Climate Change, Adaptation, and Sovereign Risk

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Abstract

Many emerging markets face high borrowing costs and exposure to natural disasters. How will fiscal constraints affect the adaptation to, and therefore the losses from, climate change in such economies? 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. 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 estimated model. In the Caribbean 10% of GDP losses from cyclones are due to default risk. This loss increases with climate change but can be mitigated by debt relief policies.

JEL Classifications: F34, F41, Q54, Q56

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1. Introduction

Climate change is projected to increase both the frequency and severity of natural disasters in many countries. Emissions reductions 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. I show 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 in Latin America and the Caribbean 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. 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] Together, this paper provides new evidence that sovereign risk exacerbates the costs of climate change for emerging market economies.

The paper proceeds in four 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 resources available for consumption, 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 tightens the budget constraint, limiting the amount the sovereign can borrow. In the model default risk will increase the costs of natural disasters by generating under-

[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.

investment in adaptation.

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 without default risk. 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 in the absence of default risk, 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 no-default benchmark. For emerging markets (relatively high spread economies), the second channel dominates and adaptation is constrained by 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. 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 and within countries 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 from IBTrACS. I map the hurricane track data to affected countries and employ a local projection approach using data on CDS spreads for more than 30 countries, and default probabilities for 80 countries. I show that a hurricane strike increases CDS spreads by 1.5% six months after the event, accumulating gradually over the horizon. 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 a statistically significant increases in default probabilities of 5%. For the high adaptation subsample, the effect is not distinguishable from zero. 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 data I use these results to calibrate the quantitative version of the 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 the 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 without the default option, adaptation is substantially restricted. In the model without default risk, adaptation in the Caribbean is 13% higher than under sovereign risk. Default risk increases the GDP effects of cyclones by 10% relative to the no default risk benchmark. Therefore the sovereign risk - adaptation channel is 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 cyclones are also diverging further from their no default risk counterparts as the probability and severity 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 two such policies. First, a long term risk free loan motivated by the IMF's Resilience and Sustainability Trust (RST). Second, an adaptation bond. Such a bond reduces coupon payments once the sovereign reaches a pre-specified adaptation target. Both of these policies leads the sovereign to increase their adaptation investment. This lessens the GDP losses from natural disasters and so eases the welfare burden of cyclones.

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), Arellano (2008), and Chatterjee and Eyigungor (2012). Two existing papers embed natural disaster shocks into a model of sovereign default. Mallucci (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.[3] 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 presents the analytical results. Section 3 outlines the empirical methodology and results. Section 4 outlines the quantitative analysis including policy counterfactuals, and Section 5 concludes.

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), and natural disasters as in Mallucci (2022). To this framework I add 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.

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

The sovereign's lifetime value is:

$$v_0 = \sum_{t=0}^{\infty} \beta^t \mathbb{E}_0 \left(u \left(c_t \right) \right),$$

where $u(c_t)$ is the household's utility from consumption. The income process is given by:

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

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 Φ_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.[4] The stock of adaptation follows the law of motion:

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

where λ_t is investment in adaptation. Adaptation investment accumulates into next period capital.

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

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

access to financial markets with exogenous probability η. The resource constraint is therefore given by:

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

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:

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

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:

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

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

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

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.

2.2. 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 Schwartzman (2024):

$$\phi(y_t) = y_2\bar{l}e^{\psi g}.$$

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.[5]

2.2.1. No Default Risk Benchmark

I begin by outlining a benchmark version of the model where there is no default risk. The sovereign cannot default on its debt and so repays the issued bonds in period

[5] I will consider quadratic default costs in the quantitative model. These default costs have better quantitative properties. Note: while the model is a model of the cycle and not the trend I call g 'growth' for simplicity: it is the rate of endowment growth between period 1 and period 2 in the simple model.

two. This benchmark will be useful for examining the effects of the default option on adaptation. In this case consumption is given by:

$$c_1 = y_1 + \frac{1}{1+r}b - b_0 - \lambda, \qquad c_2 = y_1^{\rho}(1 - x_2 d_2 F(\lambda))\epsilon^{y} - b,$$

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. [6]

2.2.2. 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:

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

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 $c_D > c_R$, where:

[6] There is also an incentive for the sovereign to decrease its borrowing under climate change: a precautionary savings motive. See Appendix B.3

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

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

$$\underbrace{g + \frac{1}{1+\psi} ln(1 - x_2 d_2 F(\lambda))}_{\tilde{g}} < \underbrace{\frac{1}{1+\psi} ln(\frac{b}{\bar{l} y_1^{\rho}})}_{\bar{g}}, \tag{8}$$

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:

$$\begin{aligned} s(b, \lambda) &= \Pr\left[\tilde{g}' < \bar{g}(b)\right] \\ &= (1-p)\Phi_g(\bar{g}) + pE_{d'}\left[\Phi_g\left(\bar{g} - \frac{1}{1+\psi} ln(1 - d_2(F(\lambda))\right)\right] \end{aligned} \tag{9}$$

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

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

$$\frac{\partial s}{\partial p} = -\Phi_g(\bar{g}) + E_{d'}\Phi_g\left(\bar{g} - \frac{1}{1+\psi} ln(1 - d_2 F(\lambda)\right) > 0.$$

Proof. *Appendix B.*

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

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

Proof. *Appendix B.*

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*

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

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:

$$c_1 = y_1 + \frac{1-s}{1+r}b - b_0 - \lambda,$$

and the expected value of consumption in period two is the given by the default probability and the default and repayment values as in (B.5). 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:

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

The presence of default risk introduces two additional terms relative to the no default risk 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 no default risk 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 no default risk 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 no default risk 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 with default risk than without. Whether adaptation is higher or lower under default risk 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 without. However, for calibrations giving reasonable spread values for emerging economies, the second channel dominates and adaptation is restricted relative to the no default risk benchmark. Economic fundamentals are important for determining whether a sovereign will be enabled or restricted from investing in adapta-

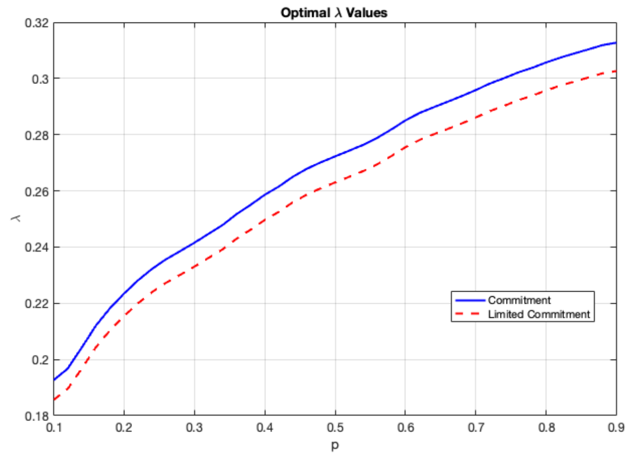

FIGURE 1. Optimal adaptation for a range of values of the probability of a disaster. The blue line shows the case with no default risk, the red dotted line shows the case with such risk. Parameter values are standard for emerging markets: $\beta = 0.9$, $b_0 = 0$, $\bar{l} = 0.7$, $\psi = 7$, $r = 0.01$.

tion by the presence of default risk.[7] Figure 1 shows a representative emerging market calibration where baseline spreads are high and adaptation is lower under default risk than without for all values of the probability of a disaster. Figure 2 shows that adaptation is also declining with the intensity of sovereign risk. For higher initial levels of debt, the spread is higher restricting adaptation via increases marginal costs.

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). Therefore the model predicts climate change will be less impactful for default probabilities than previous literature.

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 predicts that

[7]Appendix B outlines the forces determining this tradeoff. Adaptation will be higher under limited commitment only if spreads are very low while also being very responsive to adaptation. Such calibrations are counterfactual for emerging markets.

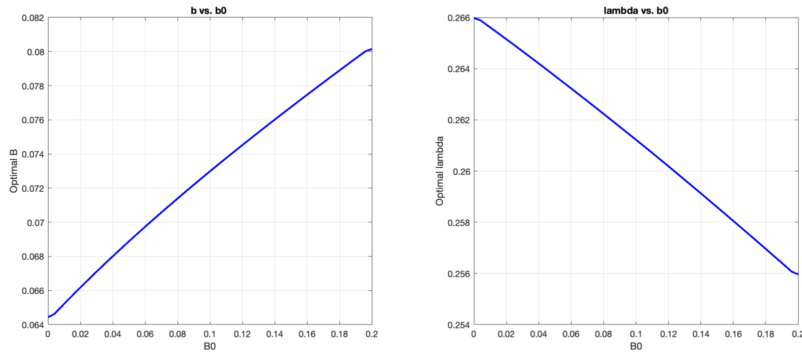

FIGURE 2. Adaptation and Borrowing choices for a range of initial debt levels.

climate change will be more damaging. 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.

3. 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.

3.1. 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.

3.1.1. 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

[8]See Carleton et al. (2024) for a review of the empirical literature on adaptation to climate change.
[9]See IPCC AR6 for a review.

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 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

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

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] 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 an example I include documentation of the line items included for the Bahamas in 2024 in Appendix A.

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 use 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).[13] This results in an unbalanced panel of 19 countries in Latin America and the Caribbean with a sovereign rating from 2014-2025. [14]

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

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

[13]This dataset on fiscal space results in the largest possible panel for my analysis. Results using alternative measures of sovereign risk (CDS spreads, EMBI spreads) are presented in Appendix A.13.

[14]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.6

3.1.2. 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.

TABLE 1. Summary Statistics

	N	Mean	St. Dev.	Min	Max
Adaptation Total / GDP	163	0.31%	0.0011	0.001	0.0187
Adaptation Total / Expenditure	163	1.1%	0.0090	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

These results imply that on average adaptation investment is about a tenth of health expenditure, or a fifth of agricultural spending.[15] The closest existing statistic 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 the underlying assumption that adaptation is increasing with exposure using my dataset. 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. This positive relationship between historical exposure to disasters and adaptation indicates that governments respond to their climatic 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.

[15] Source: Economic Commission for Latin America and the Caribbean (ECLAC)

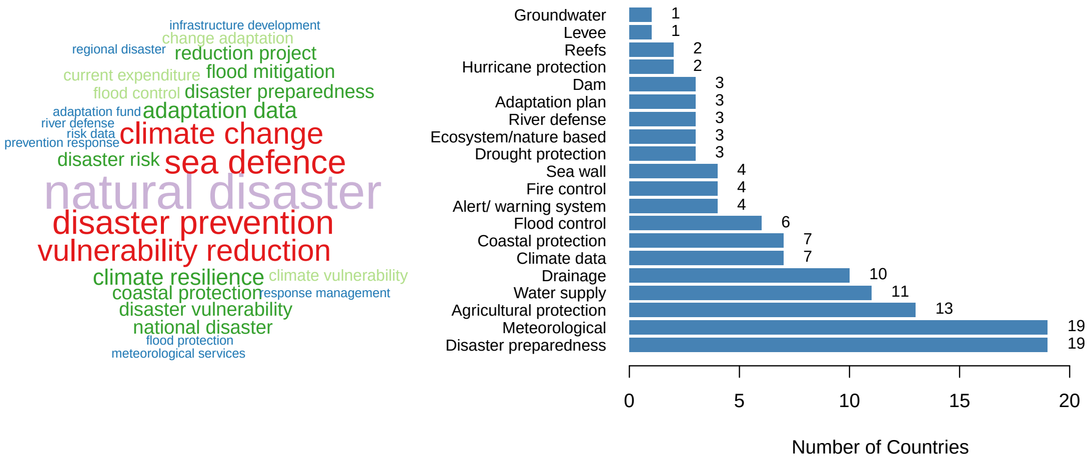

FIGURE 3. Adaptation is disaggregated by subtype. The left panel shows the most frequently used terms in budget entries flagged by the algorithm. The right panel shows the most common categories of adaptation by country in 2022.

The left panel of figure 3 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 A4. To further investigate the components of adaptation I categorize the search terms and construct count variables for each component. The right panel of figure 3 documents the most common components of adaptation. After disaster preparedness and meteorological expenditure, agricultural, water supply, and coastal protection are the most common forms of adaptation. Appendix A.9 shows that countries tend to spend more adapting to disasters they are relatively more exposed to.

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 4 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 5. To further examine the relationship I run the following regression:

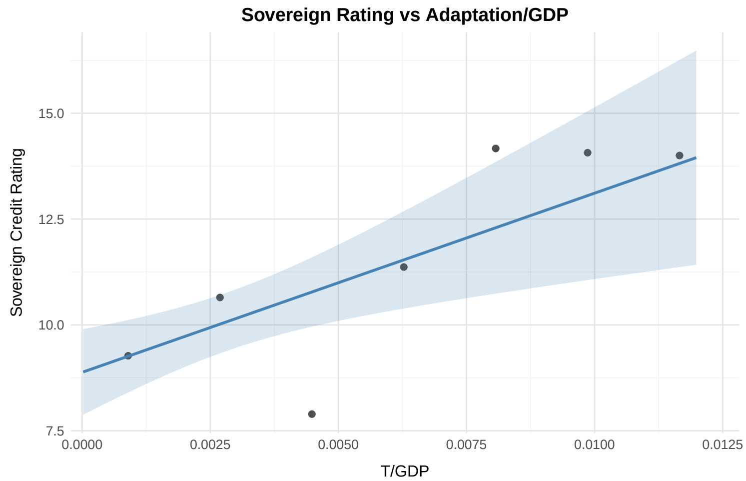

FIGURE 4. Adaptation Investment and Sovereign Ratings. Sovereign ratings are an average of the previous three years, on a scale from 0-21 from the World Bank fiscal space database (Kose et al. 2022). The adaptation measure is total adaptation spending as derived from the computational linguistics measure, shown as a proportion of GDP and in 8 bins. The shaded region shows standard errors at the 90% level.

