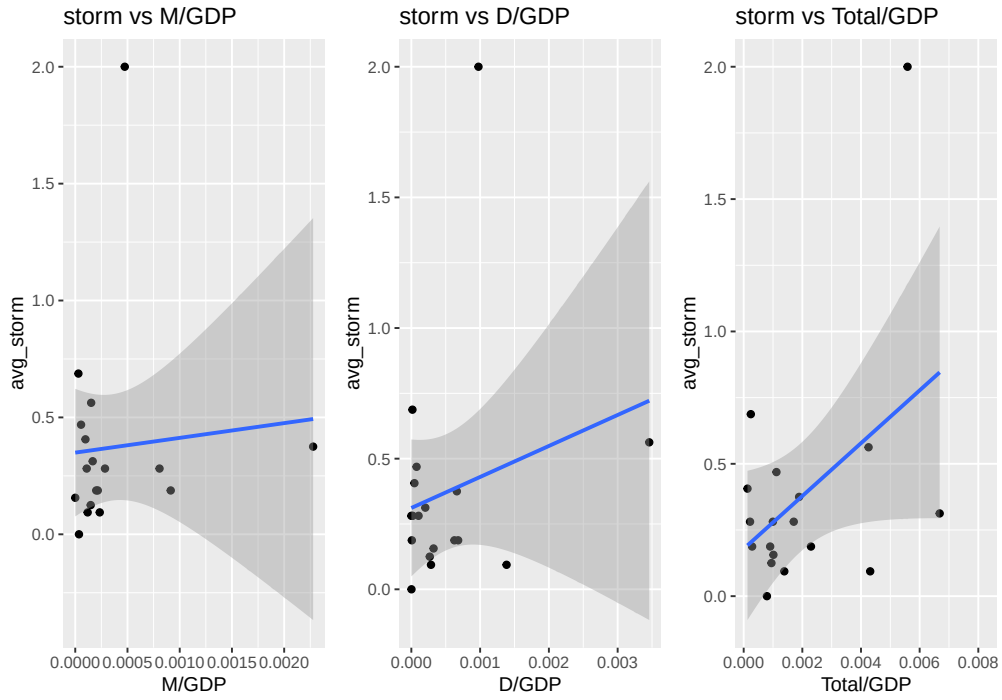


FIGURE A5. Adaptation Investment and Historical Exposure to storms. Each plot shows the relationship between one measure of adaptation and the historical average number of storms per year from the EMDAT database 1980-2010.The leftmost panel has meteorological spending as a proportion of GDP, the middle panel disaster preparedness spending as a proportion of GDP, and the rightmost panel total adaptation spending as derived from the computational linguistics measure as a proportion of GDP.

A.9.2. Caribbean Subsample

This section presents the results restricted to the subsample of Caribbean countries.

Figure A6 shows the relationship between sovereign ratings and adaptation for this subsample of countries.