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

where *Adaptation* is the a measure of adaptation as constructed above measured in 2017 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 government effectiveness from the World Bank.[16] Table 2 shows the results of this estimation. The first column controls for exposure and government effectiveness, 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 $67 million according to the first specification, and $31 million according to the second. Regression results for disaster preparedness and meteorological expenditure are shown in Appendix A.11.

This positive relationship between adaptation and sovereign ratings is consistent

[16]For more information on the controls see Appendix A.8.

	adapt	
sovrate	67,554,921***	30,964,525***
	(16,647,312)	(9,241,031)
gdp	0.0022***	0.0069***
	(0.0002)	(0.0018)
exposure	143,757,032**	
	(62,519,154)	
government effectiveness	121,350,937**	
	(48,299,257)	
Country Fixed Effects	No	Yes
Year Fixed Effects	Yes	Yes
Observations	98	105
R-squared	0.95	0.84
Note:	*p<0.1; **p<0.05; ***p<0.01	

TABLE 2. Regression Results. adapt and gdp are in millions of 2017 US dollars. sovrate is an index from 0-21. Exposure is historical average maximum windspeed scaled by land area, and standardized to have mean 0 and standard deviation 1. Government effectiveness is an index from the World Bank standardized to have mean 0 and standard deviation 1. Standard errors are clustered by country and year.

with the model. The model predicts both that higher sovereign ratings cause adaptation to be higher, and that greater adaptation spending reduces sovereign risk. None of the major rating agencies explicitly include adaptation in their rating methodologies. Therefore it is likely that the empirical results as presented indicate that sovereign risk restricts adaptation expenditure. This is consistent with statements from borrowing constrained governments.[17]

3.2. 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

[17] For additional narrative evidence and discussion of rating agency methodologies see Appendix A.14.

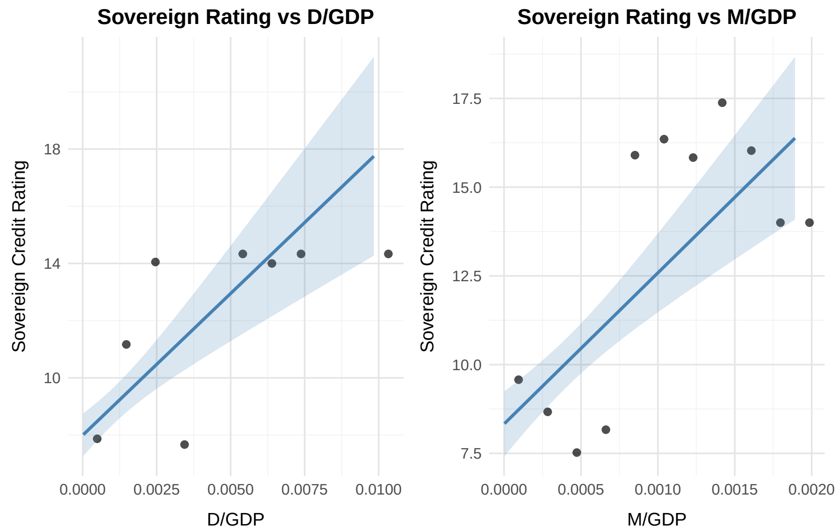

FIGURE 5. Adaptation Investment and Sovereign Ratings. Sovereign ratings are an average of the previous three years, on a scale from 0-21 from the World Bank fiscal space database (Kose et al. 2022). The adaptation measures are disaster preparedness expenditure and meteorological services expenditure, both scaled by GDP.

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.[18] Felbermayr and Gröschl (2014), show that the use of such data leads to estimation bias when estimating growth effects of disasters on a global panel 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, and to validate the second and third predictions of the model.

[18] `www.emdat.be`

3.2.1. 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 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.17. 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. [19] 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.17.

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.

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

3.2.2. 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 $h = 0, \ldots H$ is the horizon, y is the dependent variable of interest - here either $log(CDS)$ or $SovCrisis$ - and D is the cyclone indicator variable. Equation 14 is estimated using OLS for the sample described above.[20] 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.

3.2.3. Results

Figure 6 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

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

the process of recovery to the shock. It is also consistent with the prediction of the model that cyclones increase default probabilities.[21]

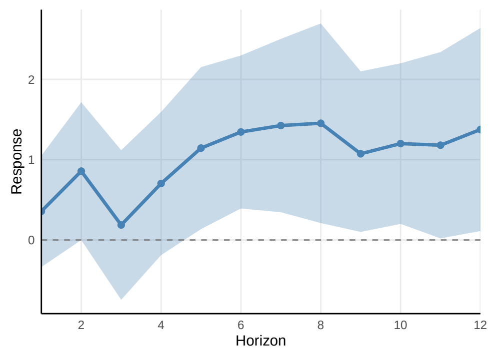

FIGURE 6. Impulse Response Function of CDS spreads to a cyclone shock over a horizon of six months. 90% confidence bands are shaded in blue.

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.[22] 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.

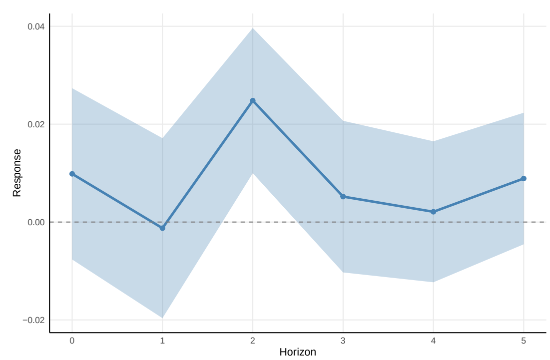

FIGURE 7. Impulse Response Function of Sovereign Crisis dummy to a cyclone shock over a horizon of six years. 90% confidence bands are shaded in blue.

Figure 7 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

[21]For the table summarizing these results see Appendix A.18

[22]However, the result presented in Figure 6 that cyclones cause CDS spreads to increase does still hold in the restricted sample of countries also included in the adaptation sample.

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 8 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. I show that these results are robust to using alternative measures of default in Appendix A.19.

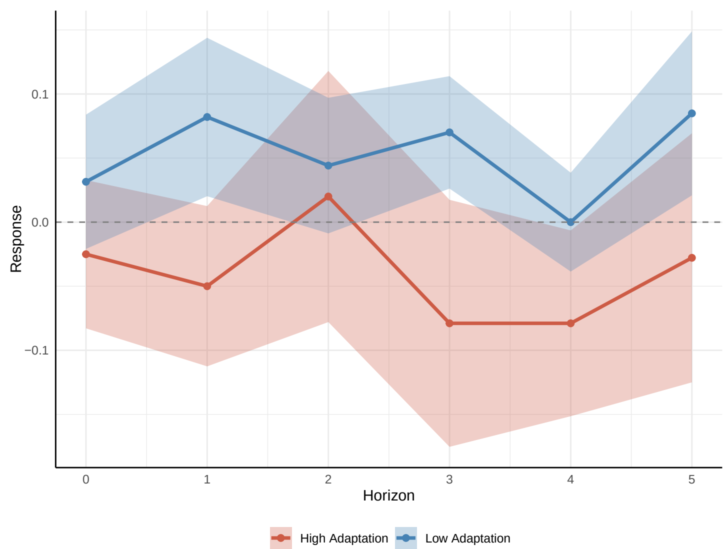

FIGURE 8. IRF of Sovereign Crisis dummy to a cyclone shock. 90% confidence bands are shaded in blue. Left panel shows IRF for the subsample of countries with above the median level of adaptation investment as a proportion of GDP. The right panel shows the IRF for the subsample with below the median level of adaptation.

4. 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.

4.1. Quantification

Output costs of default are given by the function $\phi(y_t)$. As in Chatterjee and Eyigungor (2012) output costs of default are quadratic:

$$\phi(y) = \max\left\{-d_0 y + d_1 y^2, 0\right\}.$$

Therefore it is proportionally more costly to default in good times. Such 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.[23] For the baseline calibration I restrict attention to Caribbean economies included in my adaptation expenditure dataset. For these economies, hurricanes are by far the most frequent and severe natural disaster, allowing me to calibrate the endowment process using physical data on hurricanes. 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.

[23]As in Mallucci (2022) this is for the reason that GDP series for Caribbean economies at the quarterly frequency are available only sparsely and in recent years. Longer time series are needed to estimate the effects of rare shocks such as hurricanes.

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	0.92	Debt/GDP
Default cost	d_0	0.621	Mean Spread
Default cost	d_1	0.978	Std. dev 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 default cost parameters, d_0 and d_1, are set to match the debt to GDP ratio, the mean spread and the standard deviation of the spread. Data on these variables are obtained from the Global Macro Database and the JP Morgan EMBI. All moments are weighted by population.

Solution. 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 no-default benchmark in which the default policy is set to zero in all states.

4.2. Model Performance

Model fit is shown in Table 4. 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. [24] Welfare losses 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.

[24] 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	0.401	0.414
GDP loss | Cyclone	0.052	0.050
Mean Spread	502	526
Std. dev Spread	352	374
Untargeted		
Default Frequency	0.048	0.051
Median Spread	121	143
Spread Increase | Cyclone	0.015	0.01
Untargeted		
Adaptation Capital/GDP	0.029	
Percent Damages Avoided	0.45	
Market Value Debt/GDP	0.37	
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 2.2 are visible in the full model. Figure 9 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 decreasing 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.

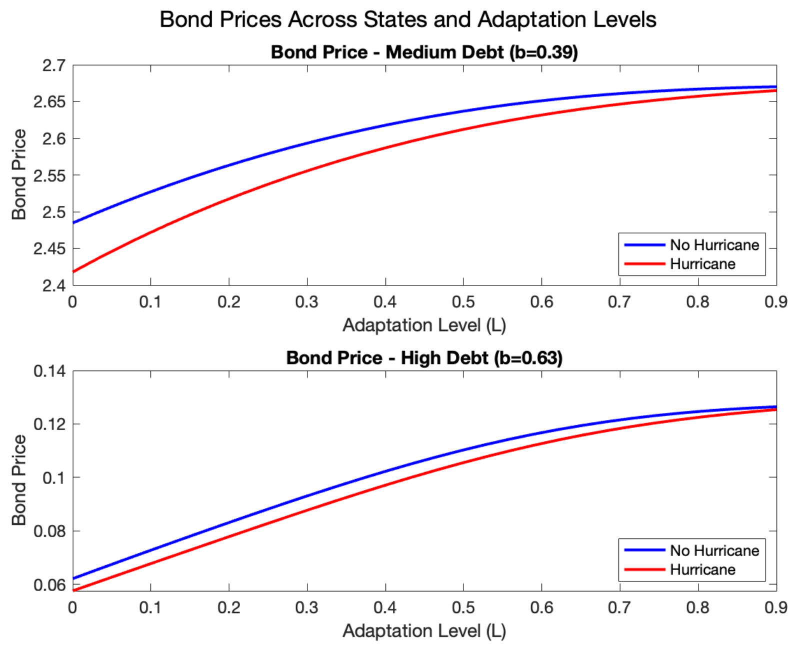

FIGURE 9. Sovereign Bond prices for different levels of adaptation. The panes show results for different levels of debt.

4.3. Counterfactuals

4.3.1. No Default Risk Benchmark

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.

In the absence of default risk 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	No Default Risk
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: No Default Counterfactual.
The first column presents simulated moments from the baseline model. The second column presents moments from a no default risk counterfactual. In this counterfactual the default policy is set to zero in all periods.

4.3.2. 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 without? 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.[25] 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

[25]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 no default risk counterfactual adaptation investment/GDP is 31% higher. The wedge between adaptation investment under default risk vs without is therefore higher as hazard exposure increases. In the absence of default risk 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 than the investment wedge. GDP losses from cyclones are 13% greater due to the sovereign risk-adaptation channel under the climate change scenario.

4.4. Debt Relief:

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. For example, the Bridgetown Initiative, a proposal spearheaded by Prime Minister of Barbados Mia Mottley has called for financing solutions to allow fiscal space for climate resilience. In particular, the argument has been that financing for disaster *recovery* is not sufficient: "Liquidity is not enough: these crises have systemic roots. Only investment will change their course... lending should prioritize building climate resilience in climate vulnerable countries."[26].

Debt relief for climate resilience could take many forms: an increase in official lending, coupon suspensions, explicitly adaptation-linked finance. In contrast with existing literature which has focused on policies which limit the effects of natural disaster shocks (Catastrophe Bonds, Insurance), I consider policies which ex-ante aim to increase fiscal space for climate resilience purposes. Could such policies be effective? I consider two such policies, showing that debt-relief can be effective at boosting adaptation and climate resilience.

[26] `https://www.bridgetown-initiative.org/`

	Baseline	Frequency $1.292 \cdot p$	Severity $1.485 \cdot \mu_d$	Both	No Default Risk
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	0.0632
Percent Damages Avoided	0.45	0.47	0.47	0.50	0.57
Debt					
Debt/GDP	0.40	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.

4.4.1. 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.[27] 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

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

2019). Therefore I consider such a loan to be default free.

In this counterfactual the sovereign gets F as a lump-sum in period $t = t^*$. A grace period follows in which the sovereign does not have to repay the loan.[28] 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.

	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.

The loan program generates substantial benefits. The sovereign primarily uses the loan to increase adaptive investments. In particular, adaptation investment as a proportion of GDP rises by almost 5%. This is 35% of the gap between adaptation under default risk versus the no-default risk counterfactual. As a result of greater adaptation investment, the stock of adaptive capital increases, reducing the losses from hurricanes.

[28] 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.

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.

4.4.2. An Adaptation Bond

In this section I modify the baseline model to include a coupon reduction associated with elevated adaptation.[29] Green sovereign bonds have become more popular in recent years. The BIS sustainable bonds database indicates that such bonds outstanding rose more than fourfold from January 2019 to the end of 2022.[30] These bonds typically take one of two types. "Use of proceeds" bonds earmark the proceeds of bond sales for environmental projects. "Outcome-based" bonds have decreased coupon payments if contractually specified environmental performance targets are met.[31] Thus far outcome-based green bonds have largely focused on climate mitigation and/or nature protection. For example, Chile issued a sustainability linked bond in 2022 with two performance targets: reducing the overall level of greenhouse gases produced in Chile, and converting energy usage to renewable energy. Uruguay issued a similar bond with an additional target of maintaining the total area of local forest.

I propose an outcome-based green bond that is instead linked to performance on adaptation.[32] The rationale is that such a bond loosens the sovereign's budget constraint in high adaptation states. This provides additional incentives to invest in adaptation, opening the possibility for a positive feedback loop between high adaptation investment and lower default risk.

The value functions are defined as in section 2 with the following adjustments to the resource constraint and bond price function. If adaptation is above some threshold value Λ^* defined in the adaptation bond contract, the investor receives a lower coupon payment where c denotes the discount:

[29] I thank Patrick Bolton and Jan Starmans for helpful conversations which prompted this counterfactual exercise.

[30] `https://www.bis.org/publ/qtrpdf/r_qt2209d.pdf`

[31] See Cheng et al. (2024) for background. I focus on outcome based or sustainability linked bonds as they are not associated with the loss of control over budget priorities or lack of fungibility of revenue that has created constitutional and other political issues for use of proceeds bonds.

[32] To the best of my knowledge, while the proceeds from 'use of proceeds' green bonds have sometimes been used to fund adaptation projects, there has not been an instance of a sovereign issuing an 'outcome-based' green bond linked to performance on adaptation targets.

(15) $$c_t|_{D_t=0} = y_t + q_t^{AB}(b_{t+1} - (1-\psi)b_t) - b_t\left(1 - c\mathbb{1}_{\Lambda_t > \Lambda^*}\right) - \lambda_t,$$

(16) $$q_t^{AB} = \frac{1}{1+r}\mathbb{E}\left((1-D_{t+1})(1 - c * \mathbb{1}_{\Lambda_{t+1} > \Lambda^*}) + (1-D_{t+1})(1-\psi)q_{t+1}^{AB}\right).$$

The bond price accounts for the expected value of the coupon reduction in high adaptation states. Appendix B.5 outlines the implications of the adaptation bond in the restricted model which permits analytic solutions.

For the simulations I set $c = 0.025$, and $\Lambda^* = 0.0305$. This implies that the sovereign gets a 2.5% coupon reduction if adaptation capital is 5% greater than in the no adaptation bond simulation. The introduction of such an adaptation bond is effective in increasing adaptation. Table 8 presents simulated moments.

	Baseline	Adaptation Bond
Adaptation		
Adaptation Investment/GDP	0.003	0.0033
Adaptation Capital/GDP	0.029	0.031
Cyclones		
GDP loss per Cyclone	0.05	0.046
Percent damages avoided	0.45	0.52

TABLE 8. Simulated Moments: Adaptation Bond Counterfactual.
The first column presents simulated moments from the baseline model. The second column presents moments from the adaptation bond counterfactual.

The introduction of the adaptation contingent bond increases adaptation investment by 10% (compared to 13% for the no default risk counterfactual). As a result the GDP losses per cyclone are on average 4.6% (compared to 4.5% in the absence of default risk). Therefore the adaptation contingent bond is effective at increasing incentives to adapt. Adaptation investment under this counterfactual is almost as large as it would have been absent default risk all together.

5. 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. Both an interest free loan and an adaptation contingent bond are effective in increasing adaptation investment, 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_zone	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 65 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. Adaptation Entries: The Bahamas 2023-2024

This section shows screenshots of pages of the budget of the Bahamas 2023-2024. Line items highlighted in yellow are those picked up by the algorithm and included in the final adaptation measure.

SUMMARY OF AGENCIES
RECURRENT EXPENDITURE 2023/2024

HEAD NO.	MINISTRY/DEPARTMENT	PROVISIONAL ACTUAL EXPENDITURE 2021/2022 $	EXPENDITURE (PROVISIONAL) JUL - MAR 2022/2023 $	REVISED APPROVED ESTIMATES 2022/2023 $	ESTIMATES 2023/2024 $	PRELIMINARY FORECAST ESTIMATES 2024/2025 $	PRELIMINARY FORECAST ESTIMATES 2025/2026 $
043	MINISTRY OF SOCIAL SERVICES AND URBAN DEVELOPMENT	11,853,711	9,527,813	13,544,180	15,336,260	14,382,191	14,468,047
044	DEPARTMENT OF SOCIAL SERVICES	53,808,368	35,997,500	52,103,091	46,189,742	46,755,469	47,399,544
045	DEPARTMENT OF HOUSING	1,840,204	2,290,549	2,972,529	3,216,484	3,331,594	3,769,002
047	MINISTRY OF YOUTH, SPORTS AND CULTURE	14,500,725	21,389,325	26,535,786	26,706,494	23,049,794	22,953,164
048	DEPARTMENT OF LABOUR	1,864,454	2,591,935	3,752,923	3,999,277	4,075,117	4,160,387
049	MINISTRY OF ECONOMIC AFFAIRS	5,866,773	8,699,175	12,871,952	11,614,394	11,644,197	11,663,979
051	POST OFFICE DEPARTMENT	6,809,901	6,510,482	9,201,089	9,340,930	9,490,104	9,971,084
053	PORT DEPARTMENT	8,239,794	6,567,442	9,014,970	9,145,089	9,153,700	9,501,326
054	DEPARTMENT OF ROAD TRAFFIC	5,288,088	5,239,486	6,944,828	6,976,416	6,976,416	7,276,416
055	DEPARTMENT OF METEOROLOGY	2,087,999	1,508,292	2,792,064	2,437,303	2,557,564	2,714,632
056	MINISTRY OF AGRICULTURE, MARINE RESOURCES AND FAMILY ISLAND AFFAIRS	21,237,508	20,012,587	28,763,889	28,221,348	28,276,298	29,477,488
057	DEPARTMENT OF AGRICULTURE	4,996,466	3,747,395	5,543,196	5,566,525	5,609,321	6,268,220
058	DEPARTMENT OF MARINE RESOURCES	2,330,771	1,598,106	2,823,060	2,449,563	2,620,779	2,923,668
060	MINISTRY OF HEALTH AND WELLNESS	373,846,036	242,928,786	315,021,918	299,367,187	300,208,287	300,558,537
065	DEPARTMENT OF ENVIRONMENTAL HEALTH SERVICES	50,293,460	48,021,999	61,702,188	59,505,886	60,245,925	60,869,912
066	DEPARTMENT OF PUBLIC HEALTH	45,337,948	38,234,895	56,146,001	48,682,297	48,987,997	48,997,559
067	MINISTRY OF TOURISM, INVESTMENTS AND AVIATION	148,111,959	90,353,548	132,562,117	135,034,206	140,814,071	141,249,711
070	MINISTRY OF LABOUR AND IMMIGRATION	5,002,443	3,049,217	4,244,490	4,974,482	5,273,809	5,301,377
072	MINISTRY OF THE ENVIRONMENT AND NATURAL RESOURCES	17,859,554	10,207,436	16,026,382	13,878,562	13,657,942	13,764,213
073	DEPARTMENT OF INFORMATION AND COMMUNICATIONS TECHNOLOGY	53,251,306	21,783,239	34,143,676	29,230,202	31,485,777	30,349,947
074	MINISTRY FOR GRAND BAHAMA	10,018,186	14,767,945	19,188,189	17,983,328	18,108,654	18,538,774
075	MINISTRY OF DISASTER RISK MANAGEMENT	1,504,339	9,761,377	15,975,932	9,943,301	13,317,965	13,404,278
076	OFFICE OF THE DIRECTOR OF PUBLIC PROSECUTIONS	2,355,847	1,230,775	2,759,729	2,931,230	3,018,761	3,361,449
	GRAND TOTAL	**3,044,069,825**	**2,134,807,682**	**3,073,728,214**	**3,085,536,785**	**3,131,500,001**	**3,154,399,500**

MEMORANDUM
Consistent with Government Finance Statistics (GFS) methodology, Public Debt Redemption is treated as a financing transaction and, therefore, has no impact on the deficit. Public Debt Servicing-Interest & Other Charges is now being shown separately as Head 26.

[Head 013] MINISTRY OF FOREIGN AFFAIRS AND THE PUBLIC SERVICE

ITEM NO.	TITLE OF ITEM	PROVISIONAL ACTUAL EXPENDITURE 2021/2022 $	EXPENDITURE (PROVISIONAL) JUL - MAR 2022/2023 $	REVISED APPROVED ESTIMATES 2022/2023 $	ESTIMATES 2023/2024 $	PRELIMINARY FORECAST ESTIMATES 2024/2025 $	PRELIMINARY FORECAST ESTIMATES 2025/2026 $
22810EE	**Special Financial Transactions**						
2281105	VAT Expenses	157	0	0	0	0	0
	Special Financial Transactions	**157**	**0**	**0**	**0**	**0**	**0**
	Use of Goods & Services	**9,410,520**	**10,860,749**	**16,658,898**	**16,813,202**	**19,264,761**	**19,807,593**
26000EE	**Grants**						
26200EE	**Grants to International Organizations**						
2621101	Operations for IMO (International Maritime Organization)	0	0	0	260,000	260,000	260,000
2621105	Caribbean Regional Drug Testing Lab	0	0	15,360	15,360	15,360	15,360
2621106	Caribbean Regional Secretariat (CARICOM)	2,248,399	2,248,399	2,248,399	2,544,834	2,748,426	2,748,426
2621107	Caribbean Agriculture Research and Development	0	0	150,400	150,400	150,400	150,400
2621108	Caribbean Centre For Development Administration	9,600	9,600	9,600	9,600	9,600	9,600
2621110	Caribbean Environment Health Institute	33,760	0	33,760	33,760	33,760	33,760
2621111	Caribbean Emergency Disaster Preparedness	85,586	85,586	85,586	226,295	226,295	226,295