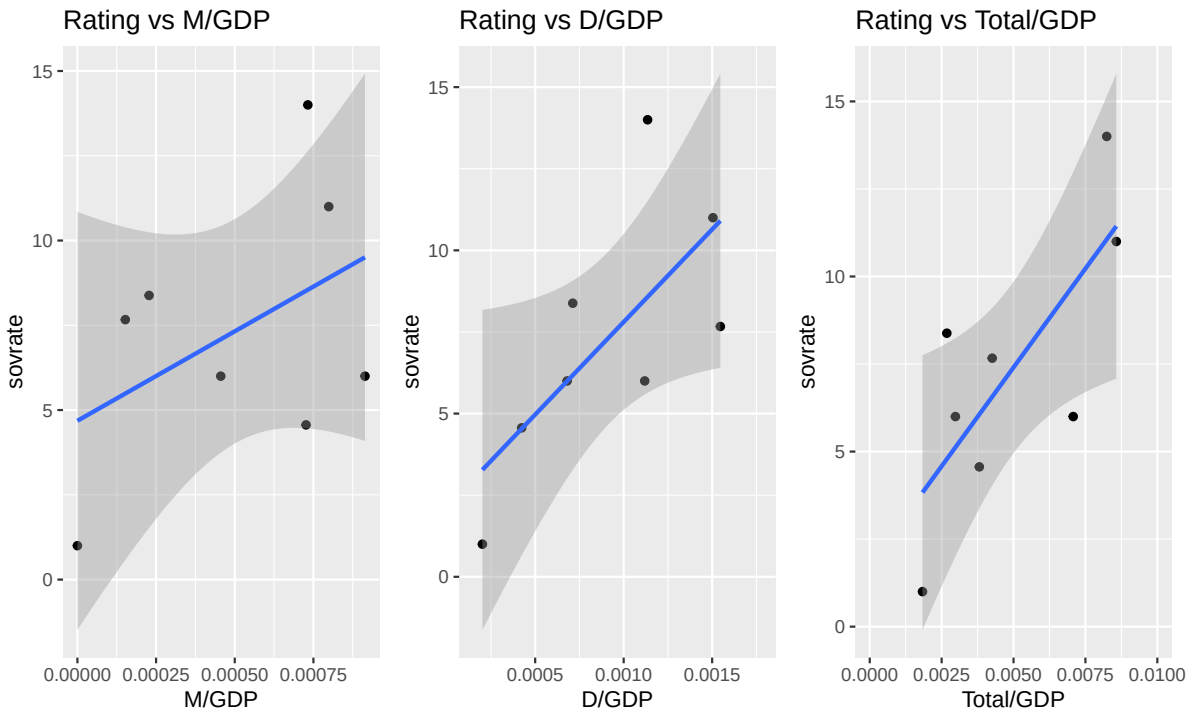


FIGURE A6. Adaptation Investment and Sovereign Ratings. Each plot shows the relationship between one measure of adaptation and sovereign ratings. Sovereign ratings are an average of the previous three years, on a scale from 0-21 from the World Bank fiscal space database (Kose et al. 2022). The leftmost panel has meteorological spending as a proportion of GDP, the middle panel disaster preparedness spending as a proportion of GDP, and the rightmost panel total adaptation spending as derived from the computational linguistics measure as a proportion of GDP.

Figure A7 shows the wordcloud for commonly used terms from the construction of the adaptation measure restricted to the Caribbean subsample.

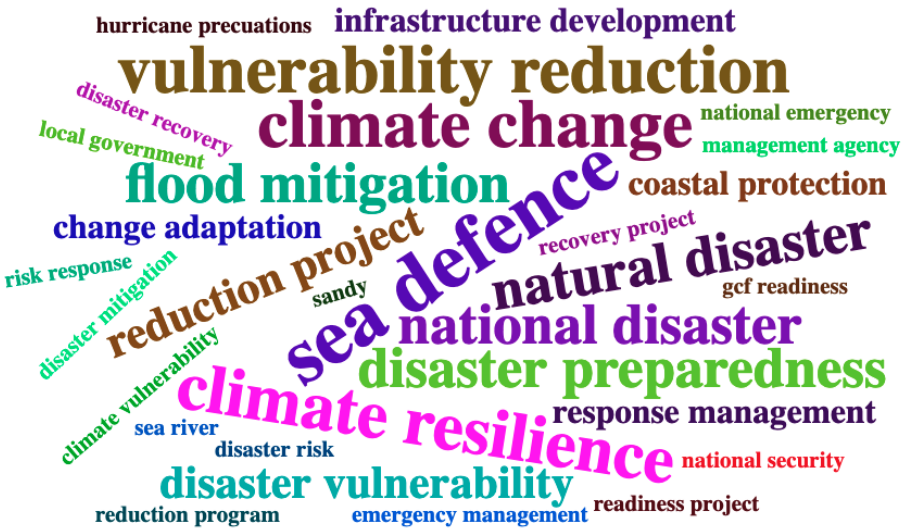


FIGURE A7. Word Cloud Representing the most frequently used terms in budget entries picked up when building the total adaptation measure: Caribbean subsample.

A.10. Narrative Evidence

The result presented in section 2 that adaptation is decreasing in sovereign risk is consistent with narrative evidence from ratings agencies, government speeches, and development banks.

In the note released upon Fitch's upgrade of Barbados to B+, the agency notes:

"As a small, open tourist economy, Barbados is highly exposed to external shocks, including, economic and natural disaster-related events. The government is working to build resilience to shocks by strengthening its fiscal resources, including reserve funds and insurance policies, and by aiming to improve infrastructure and facilitate greater self-reliance in the private sector. However, given the lack of meaningful fiscal space and limited resources currently available, a severe shock would be difficult to manage. Permanent institutionalization of these reforms is still in progress."[25]

This corroborates the pressure that high borrowing costs may put on a sovereign's ability to adapt to climate change.