[Head 072] MINISTRY OF THE ENVIRONMENT AND NATURAL RESOURCES

ITEM NO.	TITLE OF ITEM	PROVISIONAL ACTUAL EXPENDITURE 2021/2022 $	EXPENDITURE (PROVISIONAL) JUL - MAR 2022/2023 $	REVISED APPROVED ESTIMATES 2022/2023 $	ESTIMATES 2023/2024 $	PRELIMINARY FORECAST ESTIMATES 2024/2025 $	PRELIMINARY FORECAST ESTIMATES 2025/2026 $
2241206	Publications	0	1,434	2,450	2,563	2,738	2,738
2241211	Cleaning & Toilet Supplies	4,657	241	1,000	1,000	1,000	1,000
2241212	Computer Software Supplies & Materials	1,655	997	6,156	5,000	5,500	6,000
2241213	Clothing & Clothing Supplies	663	3,034	8,000	8,000	8,250	8,500
2241237	Operation Exp. Botanical Gar.	0	38,764	80,000	60,000	60,000	60,000
2241299	Other Supplies & Materials	3,032	1,808	4,074	4,500	5,120	5,220
	Supplies & Materials	**20,564**	**48,173**	**108,100**	**87,483**	**89,057**	**89,907**
22510EE	**Services**						
2251101	Printing & Duplication Service	7,333	0	0	0	0	0
2251102	Advertising & Public Notices	2,350	15,189	45,000	20,252	20,720	20,820
2251107	Workshops, Conferences, Seminars, Meetings & Exhibits	7,945	1,548	7,380	418,000	7,000	8,000
2251108	Tuition, Training, In-service Awards, Subsistence	5,131	0	14,738	7,000	7,100	7,300
2251109	Licencing & Inspection of Vehicles	1,950	0	0	0	0	0
2251115	Consultancy Services	80,431	101,522	290,000	125,000	135,000	150,000
2251128	Fees & Other Charges	22,829	19,187	29,470	18,280	19,127	19,377
2251129	Staff Engagement	11,384	4,040	12,000	5,387	5,500	5,600
2251201	Local Transportation of Goods	1,196	283	1,520	2,000	2,143	2,143
2251203	Freight & Express	2,159	1,349	4,000	4,300	4,557	4,757
2251306	Computers, Business Machines & Related Equipment	761	2,061	4,500	4,500	5,000	5,000
2251310	Grounds Maintenance	936	0	5,000	0	0	0
2251330	Upkeep & Maintenance of Instruments & Apparatus	270	153	1,107	500	500	500
2251336	Sanitact Maintenance Contract	1,836	0	3,360	3,360	3,360	3,360
2251337	Operation of Facilities or Other Services	36,190	18,499	38,775	29,700	29,700	29,700
	Services	**182,701**	**163,831**	**456,850**	**638,279**	**239,707**	**256,557**
22610EE	**Minor Capital Repairs**						
2261201	Transportation Equipment Upkeep	3,157	887	10,000	10,000	10,000	10,000
	Minor Capital Repairs	**3,157**	**887**	**10,000**	**10,000**	**10,000**	**10,000**
22710EE	**Operational Expenses**						
2271001	Operational Expenses	40,466	25,095	55,000	40,000	40,000	40,000
2271037	Grand Bahama Climate Resilience Master Planning Exercise	0	18,122	80,000	80,000	80,000	80,000
2271038	Development of Marine Protected Area	0	47,221	100,000	50,000	60,000	70,000
	Operational Expenses	**40,466**	**90,438**	**235,000**	**170,000**	**180,000**	**190,000**
22810EE	**Special Financial Transactions**						
2281001	Special Financial Transactions	13,976	10,301	10,500	10,500	10,500	10,500
2281105	VAT Expenses	122	0	0	0	0	0
2281162	International Conferences	9,781	35,506	100,000	50,000	50,000	60,000
	Special Financial Transactions	**23,879**	**45,807**	**110,500**	**60,500**	**60,500**	**70,500**
	Use of Goods & Services	**422,863**	**458,411**	**1,145,441**	**1,192,543**	**808,388**	**848,828**

[Head 021] MINISTRY OF FINANCE

ITEM NO.	TITLE OF ITEM	PROVISIONAL ACTUAL EXPENDITURE 2021/2022 $	EXPENDITURE (PROVISIONAL) JUL - MAR 2022/2023 $	REVISED APPROVED ESTIMATES 2022/2023 $	ESTIMATES 2023/2024 $	PRELIMINARY FORECAST ESTIMATES 2024/2025 $	PRELIMINARY FORECAST ESTIMATES 2025/2026 $
28000EE	**Other Payments**						
28200EE	**Transfers N.E.C.**						
2822007	Energy Restoration & Renewable Energy	15,039,734	9,132,927	23,000,000	23,000,000	23,000,000	0
2822010	Public Private Partnership	3,000,000	2,812,066	9,000,000	27,800,000	26,000,000	25,000,000
2822011	Capital Subscriptions to International Agencies	959,500	4,306,826	2,000,000	2,000,000	2,000,000	2,000,000
2822025	PFR/PFM	4,224,806	1,137,863	3,400,000	3,000,000	3,000,000	2,000,000
2822031	Small and Medium Size Business Support	8,204,923	1,000,000	4,000,000	5,500,000	5,500,000	6,500,000
2822056	National Sports Authority	750,766	0	0	0	0	0
2822063	Capitalization - Bahamas Development Bank	0	500,000	2,000,000	3,000,000	3,000,000	4,000,000
2822065	Capital Budget Reserve Appropriation	5,721,392	31,800	23,444,153	19,256,700	20,106,729	22,424,000
	Transfers N.E.C.	**37,901,121**	**18,921,482**	**66,844,153**	**83,556,700**	**82,606,729**	**61,924,000**
	OTHER CHARGES	**37,901,121**	**18,921,482**	**66,844,153**	**83,556,700**	**82,606,729**	**61,924,000**
31000EE	**Acquisition of Non-Financial Assets**						
31100EE	**Acquisition of Fixed Assets**						
3111116	Rent to Own Housing Programme	0	0	0	3,500,000	3,500,000	3,500,000
3111211	Performing Arts School	0	0	0	1,000,000	1,000,000	1,000,000
3111309	Hurricane Precautions	0	250,000	1,000,000	1,000,000	1,000,000	1,000,000
3111318	Construction of Women Shelter & Support Centre	0	0	0	500,000	500,000	500,000
3111326	National Museum Project	0	0	0	1,000,000	1,000,000	800,000
3111331	Swimming Pool	0	0	0	700,000	1,000,000	2,000,000
3111388	Family Island Capital Development	0	0	2,000,000	13,000,000	13,200,000	16,000,000
3112101	Acquisition of Transportation Equipment (Land)	400,000	1,578,696	2,000,000	2,800,000	2,500,000	2,500,000
3112202	Equipment Maintenance	0	980,000	1,000,000	1,000,000	1,000,000	1,000,000
3112299	Other Machinery & Equipment	278,312	0	0	0	0	0
3113002	Minor Capital Projects	7,600,235	5,429,164	3,500,000	3,000,000	3,000,000	3,700,000
3113003	Acquisition of Assets - Government Ministries and Departments	1,989,985	2,759,250	2,500,000	4,000,000	4,000,000	4,000,000
3113010	Subdivision Infrastructure	70,880	0	0	0	0	0
3113011	Electronic Hansard	1,527,663	367,256	667,256	300,000	0	0
	Acquisition of Fixed Assets	**11,867,075**	**11,364,366**	**12,667,256**	**31,800,000**	**31,700,000**	**36,000,000**
31400EE	**Nonproduced Assets**						
3141101	Purchase of Properties	1,400,000	0	2,000,000	2,000,000	2,000,000	2,000,000
	Nonproduced Assets	**1,400,000**	**0**	**2,000,000**	**2,000,000**	**2,000,000**	**2,000,000**
	Acquisition of Non-Financial Assets	**13,267,075**	**11,364,366**	**14,667,256**	**33,800,000**	**33,700,000**	**38,000,000**
	MINISTRY OF FINANCE TOTAL EXPENSES	**51,168,196**	**30,285,848**	**81,511,409**	**117,356,700**	**116,306,729**	**99,924,000**

The Accounting Officer for this Head is the FINANCIAL SECRETARY

ITEM NO.	TITLE OF ITEM	PROVISIONAL ACTUAL EXPENDITURE 2021/2022 $	EXPENDITURE (PROVISIONAL) JUL - MAR 2022/2023 $	REVISED APPROVED ESTIMATES 2022/2023 $	ESTIMATES 2023/2024 $	PRELIMINARY FORECAST ESTIMATES 2024/2025 $	PRELIMINARY FORECAST ESTIMATES 2025/2026 $
28000EE	**Other Payments**						
28200EE	**Transfers N.E.C.**						
2822007	Energy Restoration & Renewable Energy	0	0	250,000	0	0	0
2822013	National Disaster Recovery Project	11,457,258	2,950,711	6,500,000	4,630,000	5,000,000	5,762,600
2822014	Post National Disaster Recovery Project	392,774	0	0	0	0	0
2822022	Research, Surveys, Studies, Evaluations	1,865,930	561,618	553,831	564,907	576,205	587,729
2822025	PFR/PFM	806,637	2,276,332	5,950,021	5,552,759	5,615,460	5,973,646
	Transfers N.E.C.	**14,522,599**	**5,788,661**	**13,253,852**	**10,747,666**	**11,191,665**	**12,323,975**
	OTHER CHARGES	**14,522,599**	**5,788,661**	**13,253,852**	**10,747,666**	**11,191,665**	**12,323,975**
31000EE	**Acquisition of Non-Financial Assets**						
31100EE	**Acquisition of Fixed Assets**						
3111207	Building Maintenance	10,495,671	12,237,287	12,937,159	12,846,390	17,562,384	16,816,315
3111216	Planning for New Parliament Building (New Providence)	0	0	0	2,000,000	3,000,000	2,000,000
3111268	Construction of Gymnasiums	3,635,025	1,195,394	2,620,159	2,500,000	3,000,000	5,947,862
3111301	Bridge Repair & Maintenance	1,542,647	1,261,248	2,771,402	3,000,000	3,114,026	4,127,889
3111302	Ports & Docks	3,624,863	2,986,593	6,546,512	6,500,000	10,258,863	10,434,047
3111303	Sidewalks	589,156	172,533	1,100,000	700,000	1,144,440	1,167,329
3111307	Road Repairs & Maintenance	19,108,876	12,115,068	22,942,206	20,000,000	27,957,773	28,516,931
3111309	Hurricane Precautions	208,388	198,070	1,500,000	1,500,000	1,589,481	1,607,270
3111310	Water Infrastructure	0	0	1,500,000	0	0	0
3111311	Cemeteries Improvements & Upkeep	377,737	2,036,709	1,201,764	2,000,000	1,250,315	1,275,322
3111313	Maintenance - Standposts/Faucets/Wells/Drains	945,790	1,039,305	1,200,000	1,200,000	1,248,480	1,273,450
3111320	Traffic Study & Systems	3,340,638	800,000	1,346,764	1,373,699	1,401,173	1,429,197
3111321	New Providence Roadworks	9,815,798	12,689,218	11,150,000	11,730,000	11,964,600	12,203,892
3111324	New Bight Airport Redevelopment	0	0	0	6,000,000	6,000,000	2,000,000
3111330	Q.E. Sports Centre Redevelopme	0	0	0	10,000,000	8,000,000	12,000,000
3111338	Construction & Expansion - Buildings & Structures	40,127,114	3,026,239	3,000,000	2,952,000	4,000,000	4,000,000
3111377	Airport Infrastructure Programme	13,341,456	5,747,246	9,154,951	13,141,050	14,660,114	14,953,318
3111389	Road Remediation - Drainage Infrastructure	0	1,367,137	2,290,000	1,500,000	1,500,000	1,500,000
3111399	Other Structures	687,196	0	0	0	0	0
3111403	Improvement of Parks & Grounds	2,017,932	3,848,121	4,000,000	4,000,000	4,369,680	4,457,074
3112101	Acquisition of Transportation Equipment (Land)	0	974,879	1,000,000	0	0	0
3112202	Equipment Maintenance	64,998	313,215	401,353	401,360	417,568	425,919
3112203	Other Office Equip & Furniture	0	18,067	50,000	50,000	50,000	50,000
3112210	Landscape Equipment	0	36,786	150,000	100,000	200,000	200,000
3112211	Machinery & Generators Mainten	355,484	232,958	773,726	500,000	1,196,460	1,220,389
3113005	Software	946,138	357,372	391,933	400,000	0	0
3113006	Hardware	5,799	116,893	117,500	100,000	0	0
	Acquisition of Fixed Assets	**111,230,706**	**62,770,338**	**88,145,429**	**104,494,499**	**123,885,357**	**127,606,204**
	Acquisition of Non-Financial Assets	**111,230,706**	**62,770,338**	**88,145,429**	**104,494,499**	**123,885,357**	**127,606,204**
	MINISTRY OF WORKS AND UTILITIES TOTAL EXPENSES	**125,753,305**	**68,558,999**	**101,399,281**	**115,242,165**	**135,077,022**	**139,930,179**

ANNEX 16 - PUBLIC INVESTMENT PROJECTS (ONGOING)

Code	Project Description	Project Start Date	Total Project Cost	Cumulative Expenditure	Projections 2023/2024	Preliminary 2024/2025	Preliminary 2025/2026
MINISTRY OF WORKS & UTILITIES							
033-0136-0441-011-2822025-15	BNT Consultancy - Climate Resilient Coastal Management And Infrastructure Program	01/31/2021	1,785,714	1,246,429	539,286	0	0
033-0136-0441-220-2822025-15	Baseline Coastal Studies And Engineering Design - Junkanoo Beach-Long Wharf, New Providence	03/31/2022	1,406,209	200,000	1,206,209	0	0
033-0138-0467-011-3111207-15	Repair And Renovations Of Government House, New Providence	10/31/2020	19,982,803	19,671,422	311,381	0	0
033-0138-0467-011-3111207-15	Jack Hayward Senior High School Gymnasium Repairs & Renovations Project	08/31/2022	1,484,807	1,373,568	111,239	0	0
033-0138-0467-011-3111207-15	Renovation And Repair To Eight Mile Rock High School Gymnasium	03/31/2023	2,113,666	1,181,258	932,408	0	0
033-0138-0467-011-3111207-15	Repairs And Renovations Of The Thomas A Robinson Stadium Phase 1	01/31/2023	2,310,000	1,738,501	571,499	0	0
033-0138-0467-011-3111207-15	Fort Fincastle Tower Repairs	06/30/2023	3,000,000	1,500,000	1,500,000	0	0
033-0138-0467-011-3111207-15	Bolam House Completion	06/30/2023	2,000,000	1,500,000	500,000	0	0
033-0138-0467-011-3111207-15	Clifford Park Redevelopment For 50th Independence Celebrations	06/30/2024	3,000,000	2,700,000	300,000	0	0
033-0138-0467-011-3111338-15	Construction Of South Andros All Purpose Gymnasium - Phase 2	12/31/2020	9,930,829	9,423,108	507,721	0	0
033-0137-0465-273-3111301-15	Replacement Of Staniard Creek Bridge	43799	9,604,205	9,393,390	210,815	0	0
033-0137-0465-235-3111302-15	Shoreline Stabilization And Roadworks, Hope Town, Elbow Cay, Abaco	06/30/2019	3,449,701	3,193,524	256,177	0	0
033-0137-0465-372-3111302-15	Replacement Of Main Government Dock And Fisherman's Dock, Rock Sound, Eleuthera	06/30/2020	2,959,367	2,804,401	154,966	0	0
033-0137-0465-295-3111302-15	Refurbishment Of Lisbon Creek Dock And Ramp, Mangrove Cay, Andros	08/31/2022	2,631,314	2,530,788	100,526	0	0
033-0137-0466-387-3111307-15	Exuma Road Repairs And Carriageway Rehabilitation	04/30/2020	7,316,105	6,998,717	317,388	0	0
033-0137-0466-386-3111307-15	Black Point Exuma Road Repairs And Carriageway Rehabilitation	04/30/2020	1,316,910	1,246,710	70,200	0	0
033-0137-0466-413-3111307-15	Long Island Road Repairs & Carriageway Rehabilitation	05/31/2020	3,809,060	3,413,133	395,926	0	0
033-0137-0466-201-3111307-15	Grand Bahama Road Repairs And Carriageway Rehabilitation	09/30/2020	5,534,144	4,500,144	1,034,000	0	0
033-0137-0466-234-3111307-15	Abaco Seawalls & Carriageway Rehabilitation Project	10/31/2020	1,335,993	1,204,023	131,971	0	0
033-0137-0466-362-3111307-15	Harbour Island Road Repairs And Carriageway Rehabilitation	02/28/2021	2,658,667	2,658,667	0	0	0

ANNEX 17 - PUBLIC INVESTMENT PROJECTS (NEW)

Code	Name of Project	Project Description	Total Project Cost	Budget Projections 2023/2024	Preliminary Forecast 2024/2025	Preliminary Forecast 2025/2026
MINISTRY OF WORKS & UTILITIES						
033-0138-0467-011-3111207-15	Thomas A Robinson Stadium Renovations Phase 2 to 5	Building Maintenance	12,000,000	10,000,000	2,000,000	0
033-0138-0467-011-3111207-15	Fort Fincastle Straw Market and Environs	Building Maintenance	10,000,000	2,000,000	4,000,000	4,000,000
033-0137-0465-387-3111301-15	Barratarre Bridge I - Exuma	Bridges	15,000,000	2,000,000	5,000,000	8,000,000
033-0137-0465-387-3111301-15	Ferry Bridge - Exuma	Bridges	15,000,000	2,000,000	5,000,000	8,000,000
033-0137-0465-272-3111301-15	Fresh Creek Bridge - Andros	Bridges	35,000,000	2,000,000	13,000,000	20,000,000
033-0137-0465-355-3111301-15	Glass Window Bridge (Eleuthera)	Bridges	40,000,000	3,000,000	17,000,000	20,000,000
033-0137-0465-280-3111301-15	Stafford Creek Bridge - Andros	Bridges	15,000,000	2,000,000	7,000,000	6,000,000
033-0137-0465-386-3111302-15	Blackpoint Dock	Ports & Docks	6,000,000	2,000,000	2,000,000	2,000,000
033-0137-0465-231-3111302-15	Abaco Docks	Ports & Docks	4,500,000	2,000,000	2,500,000	0
033-0137-0465-280-3111302-15	North Andros Docks	Ports & Docks	2,500,000	1,000,000	1,500,000	0
033-0137-0465-311-3111302-15	Bullock Harbour Dock, Berry Islands	Ports & Docks	2,500,000	1,000,000	1,500,000	0
033-0137-0465-011-3111302-15	Yamacraw Seawall and Road Renovations, NP	Ports & Docks	2,000,000	1,000,000	1,000,000	0
033-0137-0465-355-3111302-15	Gregory Town Seawall in Eleuthera	Ports & Docks	2,500,000	1,000,000	1,500,000	0
033-0137-0465-221-3111302-15	High Rock Construction of Seawall (Grand Bahama)	Ports & Docks	8,000,000	2,000,000	4,000,000	2,000,000
033-0137-0465-212-3111302-15	West End Ramp, Construction of Seawall, Restroom and Fish Fry Amenities (Grand Bahama)	Ports & Docks	2,000,000	1,000,000	1,000,000	0
033-0137-0466-011-3111321-15	Carmichael Road Development (New Providence)	New Providence Road Works	1,400,000	1,400,000	0	0
033-0137-0466-011-3111321-15	Gladsone Road Improvement Project - Construction Phase	New Providence Road Works	20,000,000	5,000,000	8,000,000	7,000,000
033-0137-0466-011-3111321-15	Corridor 41 - Milo Butler Extension from Carmichael to Cowpen	New Providence Road Works	20,000,000	5,000,000	5,000,000	10,000,000
033-0137-0466-011-3111321-15	Development of Killarney Lake Parkway	New Providence Road Works	2,000,000	2,000,000	0	0
033-0138-0467-011-3111338-15	The refurbishment of the former BTC Building on JFK Drive	Construction and Expansion of Buildings and Structures	8,000,000	4,000,000	4,000,000	0

ANNEX 17 - PUBLIC INVESTMENT PROJECTS (NEW)

Code	Name of Project	Project Description	Total Project Cost	Budget Projections 2023/2024	Preliminary Forecast 2024/2025	Preliminary Forecast 2025/2026
033-0137-0466-011-3111389-15	Bay Street Drainage Rehabilitation Project	Drainage	12,000,000	3,000,000	6,000,000	3,000,000
033-0137-0466-011-3111389-15	Coral Harbour Drainage and Road Project	Drainage	3,500,000	1,500,000	2,000,000	0
033-0137-0466-011-3111389-15	Pine Wood Garden Flooding Remediation (New Providence)	Drainage	12,000,000	3,000,000	6,000,000	3,000,000
033-0134-0467-011-3111403-15	Clifford Park Redevelopment	Parks	15,000,000	3,000,000	5,000,000	7,000,000
033-0210-0466-246-3111377-15	North Eleuthera - Landside Construction	Airport Infrastructure Program	25,000,000	5,000,000	6,000,000	14,000,000
033-0210-0466-246-3111377-15	North Eleuthera-Airside Construction	Airport Infrastructure Program	25,000,000	8,000,000	7,000,000	10,000,000
033-0210-0466-387-3111377-15	Exuma-Airside Construction	Airport Infrastructure Program	25,000,000	7,000,000	5,000,000	13,000,000
033-0210-0466-243-3111377-15	Treasure Cay	Airport Infrastructure Program	1,661,000	1,661,000	0	0
033-0136-0441-011-2822025-15	Construction works - JBLW	Beach and dune stabilization in Junkanoo Beach - New Providence	16,490,000	1,649,000	10,000,000	4,841,000
033-0136-0441-220-2822025-15	Construction works - EGB	Sustainable coastal protection infrastructure - East Grand Bahama (EGB)	2,000,000	421,500	1,578,500	0
033-0136-0441-413-2822025-15	Construction works - CLI	Costal flood reduction infrastructure - Central Long Island	2,250,000	450,000	1,800,000	0
		Total	**363,301,000**	**86,081,500**	**135,378,500**	**141,841,000**

A.8. Summary Statistics

Country	Observations	Mean T/GDP	Mean M/GDP	Mean D/GDP	SD T/GDP
Argentina	2	0.031	0.002	0.003	
Bahamas	12	0.195	0.021	0.066	0.049
Barbados	12	0.294	0.055	0.020	0.083
Belize	11	0.160	0.029	0.052	0.067
Chile	12	0.260	0.102	0.000	0.059
Colombia	4	0.084	0.007	0.037	0.052
Costa Rica	8	0.060	0.008	0.048	0.057
Dominican Republic	12	0.112	0.005	0.007	0.032
Ecuador	3	0.083	0.003	0.010	0.004
Grenada	11	0.786	0.017	0.078	0.449
Guatemala	10	0.123	0.010	0.070	0.057
Honduras	9	0.492	0.021	0.117	0.147
Jamiaca	12	0.253	0.014	0.069	0.301
Mexico	10	0.162	0.002	0.035	0.065
Panama	2	0.138	0.023	0.037	
Peru	6	0.589	0.004	0.431	0.279
SVG	5	0.746	0.043	0.106	0.219
Turks and Caicos	12	0.858	0.099	0.214	0.194
Uruguay	10	0.035	0.027	0.003	0.013

TABLE A3. Adaptation Expenditure Summary Statistics by Country. Expenditure is given as a percentage of GDP and shown as a percentage.

I also 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 statistically significant correlation between the number of line items identified in a budget and the dollar amount of adaptation expenditure listed.

A.8.1. Regression Controls: Summary Statistics

	Wind Speed	Regulatory Quality (Mean)	Regulatory Quality (SD)	Govt-effect (Mean)	Govt-effect (SD)
Cross-Country Average	0.24	0.148		0.065	
Cross-Country SD	0.45	0.479		0.547	
Argentina	0.0003	-0.483		-0.378	
Bahamas	0.0640	0.070	0.120	0.509	0.147
Barbados	1.1100	0.463	0.077	0.724	0.331
Belize	0.0212	-0.502	0.079	-0.562	0.112
Chile	0.0011	1.174	0.211	0.793	0.153
Colombia	0.0005	0.121	0.028	-0.031	0.063
Costa Rica	0.0098	0.508	0.051	0.239	0.111
Dominican Republic	0.0121	0.029	0.063	-0.249	0.197
Ecuador	0.0018	-0.633	0.150	-0.348	0.131
Grenada	1.1462	0.060	0.244	-0.072	0.083
Guatemala	0.0044	-0.310	0.032	-0.762	0.094
Honduras	0.0052	-0.495	0.038	-0.699	0.126
Jamaica	1.1104	0.100	0.059	0.491	0.110
Mexico	0.0059	-0.013	0.166	-0.216	0.131
Panama	0.0061	0.119		-0.210	
Peru	0.0004	0.333	0.176	-0.322	0.122
SVG	1.2009	0.337	0.017	0.233	0.138
Turks and Caicos	0.9225	0.412	0.082	0.324	0.142
Uruguay	0.0030	0.661	0.046	0.638	0.176

TABLE A4. Control Variable Summary Statistics by Country. Wind Speed is historical maximum average windspeed scaled by land area from the GeoMet database. Regulatory Quality and Government Effectiveness are indices from the World Bank.

Government Effectiveness and Regulatory Quality are indices from the Worldwide Governance Indicators compiled by the World Bank.[33]

Government Effectiveness captures "perceptions of the quality of public services, the quality of the civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies." Sources used to construct the index include a measure of institutional effectiveness from the Economist Intelligence Unit, the likelihood of infrastructure disruption, state failure or political instability from S&P

[33] `www.govindicators.org` Kaufmann, Kraay, and Mastruzzi (2010)

Global, and quality of financial and revenue management.

Regulatory Quality captures: "perceptions of the ability of the government to formulate and implement sound policies and regulations that permit and promote private sector development." This includes the risk that business operations become more costly due to the regulatory environment, and the risk that fines and penalties will be levied for non-compliance with a tax code that appears disproportionate or manipulated for political ends.

Table A5 shows results using regulatory quality rather than government effectiveness:

	adapt	
sovrate	198,917,071***	52,498,372***
	(76,413,625)	(11,142,294)
gdp	0.001***	0.0054***
	(0.0001)	(0.0011)
exposure	164,980,764**	
	(82,519,154)	
regulatory quality	19,071,555	
	(54,779,990)	
Country Fixed Effects	No	Yes
Year Fixed Effects	Yes	Yes
Observations	98	105
R-squared	0.95	0.84
Note:	*p<0.1; **p<0.05; ***p<0.01	

TABLE A5. Regression Results. adapt and gdp are in millions of 2017 US dollars. sovrate is an index from 0-21. Exposure is historical average maximum windspeed scaled by land area, and standardized to have mean 0 and standard deviation 1. Regulatory quality is an index from the World Bank standardized to have mean 0 and standard deviation 1. Standard errors are clustered by country and year.

A.9. Adaptation and Exposure

A.9.1. Wind Speed

Hurricanes are responsible for the largest share of damages from natural disasters. Therefore as a proxy for exposure to natural disasters I take a measure of historical average wind speeds scaled by land area. This measure comes from the GeoMet database (Felbermayr and Gröschl 2014). Figure A1 shows that there is a statistically significant, positive correlation between historical exposure to storms and adaptation expenditures.