Similarly, Moody's noted that:

"Barbados's economy is exposed to environmental risks (E-4 issuer profile score) due to the impact of weather-related shocks which are expected to increase in severity due to climate change. Exposure to physical climate risk due to recurring hurricanes negatively impacts economic performance, particularly the tourism sector, a key industry for the island. Barbados exposure is somewhat mitigated through ongoing efforts to improve resilience to shocks, transition to renewable energy sources and support from development partners."

In fact, in Moody's ESG methodology they note that they explicitly take adaptive capacity into account:

"The credit impact of long-term environmental trends or future hazards may be curbed or offset by other influences. These could include the implementation of regulations or technological changes that mitigate the effects of the trend, adaptation strategies such as improvements in physical and institutional infrastructure, or rising

[25] https://www.fitchratings.com/research/sovereigns/fitch-upgrades-barbados-to-b-outlook-stable-15-10-2024

income levels that increase a government's tax base, allowing it to finance needed improvements. Some environmental considerations straddle these categories, such as waste and pollution, where we consider the policy response and the potential direct effect of the hazards that may result."

"We apply qualitative judgment, in particular regarding the effectiveness of mitigants to environmental risks, considering the extent to which a sovereign's policies and plans designed to address these risks are sufficiently concrete and material. These mitigating measures may include investment in climate change adaptation."

A.11. Composition of Debt

Table A.3 shows that climate vulnerable countries in Latin America and the Caribbean tend to have relatively low shares of official debt out of total. The data comes from Fang, Hardy, and Lewis (2024).This underlies the relevance of sovereign ratings for borrowing costs and investment decisions.

Country	Share of Official Debt (%)
Argentina	7
The Bahamas	3
Barbados	20
Chile	3
Colombia	14
Costa Rica	7
Dominican Republic	16
Ecuador	29
Guatemala	26
Jamaica	22
Mexico	4
Panama	25
Peru	8
Uruguay	7
Average	14

TABLE A5. Share of Official Debt in Total Public Debt (2018)

Additionally relevant is the point often made by politicians in these countries, that due to their relatively strong fundamnetals they are not eligible for concessional finance from organisations such as the IMF. This further restricts their ability to borrow in order to adapt.

A.12. Total Government Expenditure and Sovereign Risk

The positive relationship between adaptation expenditure as a proportion of GDP and sovereign ratings can also be found in the more general case of total government expenditure as a proportion of GDP. Using data from the Global Macro Database (Müller et al. 2025) linked with the sovereign rating data from Kose et al. (2022), I document this relationship.

Figure A8 shows that in 2022 countries with higher sovereign ratings tended to have higher government expenditures as a proportion of GDP.



FIGURE A8. Bin scatter plot of government expenditure as a proportion of GDP, against sovereign rating average from the previous three years. The plot uses data on expenditure from the Global Macro Database for the year 2022.

When I restrict attention to the countries in my sample from Section 3, however, this positive effect is no longer visible. In the matching of the datasets I lose the observation of Turks and Caicos. Figure A10 shows a scatterplot of government expenditure as a proportion of GDP against sovereign ratings. Here the relationship between the variables is flat.

This could be taken to indicate that the relationship between adaptation investment and sovereign risk is stronger than that between total expenditure and sovereign risk. In both cases it could be argued that higher ratings allow governments to borrow and

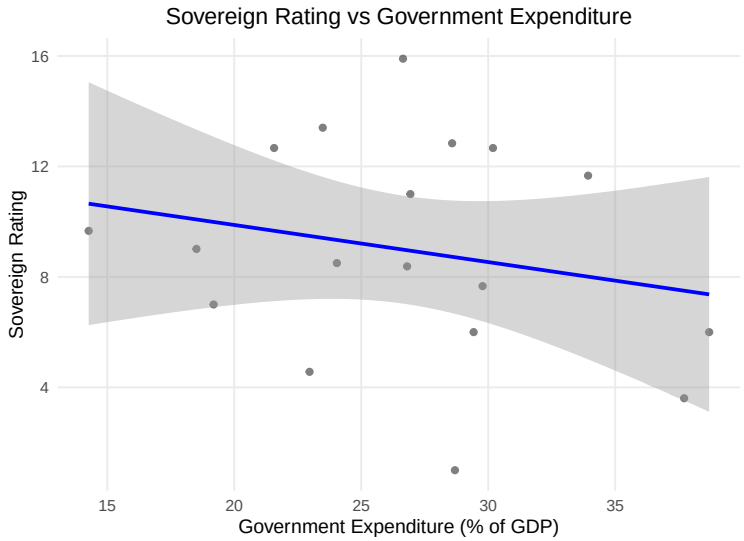


FIGURE A9. Bin scatter plot of government expenditure as a proportion of GDP, against sovereign rating average from the previous three years. The plot uses data on expenditure from the Global Macro Database for the year 2022. The sample is restricted to the 19 countries included in the main analysis.

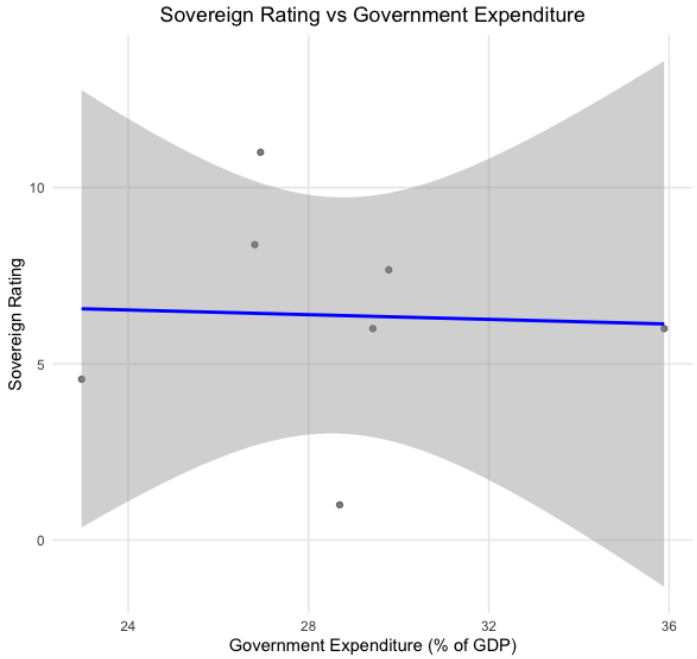


FIGURE A10. Bin scatter plot of government expenditure as a proportion of GDP, against sovereign rating average from the previous three years. The plot uses data on expenditure from the Global Macro Database for the year 2022. The sample is restricted to the 7 Caribbean countries included in the main analysis.

spend more. However, in the total expenditure case this higher spending may cause markets to lose confidence in the fiscal prudence of the sovereign. In the adaptation case, however, as the model indicates higher adaptation spending causes spreads to reduce as such spending reduces exposure to future bad shocks, lowering the probability of default.

A.13. Summary Statistics

TABLE A6. Mean Cyclone Frequency by Country: 1980-2025

country	mean
Algeria	0.02
Antigua and Barb.	0.15
Australia	0.98
Bahamas	0.50
Bangladesh	0.72
Barbados	0.11
Belize	0.37
Bermuda	0.07
Botswana	0.09
Brazil	0.04
Cabo Verde	0.09
Cambodia	0.43
Canada	0.70
China	0.96
Colombia	0.09
Costa Rica	0.02
Cuba	0.61
Dominica	0.07
Dominican Rep.	0.39
El Salvador	0.09
Ethiopia	0.04
Fiji	0.41
France	0.41
Greenland	0.04
Grenada	0.09
Guatemala	0.35
Haiti	0.26
Honduras	0.37

Hong Kong	0.11
Iceland	0.04
India	0.89
Indonesia	0.39
Iran	0.02
Ireland	0.15
Jamaica	0.15
Japan	0.96
Laos	0.83
Madagascar	0.85
Malawi	0.09
Malaysia	0.04
Mauritius	0.04
Mexico	0.96
Mongolia	0.02
Morocco	0.02
Mozambique	0.54
Namibia	0.04
Nepal	0.02
Netherlands	0.04
New Zealand	0.33
Nicaragua	0.48
Norway	0.04
Oman	0.24
Pakistan	0.17
Papua New Guinea	0.33
Philippines	0.96
Portugal	0.02
Puerto Rico	0.22
Russia	0.74
Saint Lucia	0.09
Saudi Arabia	0.04