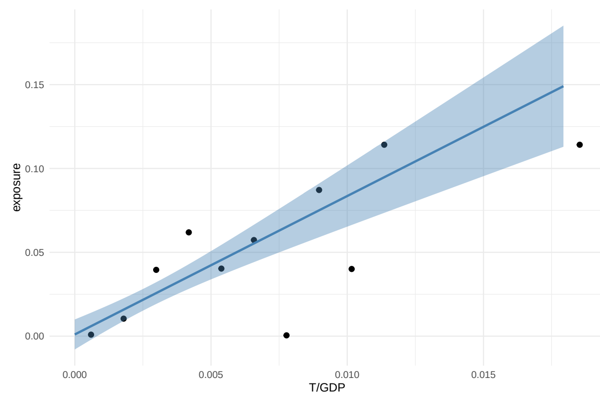

FIGURE A1. Relationship between adaptation expenditure and natural disaster exposure. The exposure measure is historical average maximum wind speeds scaled by land area. Windspeed data comes from the GeoMet database (Felbermayr and Gröschl 2014)

A.9.2. INFORM Risk

The INFORM Risk index is an open-source risk assessment for different varieties of crises and disasters. The European Commission Joint Research Centre is the scientific lead.[34] In the hazard and exposure dimension the database includes an index of exposure to natural hazards which can be sub-divided by variety. As countries in my sample are most exposed to Tropical storms and droughts I take the aggregate index of exposure to natural hazards as well as the specific tropical cyclone and drought indicators. Table A6 documents summary statistics.

Table A16 presents regression results linking adaptation expenditures and natural hazard exposure. From the table we can see that the measure of historical average wind-speeds has the greatest explanatory power for the variation in adaptation expenditures.

[34] https://drmkc.jrc.ec.europa.eu/inform-index

Statistic	N	Mean	St. Dev.	Min	Max
Natural Disasters	19	4.77	1.49	2.30	6.60
Tropical Cyclone	19	4.58	3.33	0.00	10.00
Drought	19	2.03	1.56	0.30	5.50

TABLE A6. INFORM Risk: Summary Statistics

	Dependent variable:			
	T/GDP			
Windspeed	0.033***			
	(0.005)			
Natural		0.0002**		
		(0.0001)		
Tropical Cyclone			0.0001	
			(0.0001)	
Drought				0.0002**
				(0.0001)
Constant	0.002***	0.001**	0.002***	0.002***
	(0.0002)	(0.0005)	(0.0004)	(0.0003)
Observations	163	163	163	163
R^2	0.270	0.040	0.006	0.041
Adjusted R^2	0.265	0.031	0.003	0.032
Note:				*p<0.1; **p<0.05; ***p<0.01

TABLE A7. Regression Results: Adaptation and Climate Hazards

A.9.3. Exposure and Spending Disaggregated

Countries spend more to tackle the hazards that they are most exposed to. Figure A2 shows this. Countries that are more exposed to floods or storms spend a larger share of their adaptation budget on storm/flood protection. Countries more exposed to droughts spend more on drought protections.

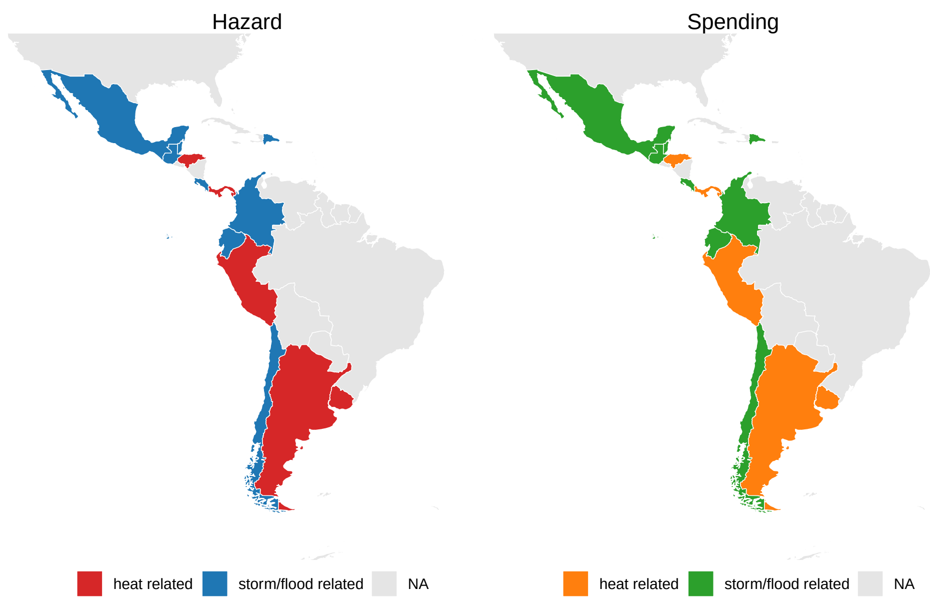

FIGURE A2. The left map colour codes countries by the type of hazard they are most exposed to. If the country is more exposed to floods or storms they are shown in blue. If they are more exposed to droughts they are shown in red. On the right I categorize countries by the share of adaptation expenditure on heat related hazards or water related hazards.

A.10. 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 A8.

TABLE A8. Summary Statistics

Statistic	N	Mean	St. Dev.	Min	Max
Adaptation Total / GDP	19	0.43%	0.0032	0.001	0.0187
Disaster Preparedness / GDP	19	0.11%	0.0022	0.0001	0.0098
Meteorological Services / GDP	19	0.03%	0.0005	0.0000	0.0009

	Adaptation Measure:			
	Total Adaptation	Disaster Preparedness	Meteorological Services	Total Adaptation
sovrate	3,900,370*	1,500,120	477,907	2,601,720*
	(2,081,275)	(1,832,566)	(512,430)	(1,498,012)
GDP	0.003***	0.003***	0.0009	0.003***
	(0.001)	(0.0007)	(0.002)	(0.001)
exposure	11,156,417*	79,546,311**	10,276,532	9,786,053*
	(6,046,099)	(38,546,311)	(22,646,099)	(5,835,924)
Government effectiveness				573,012
				(394,192)
Observations	19	19	19	19
R^2	0.909	0.939	0.382	0.951
Adjusted R^2	0.774	0.848	0.103	0.894
Note:				*p<0.1; **p<0.05; ***p<0.01

TABLE A9. The first column uses the text based measure of adaptation as the dependent variable. The second column uses disaster preparedness expenditure, and the third uses meteorological expenditure. All values are reported in 2017 US $.

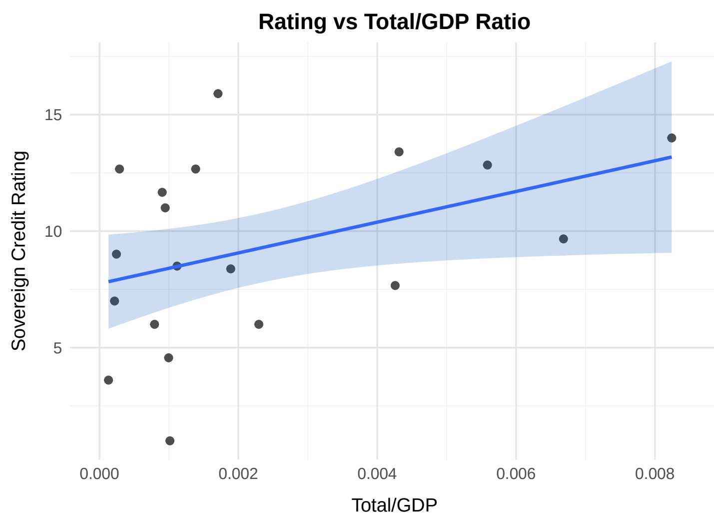

FIGURE A3. Adaptation Investment and Sovereign Ratings. Sovereign ratings are an average of the previous three years, on a scale from 0-21 from the World Bank fiscal space database (Kose et al. 2022). The adaptation measure is total adaptation spending, shown as a proportion of GDP. The shaded region shows standard errors at the 90% level. The plot includes one observation for each country in the year 2023.

A.10.1. Caribbean Subsample

Figure A4 shows the wordcloud for commonly used terms from the construction of the adaptation measure restricted to the Caribbean subsample.

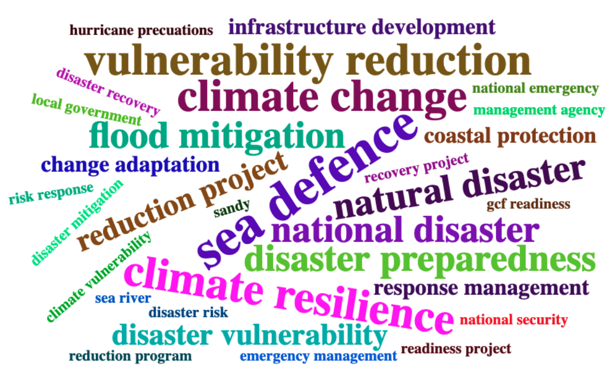

FIGURE A4. Word Cloud Representing the most frequently used terms in budget entries picked up when building the total adaptation measure: Caribbean subsample.

A.11. Disaster Preparedness and Meteorological Expenditure

	Disaster Preparedness	
sovrate	304,152,674	132,705,006
	(254,948,612)	(220,494,310)
gdp	0.0011***	0.0051***
	(0.0004)	(0.0005)
exposure	124,464,182***	
	(12,284,012)	
government effectiveness	140,177,373**	
	(65,775,964)	
Country Fixed Effects	No	Yes
Year Fixed Effects	Yes	Yes
Observations	98	105
R-squared	0.95	0.84

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

TABLE A10. Regression Results: Disaster Preparedness and Sovereign Rating

	Meteorological Services	
sovrate	268,014,394***	786,490,187***
	(103,115,274)	(81,603,371)
gdp	0.0061	0.0010**
	(0.0040)	(0.00046)
exposure	129,812,401**	
	(64,190,146)	
government effectiveness	715,689,368***	
	(18,416,559)	
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

TABLE A11. Regression Results: Meteorological Services Expenditure and Sovereign Rating

A.12. Exposure Controls

Baseline results with different proxies for exposure to natural disasters.

	adapt			
sovrate	67,554,921***	41,286,883***	38,411,248***	44,220,882***
	(16,647,312)	(9,241,031)	(14,524,916)	(11,551,834)
gdp	0.0022***	0.001***	0.001***	0.001***
	(0.0002)	(0.0001)	(0.0001)	(0.0001)
windspeed	143,757,032**			
	(62,519,154)			
natural		81,436,087*		
		(44,013,869)		
cyclone			37,428,812	
			(45,306,999)	
drought				27,727,914
				(43,063,322)
government effectiveness	121,350,937**	21,131,829	50,668,145	42,115,495
	(48,299,257)	(105,309,509)	(40,124,011)	(39,406,025)
Year Fixed Effects	Yes	Yes	Yes	Yes
Observations	98	98	98	98
R-squared	0.95	0.93	0.92	0.92
Note:	*p<0.1; **p<0.05; ***p<0.01			

TABLE A12. Regression Results. adapt and gdp are in millions of 2017 US dollars. sovrate is an index from 0-21. Other exposure measures come from INFORM and are standardized to have mean 0 and standard deviation 1. Government effectiveness is an index from the World Bank standardized to have mean 0 and standard deviation 1. Standard errors are clustered by country and year.

A.13. Sovereign Risk Measures

Here I present the baseline results with different measures for capturing sovereign risk.

A.13.1. EMBI

From Global Financial Data, I collect data on emerging market economy's JP Morgan Emerging Market Bond Index (EMBI) spreads. EMBI combines different maturity dollar denominated bonds from a given country into one spread. The composite maturity is typically 2-5 years. I do not use this data for my baseline analysis as it is only available for 38 emerging market economies, 10 of which are in my adaptation dataset. However I show here that the same relationship between sovereign risk and adaptation expenditures is visible using this data. A higher spread is indicative of higher default risk and tighter borrowing constraints, therefore the expected sign of the coefficient flips to negative. The coefficient in the second specification is not statistically significant, potentially due to the lower sample size.

	Adaptation Expenditure	
EMBI	–16,641,818*	–1,725,994
	(1,773,254)	(1,510,511)
gdp	0.001***	0.001***
	(0.0003)	(0.0003)
exposure	109,104,732*	
	(40,190,146)	
government effectiveness	89,042,884	
	(80,729,185)	
Country Fixed Effects	No	Yes
Year Fixed Effects	Yes	Yes
Observations	76	76
R-squared	0.761	0.758

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

TABLE A13. Regression Results. EMBI spreads and adaptation services expenditure.

A.13.2. CDS

Here I present the results of the same specification now using CDS spreads from Bloomberg as the measure of sovereign risk as used in section 3.2. Again, we find the expected negative coefficient indicating that adaptation is declining with sovereign risk. The CDS also has less coverage than the sovereign rating data used in the baseline analysis. These results cover 8 countries: Argentina, Chile, Colombia, Costa Rica, Ecuador, Mexico, Panama and Peru. With a lower number of observations the coefficient on sovereign risk is no longer significant, but it is of the expected sign.

	Adaptation Expenditure	
CDS Spread	−21,355,235*	−21,412,531*
	(11,963,353)	(11,920,214)
gdp	0.001***	0.001***
	(0.0002)	(0.0002)
exposure	97,521,463***	
	(14,003,729)	
government effectiveness	104,240,907	
	(96,738,648)	
Country Fixed Effects	No	Yes
Year Fixed Effects	Yes	Yes
Observations	71	71
R-squared	0.612	0.646

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

TABLE A14. Regression Results. CDS spreads and adaptation services expenditure.