Somalia	0.17
Somaliland	0.09
South Africa	0.09
South Korea	0.78
Sri Lanka	0.26
St. Vin. and Gren.	0.09
Taiwan	0.85
Tanzania	0.02
Thailand	0.80
Timor-Leste	0.07
Tonga	0.04
Trinidad and Tobago	0.15
Turks and Caicos Is.	0.09
United Kingdom	0.20
United States of America	0.96
Vanuatu	0.59
Venezuela	0.13
Vietnam	0.94
Yemen	0.15
Zimbabwe	0.20

TABLE A7. CDS spreads by Country

Country	mean	sd
Algeria	48.75	15.58
Australia	36.82	24.50
Belgium	42.54	62.33
Brazil	334.14	493.40
Canada	48.94	9.43
China	68.90	37.82
Colombia	200.23	123.91
Costa Rica	287.88	145.90
El Salvador	307.31	145.84
Ethiopia	297.15	148.72
France	39.21	41.10
Germany	21.68	20.71
Guatemala	176.31	63.07
Hong Kong	45.58	12.11
Iceland	111.97	44.65
India	48.75	15.58
Indonesia	170.32	106.49
Ireland	129.44	198.08
Japan	36.72	29.23
Malaysia	88.41	51.11
Mexico	134.83	66.47
Mongolia	297.15	148.72
Morocco	158.02	21.00
Namibia	297.15	148.72
Netherlands	29.50	29.19
New Zealand	47.81	11.58
Norway	15.05	10.83
Oman	131.80	33.81
Pakistan	295.63	147.21

Philippines	175.71	142.69
Portugal	163.06	259.91
South Africa	188.14	78.49
Spain	101.72	113.58
Thailand	82.95	51.33
Vietnam	129.19	77.54

A.14. Local Projection Results

Responses	h=0	Year h=1	Year h=2	Year h=3	Year h=4	Year h=5
B_h	0.36	0.86	0.19	0.70	1.14	1.34
	(0.69)	(0.86)	(0.93)	(0.89)	(1.01)	(0.95)

TABLE A8. Local Projection Results. Dependent variable: log CDS spreads.

Appendix B. Analytical Model

B.1. Proof of Propositions 2 and 3

Proof. Given 9, the partial derivative of s with respect to p is:

$$\frac{\partial s}{\partial p} = -\Phi_g(\bar{g}) + \int \Phi_g\left(\bar{g} - \frac{1}{1+\psi}\ln(1-d(F(\lambda))\right)\Phi_d\left(d'\right)$$

Since the support of Φ_d is $[0,1)$, it follows that $\frac{\partial s}{\partial p} > -\Phi_g(\bar{g}) + \int \Phi_g(\bar{g}) d\Phi_d\left(d'\right) = 0$, i.e., the spread is increasing in the probability of the disaster shock, as desired.

Furthermore, suppose $\hat{\Phi}_d$ first-order stochastic dominates Φ_d. Let $\hat{s}$ denote the spread function associated with the damage distribution $\hat{\Phi}_d$. Since $\Phi_g\left(\bar{g} - \frac{1}{1+\psi}\ln(1-d(F(\lambda))\right)$ is increasing in d', it follows that

$$E\left[\Phi_g\left(\bar{g} - \frac{1}{1+\psi}\ln(1-d(F(\lambda)))\right)\middle|\ \hat{\Phi}_d\right] \geq E\left[\Phi_g\left(\bar{g} - \frac{1}{1+\psi}\ln(1-d(F(\lambda))\right)\middle|\ \Phi_d\right].$$

It then immediately follows that $\hat{s} \geq s$, as desired.

B.2. Proof of Proposition 4

$$\frac{\partial s}{\partial \lambda} = pE_{d'}\left[\phi_g\left(\bar{g} - \frac{1}{1+\psi}\ln(1-d(F(\lambda)))\right)\cdot\frac{d\cdot F'(\lambda)}{(1+\psi)(1-d\cdot F(\lambda)}\right] < 0$$

This follows as the first term inside the square brackets is positive while the second is negative given the assumption on the domain of d and that $F(\lambda)$ is decreasing in λ. Therefore the derivative is negative.