A.14. Narrative Evidence

Section 3 presents evidence that adaptation is declining in sovereign risk. This is consistent with the model and additional narrative evidence. Rating agency methodologies do not explicitly use adaptation as an input (potentially due to a lack of adaptation related data). Therefore the positive relationship is likely driven in the opposite direction: high borrowing costs restrict adaptation expenditures.

Rating Agency Methodologies

Moody's sovereign rating methodology does not include the term 'adaptation'. The term 'climate' occurs only in conjunction with discussions of vulnerability to climate shocks, and does not discuss resilience or adaptation.[35]

S&P also do not use the term 'adaptation' in their rating methodology. They do note that they consider 'reforms in support of sustainable public-sector finances' which may include 'policies to mitigate the adverse physical effects of climate change'. However this approach is not systematized.[36]

Fitch outline a relatively sophisticated climate modeling component for their rating methodology. Their climate model uses physical inputs only, for example data from EMDAT and INFORM risk, to back out exposure to climate risk. They note that their exposure measures are 'unmitigated' exposures in that they do not incorporate potential mitigation or adaptation capacity. They note that such capacity or policy may be considered instead on an ad hoc basis by screening committees.[37]

Rating Releases

Adaptation is not systematically included in rating agency methodologies. It is also difficult to find instances of rating releases where adaptation was explicitly considered, indicating that the option to include adaptation in an ad hoc way is rarely used. This could be due to i) lack of adaptation data, or ii) lack of sufficient investment in adaptation to warrant material effects on ratings.

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

[35] https://ratings.moodys.com/api/rmc-documents/395819

[36] https://www.spglobal.com/ratings/en/regulatory/article/-/view/sourceId/10221157

[37] https://www.fitchratings.com/research/sovereigns/sovereign-rating-criteria-15-09-2025

'lack of meaningful fiscal space'.[38]

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."[39]

Therefore the narrative evidence on the rating agency side suggests that i) adaptation is not systematically included in methodologies, ii) there is scope to include adaptation in individual rating decisions, but iii) adaptation has not been a driver of rating movements thus far.

Government Statements

Due to this limited narrative support for adaptation affecting sovereign ratings, it is likely that the empirical result may result from constrained sovereigns spending less on adaptation. This is consistent with statements by numerous government officials in climate-exposed economies. Mia Mottley, the Prime Minister of Barbados, has been among the most vocal. In her speech to COP27 she noted:

"Addressing climate impacts is critical for my country and region as frontline states in the climate crisis, which are simultaneously in the world's most disaster-prone, climate vulnerable, debt ridden, and tourism dependent regions."

"As a middle-income country, Barbados' most critical need is capital to address, adapt to, or mitigate climate crisis impacts. Consequently, at the international level, we are seeking new means of financing loss and damage, promoting the five-pronged Bridgetown Initiative". [40]

The Bridgetown Initiative makes this point:

[38] https://www.fitchratings.com/research/sovereigns/fitch-upgrades-jamaica-to-bb-outlook-positive-05-03-2024.

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

[40] https://unfccc.int/sites/default/files/resource/BARBADOS_cop27cmp17cma4_HLS_ENG.pdf

"the level of financing which is made available, to which countries will have access and on what terms, are issues of survival for millions of people and for the well-being of our planet". [41]

A.15. Composition of Debt

Table A15 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 A15. 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 fundamentals they are not eligible for concessional finance from organisations such as the IMF. This further restricts their ability to borrow in order to adapt.

[41] https://www.bridgetown-initiative.org/bridgetown-initiative-3-0/

A.16. 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 A5 shows that in 2022 countries with higher sovereign ratings tended to have higher government expenditures as a proportion of GDP. Table A16 shows regression results to that effect.

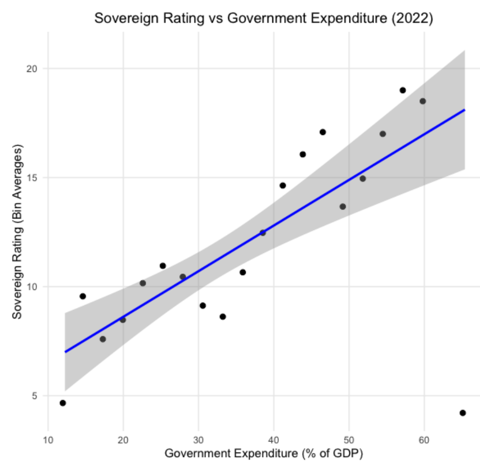

FIGURE A5. Bin scatter plot of government expenditure as a proportion of GDP, against sovereign rating average from the previous three years. The plot uses data on expenditure from the Global Macro Database for the year 2022.

When I restrict attention to the countries in my sample from Section 2.2, however, this positive effect is no longer visible. In the matching of the datasets I lose the observation of Turks and Caicos. Figure A6 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 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

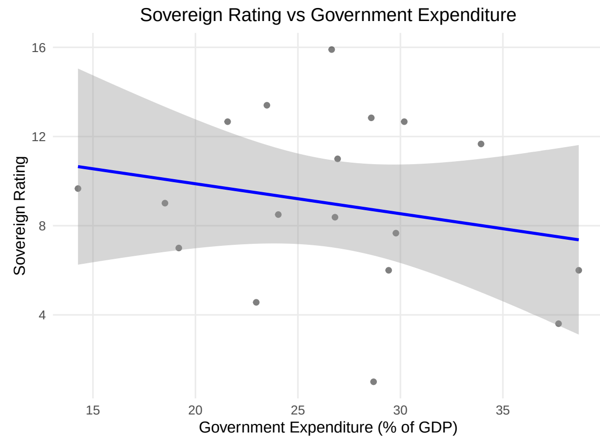

FIGURE A6. Bin scatter plot of government expenditure as a proportion of GDP, against sovereign rating average from the previous three years. The plot uses data on expenditure from the Global Macro Database for the year 2022. The sample is restricted to the 19 countries included in the main analysis.

of default.

	Dependent variable:			
	gov expenditure			
sovrate	117,691*	169,315**	486,422***	527,693***
	(67,352)	(69,411)	(91,372)	(102,301)
GDP	0.001***	0.001***	0.001**	0.001**
	(0.00004)	(0.00004)	(0.0004)	(0.0004)
Government Effectiveness			192,201	195,416
			(129,254)	(129,387)
Year Fixed Effect	No	Yes	No	Yes
Observations	3,515	3,515	2,964	2,964
R^2	0.985	0.985	0.986	0.986
Adjusted R^2	0.985	0.985	0.985	0.985
Note:			*p<0.1; **p<0.05; ***p<0.01	

TABLE A16. Regression Results: Total government expenditure and sovereign rating. Global sample.

A.17. Summary Statistics

TABLE A17. CDS spreads by Country

Country	Mean	SD	Country	Mean	SD
Algeria	48.75	15.58	Ireland	129.44	198.08
Australia	36.82	24.50	Japan	36.72	29.23
Belgium	42.54	62.33	Malaysia	88.41	51.11
Brazil	334.14	493.40	Mexico	134.83	66.47
Canada	48.94	9.43	Mongolia	297.15	148.72
China	68.90	37.82	Morocco	158.02	21.00
Colombia	200.23	123.91	Namibia	297.15	148.72
Costa Rica	287.88	145.90	Netherlands	29.50	29.19
El Salvador	307.31	145.84	New Zealand	47.81	11.58
Ethiopia	297.15	148.72	Norway	15.05	10.83
France	39.21	41.10	Oman	131.80	33.81
Germany	21.68	20.71	Pakistan	295.63	147.21
Guatemala	176.31	63.07	Philippines	175.71	142.69
Hong Kong	45.58	12.11	Portugal	163.06	259.91
Iceland	111.97	44.65	South Africa	188.14	78.49
India	48.75	15.58	Spain	101.72	113.58
Indonesia	170.32	106.49	Thailand	82.95	51.33
			Vietnam	129.19	77.54

TABLE A18. Cyclone Frequency by Country: 1980-2025

Country	Mean	Country	Mean
Algeria	0.02	Mauritius	0.04
Antigua and Barb.	0.15	Mexico	0.96
Australia	0.98	Mongolia	0.02
Bahamas	0.50	Morocco	0.02
Bangladesh	0.72	Mozambique	0.54
Barbados	0.11	Namibia	0.04
Belize	0.37	Nepal	0.02
Bermuda	0.07	Netherlands	0.04
Botswana	0.09	New Zealand	0.33
Brazil	0.04	Nicaragua	0.48
Cabo Verde	0.09	Norway	0.04
Cambodia	0.43	Oman	0.24
Canada	0.70	Pakistan	0.17
China	0.96	Papua New Guinea	0.33
Colombia	0.09	Philippines	0.96
Costa Rica	0.02	Portugal	0.02
Cuba	0.61	Puerto Rico	0.22
Dominica	0.07	Russia	0.74
Dominican Rep.	0.39	Saint Lucia	0.09
El Salvador	0.09	Saudi Arabia	0.04
Ethiopia	0.04	Somalia	0.17
Fiji	0.41	Somaliland	0.09
France	0.41	South Africa	0.09
Greenland	0.04	South Korea	0.78
Grenada	0.09	Sri Lanka	0.26
Guatemala	0.35	St. Vin. and Gren.	0.09
Haiti	0.26	Taiwan	0.85
Honduras	0.37	Tanzania	0.02
Hong Kong	0.11	Thailand	0.80
Iceland	0.04	Timor-Leste	0.07
India	0.89	Tonga	0.04
Indonesia	0.39	Trinidad and Tobago	0.15
Iran	0.02	Turks and Caicos Is.	0.09
Ireland	0.15	United Kingdom	0.20
Jamaica	0.15	United States of America	0.96
Japan	0.96	Vanuatu	0.59
Laos	0.83	Venezuela	0.13
Madagascar	0.85	Vietnam	0.94
Malawi	0.09	Yemen	0.15
Malaysia	0.04	Zimbabwe	0.20

A.18. 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 A19. Local Projection Results. Dependent variable: log CDS spreads.

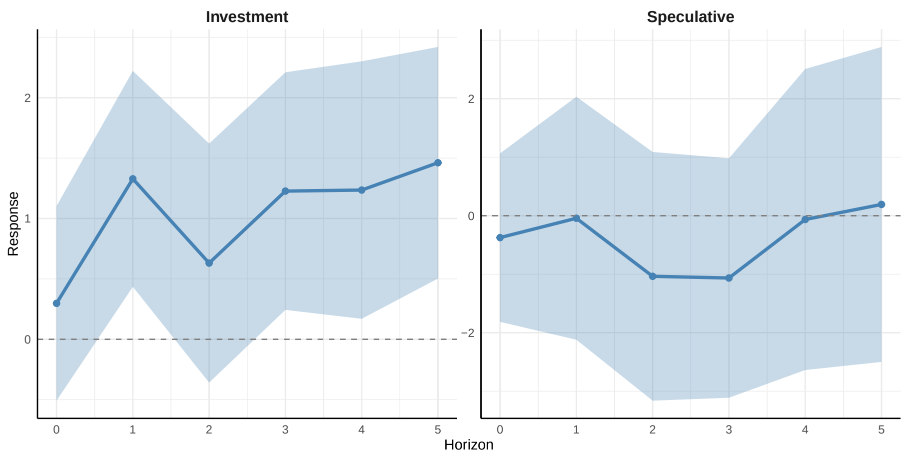

FIGURE A7. Cyclone shock on CDS spreads. Left panel restricted to only investment grade bonds. Right panel only speculative grade bonds.

A.19. Alternative Default Data

In this section I present the results of estimating the local projection presented in Figure 7 using alternative measures of default.

A.19.1. Kurvshinov and Zimmermann (2019) database

Kushinov and Zimmermann (2019) consolidate a set of different data on default. Two of the most commonly used measures included in the database are that constructed by Reinhart and Rogoff as in Reinhart and Rogoff (2011) and Reinhart and Trebesch (2011), and that constructed from Standard Poors reports as in Beers and Chambers (2006). The data runs from 1980-2010. I show that for this more limited timeframe, and for these alternative measures of default, the results as presented in section 3 continue to hold. Due to the more limited coverage, however, I cannot test the adaptation subsamples.

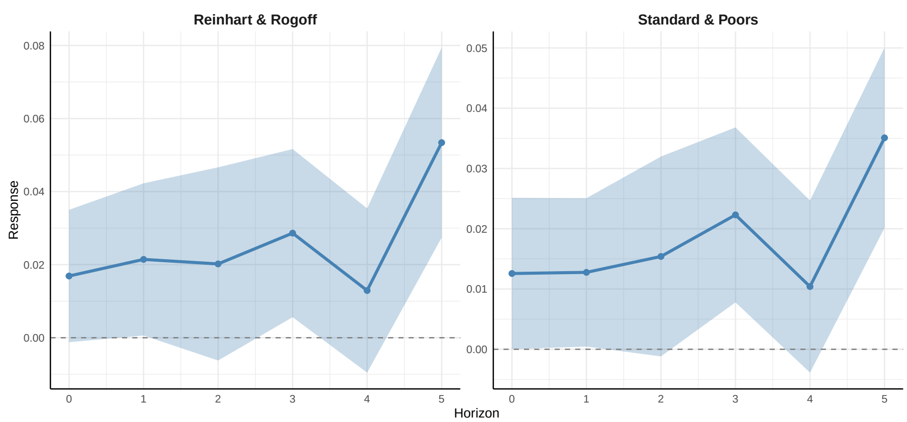

FIGURE A8. Local Projection of cyclone strike of at least category one speed on default indicators.

In both cases, the cyclone strike causes the probability of default to increase on impact. The magnitude of the increase in default probabilities is comparable in magnitude to that of the baseline results. Both IRFs also show an uptick in default probabilities three years after the cyclone, consistent with the baseline results.

A.19.2. Asonuma and Trebesch database

Asonuma and Trebesch (2016) construct a dataset of defaults and restructurings which is available up until mid 2020. I show that using this dataset, the aggregate pattern of the response of default probabilities is in line with the baseline results and those from the Kushinov and Zimmermann (2019) database. When restricted to the countries in my adaptation data sample, the effect on default probabilities is more immediate and more pronounced.

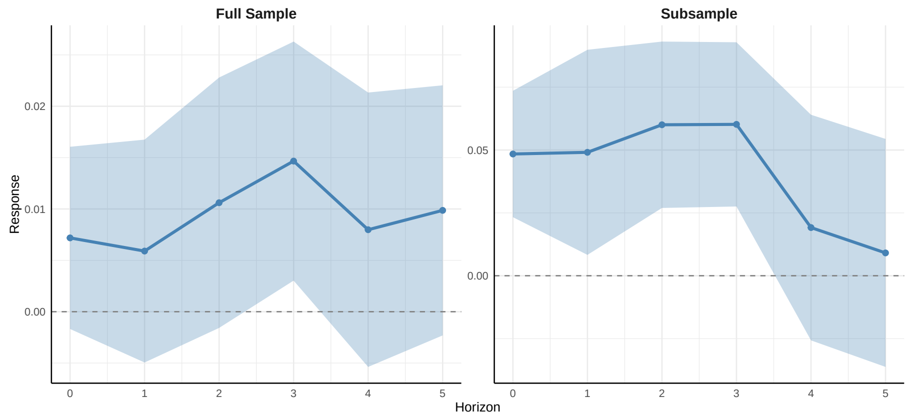

FIGURE A9. Local Projection of cyclone strike of at least category one speed on default indicator.

Additionally, with this dataset I can examine the heterogeneous effect by adaptation level. Consistent with the baseline results, the effect of cyclones on default risk is driven by the low adaptation subsample. The effect is statistically insignificant for the high adaptation subsample.

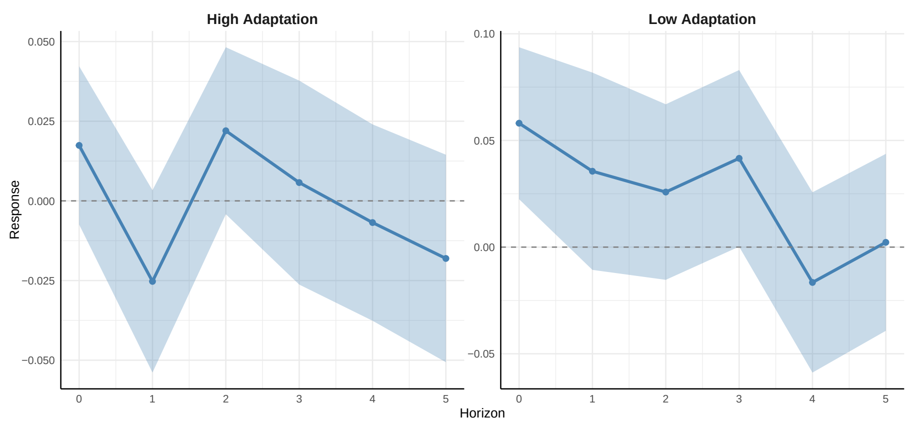

FIGURE A10. Local Projection of cyclone strike of at least category one speed on default indicator.

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:

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

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

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

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.

B.3. Borrowing

Borrowing also responds to climate change. Higher probability of a bad shock tomorrow reduces optimal borrowing. However, as the discount rate of the sovereign is below the inverse of the risk free rate the sovereign will always be a net borrower.

No Default Risk. FOC(B):

$$\frac{1}{C_1(1+r)} = \beta\, \mathbb{E}\left[\frac{1}{y_2 - b}\right]$$

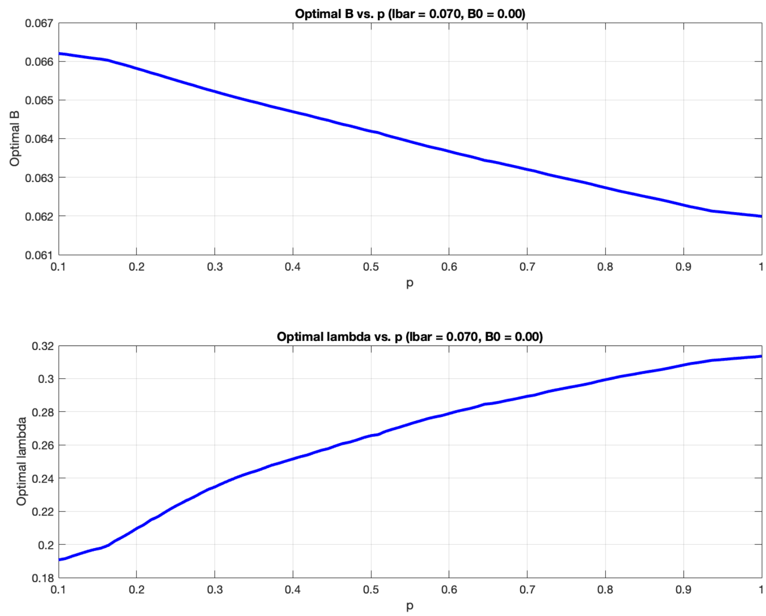

FIGURE A11. Two period model: borrowing and Adaptation.

therefore borrowing is decreasing with climate change.

Limited Commitment. FOC(B):

$$\frac{(1-s) - s'(b)b}{C_1(1+r)} = \beta\, \mathbb{E}\left[(1-s(b))\frac{1}{y_2 - b} - s'(b)\left(U(C_D) - U(C_R)\right)\right],$$

therefore as the spread is increasing in p and in b at a decreasing rate, borrowing is also declining with climate change under default risk. Figure A11 shows that borrowing is declining in the probability of a cyclone while adaptation is rising. Adaptation is more responsive to the probability of a cyclone than is borrowing: the percentage increase in adaptation is greater.

B.4. Adaptation

Section 2.2 outlined that the model prediction on the relative magnitude of adaptation under sovereign risk versus without is ambiguous. Here I outline what governs this tradeoff. I show that adaptation will be greater under sovereign risk only if spreads are low (default costs are high) while also being very responsive to adaptation (adaptation is very effective, the natural disaster threat is substantial).

The first order condition for adaptation in the absence of default risk is:

$$\frac{1}{c_{1c}} = \beta \mathbb{E}\left(\frac{y_2'(\lambda)}{c_{2c}}\right),$$

where the subscript c to denotes the no default risk or 'commitment' case. The first order condition under limited commitment is:

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

I first show that the *direct* effects: the marginal cost of adaptation and the marginal benefits of damage reduction, imply that adaptation is greater in the absence of default risk:

$$c_{1c} = y_1 + \frac{1}{1+r}b_c - b_0 - \lambda,$$

$$c_1 = y_1 + \frac{1-s}{1+r}b - b_0 - \lambda.$$

Therefore, for a given λ, the positive spread $s > 0$ reduces c_1 relative to c_{1c}. Additionally, the presence of the spread reduces the optimal debt choice further reducing c_1 relative to c_{1c}. As a result, the marginal cost of adaptation is greater under default risk than without. Next consider the direct marginal benefit: the marginal benefit of damage reduction. This effect in the limited commitment case can be rewritten as:

$$\beta \mathbb{E}\left(\frac{y_2'(\lambda)}{c_R}\frac{y_2 - s(\lambda)b}{y_2}\right),$$

where $c_R = y_2 - b > c_{2c} = y_2 - b_c$, since borrowing is greater in the absence of default risk. Additionally, with positive spreads $y_2 - s(\lambda)b < y_2$. Therefore the marginal benefit of damage reduction is lower under default risk than without. This is due to i) potential lost benefits due to output costs of default, and ii) the lower debt repayment burden.

The marginal cost of adaptation is greater and the marginal benefit of damage reduction is lower under default risk than without. Therefore, adaptation under default risk should be lower than without via these direct effects. However, it is theoretically possible for the two additional indirect marginal benefits to flip the sign. If

$$\beta\mathbb{E}\left(s'(\lambda)(u(c_D) - u(c_R))\right) - \frac{\frac{1}{1+r}s'(\lambda)b}{c_1}$$

is sufficiently large it could dominate the direct effects. These indirect marginal benefits are largest when:

a. The spread is very responsive to adaptation: $s'(\lambda)$ is large. This is likely when:
    - Disasters are a substantial threat (high frequency and/or intensity)
    - Adaptation is very effective in reducing damages
b. Default costs are high.
    - In this case the difference in utility from consumption and repayment is large, and borrowing is high magnifying the effect of reduced spreads from adaptation.

Additionally, the difference in the direct effects of adaptation with vs without default risk is shrinking as the spread declines. Therefore, it will be easier for the indirect effects to overpower the direct effects when the spread is low. For the spread to be low while borrowing is high it must be the case that default costs are high.[42]

Therefore, a calibration in which sovereign risk increases adaptation would feature i) low spreads, ii) high adaptation, and iii) high exposure to natural disasters. Such a calibration is counterfactual for the economies I am considering.

	$p = 0.1$, $\alpha = 2$	$p = 0.1$, $\alpha = 1.1$	$p = 0.5$, $\alpha = 2$	$p = 0.5$, $\alpha = 1.1$
$\bar{l}$ min	NA	0.91	NA	0.87
implied s (bps)	NA	21	NA	28

TABLE A20. The table shows the minimum value for default costs that imply that adaptation is higher under default risk than without for a set of combinations of the probability of a disaster and adaptation effectiveness. $F(\lambda) = \exp\left(-\alpha\lambda^{1/\alpha}\right)$.

Table A20 shows that it is not possible to calibrate the model such that the spread is sufficiently large while also having higher adaptation under sovereign risk than without. For the greater indirect marginal benefits to damage the effectiveness of adaptation and the cost of default must be high. For baseline values of the probability of a disaster and the effectiveness of adaptation that correspond to those estimated for the quantitative model, it is not possible to find default costs high enough such that the indirect effect dominates.

[42]High period 0 debt and low discount factors also increase borrowing but simultaneously increase the spread.

B.5. Adaptation Bond

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 $c_D > c_R$. Consumption in repayment is adjusted by the adaptation bond: the coupon payment is reduced if adaptation is above the threshold level.

$$c_R = y_1^{\rho}(1 - x_t d_t F(\lambda))\epsilon^{y} - b(1 - c\mathbb{1}_{\Lambda > \Lambda^*}), \qquad c_D = \phi(y_2) y_1^{\rho}(1 - x_t d_t F(\lambda))\epsilon^{y}.$$

As in the baseline model this implies that default occurs if the disaster adjusted growth rate $\tilde{g}$ is below an endogenous default threshold $\bar{g}$:

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

where $\tilde{g}$ is adjusted by

$$-\frac{1}{1+\psi} ln(1 - \mathbb{1}_{\Lambda > \Lambda^*})$$

relative to the baseline. This implies that the coupon reduction decreases the probability of default in high adaptation states. In the baseline model the expected payoff from buying the bond was $(1 - \mathbb{Pr}(D_2 = 1))$. Now the payoff must be adjusted for the potential coupon reduction:

$$\mathbb{E}(\text{payoff}) = \mathbb{Pr}(\Lambda \leq \Lambda^*)(1 - \mathbb{Pr}(D_2 = 1 | \Lambda \leq \Lambda^*)) + (1 - c)\mathbb{Pr}(\Lambda > \Lambda^*)(1 - \mathbb{Pr}(D_2 = 1 | \Lambda > \Lambda^*)).$$

$$q = \frac{\mathbb{E}(\text{payoff})}{1 + r}.$$

Therefore the bond price that gives the investor zero expected profit in equilibrium will have to account for the lower expected default probability as well as the lower expected coupon payment.

Rewriting, the spread is:

$s\,(b, \Lambda) =$

$$(1-p)\Phi_g(\bar{g} + \mathbb{1}_{(\Lambda>\Lambda^*)}\frac{1}{1+\psi}ln(1-c))+$$
$$pE_{d'}\left[\Phi_g\left(\bar{g} - \frac{1}{1+\psi}ln(1-d_t(F(\lambda_t)) + \mathbb{1}_{(\Lambda>\Lambda^*)}\frac{1}{1+\psi}ln(1-c)\right)\right] - c\mathbb{1}_{\Lambda>\Lambda^*}.$$

Therefore, the adaptation bond could either tighten the budget constraint by increasing spreads (final term), or loosen it by decreasing spreads via lower default probabilities.

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.[43]
    - 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.

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

- Conditional on an arbitrary b', choice probabilities over Λ' are given by:

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

with associated ex-ante value:

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

- The outer choice over b' satisfies:

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

and the ex-ante value of repayment becomes

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

- 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:

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

   - 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 A21. Simulated Moments
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.