Appendix C. Quantitative Model

C.1. Solution Algorithm

The model is solved numerically, using state-of-the-art techniques developed in the quantitative sovereign default literature. The process for output is discretized on a grid of 61 points. I also define a discrete grid for coupons and adaptation.

The iterative algorithm works as follows:

a. I form initial guesses for the unconditional debt price function and for the value functions
b. Given the initial guesses, I update the value function V_{nd} by solving the maximization problem in the market access case
   - Following Dvorkin et al. (2021), it is assumed that each possible choice of discrete values for debt and adaptation is associated with an additive taste shock.[26]
   - In this nested structure the sovereign chooses b' conditional on having chosen a particular Λ' subject to taste shocks, and that Λ' is chosen subject to taste shocks for a fixed b'.
   - In the presence of the extreme value shocks, the probability of choosing a given discrete value for debt or adaptation is increasing in the value associated with that particular choice and it is given by the multinomial logit formula.
   - Conditional on an arbitrary b', choice probabilities over Λ' are given by:

$$\Pr\left(\Lambda' = \Lambda_i \mid y, b, \Lambda, b'\right) = \frac{\exp \frac{W(y,b,\Lambda,b',\Lambda_i)}{\rho_\Lambda}}{\sum_j \exp \frac{W\left(y,b,\Lambda,b',\Lambda_j\right)}{\rho_\Lambda}} \tag{A1}$$

   with associated ex-ante value:

$$W_\Lambda\left(y, b, \Lambda, b'\right) = \rho_\Lambda \log\left[\sum_j \exp \frac{W\left(y, b, \Lambda, b', \Lambda_j\right)}{\rho_\Lambda}\right]. \tag{A2}$$

   - The outer choice over b' satisfies:

[26] Extreme value shocks follow a Type-1 Generalized Extreme Value distribution, with scale parameter ρ_{EV} which is set to 10^{-3} for both borrowing and adaptation capital. The introduction of these shocks facilitates convergence of the solution.

(A3) $$\Pr\left(b' = b_i \mid y, b, \Lambda\right) = \frac{\exp \frac{W_\Lambda(y,b,\Lambda,b_i)}{\rho_b}}{\sum_j \exp \frac{W_\Lambda\left(y,b,\Lambda,b_j\right)}{\rho_b}},$$

and the ex-ante value of repayment becomes

(A4) $$V_{nd}(y, b, \Lambda) = \rho_b \log \left[\sum_j \exp \frac{W_\Lambda\left(y, b, \Lambda, b_j\right)}{\rho_b}\right].$$

- The solution to the maximization problem defines the (average) policy function for borrowing and adaptation and conditional equilibrium price function for government debt.

c. I update the value function V by solving the discrete choice default problem.
   - I introduce extreme value shocks to the default problem in an analogous way to the problem for government borrowing and adaptation choices. The probability of default is therefore given by:

(A5) $$\tilde{d}(y, b, \Lambda) = \frac{\exp\left(\frac{1}{\rho_{EV}} V_d(y, \Lambda)\right)}{\exp\left(\frac{1}{\rho_{EV}} V_d(y, \Lambda)\right) + \exp\left(\frac{1}{\rho_{EV}} V_{\text{nd}}(y, b, \Lambda)\right)}.$$

   - The probability of choosing to default increases with the difference between the values of defaulting and repaying.

d. I update the default value function V_d making use of the update values of V and V_{nd}.
e. I repeat (b-d) until value functions have converged.
f. I update the unconditional debt price function by imposing the default policy and the average equilibrium price function.
g. I repeat (b-f) until convergence of the unconditional debt price function.

C.2. No Hurricane Counterfactual

	Baseline	No hurricane
Adaptation		
Adaptation Investment/GDP	0.003	
Adaptation Capital/GDP	0.029	
Cyclone		
GDP loss | Cyclone	0.052	
Percent Damages Avoided	0.45	
Debt		
Debt/GDP	0.410	0.481
Market Value Debt/GDP	0.37	0.45
Mean Spread	502	416
Default Frequency	0.048	0.039
Median Spread	121	88
Welfare Loss		
	5.1%	

TABLE A9. Simulated Moments: Model Fit
The table presents selected moments of the baseline model and corresponding moments from the model without hurricane risk. Simulations run for 9, 000 periods. Welfare loss is the consumption equivalent welfare change compared to the case with no hurricanes.