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Natural Disasters, Climate Change, and Sovereign Risk

Enrico Mallucci*

Abstract

I investigate how natural disaster can exacerbate fiscal vulnerabilities and trigger sovereign defaults. I extend a standard sovereign default model to include disaster risk and calibrate it to a sample of seven Caribbean countries that are frequently hit by hurricanes. I find that hurricane risk reduces government's ability to issue debt and that climate change may further restrict market access. Next, I show that "disaster clauses", that provide debt-servicing relief, improve government ability to borrow and mitigate the adverse impact of climate change on government's borrowing conditions.

JEL classification: F32, F34, Q54.
Keywords: Sovereign risk, climate change, natural disasters.

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1 Introduction

Unexpected shocks may tip vulnerable governments in a default. While, the literature has highlighted the fundamental role of macroeconomic and financial shocks, such as a decline of commodity prices (Reinhart et al., 2016) or banking crises (Balteanu and Erce, 2018), in shaping sovereign risk, non-economic shocks, such as political events or extreme weather, are equally important.[1] Extreme weather appears especially salient in light of the key role played by natural disasters in recent default episodes (i.e. Grenada 2004, Antigua y Barbuda 2004 and 2009) and the ongoing debate around climate-change adaption strategies. In particular, the increasing frequency and intensity of natural disasters, such as hurricanes and tropical storms, has led economists and policy makers to advocate in favor of "disaster clauses", that allow for a temporary debt moratorium when countries are hit by natural disasters. Using a quantiative model of sovereign default, I study the impact of extreme weather and climate change on the price of government bonds and governments' borrowing and default decisions. Additionally, I show that disaster clauses can improve governments' market access allowing them to borrow more.

I extend a standard sovereign default à la Arellano (2008) to allow for natural disasters, that are modeled as exogenous shocks. The model is calibrated to a sample of seven Caribbean economy and is employed to quantify the impact of hurricanes on sovereign risk and government's policies. First, I evaluate the impact of extreme weather comparing model predictions in the baseline model with model predictions when hurricane risk is eliminated. I find that extreme weather restricts government's access to financial markets. Absent disaster risk, governments borrow more.

Second, I evaluate the impact of climate change on public finances, investigating how government policies respond to an increase of the frequency and the intensity of hurricanes. I find that governments face worse borrowing conditions when extreme weather becomes more frequent and more intense and, as a result, governments issue less debt leading to a decline of the debt-to-GDP ratios.

Finally, I analyze whether disaster clauses may help. In particular I consider the case of a clauses that allow governments to suspend payments when extreme weather hits. I find that such clauses facilitate market access allowing governments to borrow at better rates. Yet, disaster clauses also induce governments to engage in "gambling for debt-servicing suspension" behavior. Knowing that debt payments will be suspended in the event of a natural disaster, governments expand borrowings and spreads increase.

Our paper contributes to two main strands of the literature. First, I contribute to the quantitative literature on sovereign defaults in the tradition of Eaton and Gersovitz (1981) and Arellano (2008). In particular, this is the first paper to highlight and quantify the

[1] The ongoing COVID-19 pandemic is also an example of a non-economic shock that may exacerbate existing fiscal weaknesses.

impact of natural disasters and climate change on sovereign risk. In doing so, this paper also highlights the importance of non-economic events in explaining default risk.[2]

Second, I contribute to the literature that quantifies the impact of disaster risk on asset prices (Barro, 2009) and the macroeconomy (Gourio, 2012). In particular, this paper is related to the work of Mejia (2016) and Nordhaus (2010) that estimate the economic cost of hurricanes in the Caribbean and in the United States and their projected evolution with climate change.[3] This paper pushes this line of research further, as it evaluates the implications of such costs for public finances, the price of government debt, and sovereign risk.

The rest of the paper is organized as follows. Section 2 presents background information on the interaction between sovereign risk and extreme weather with a special emphasis on Grenada. Section 3 introduces the theoretical model. Section 4 presents the calibration strategy for the quantitative analysis. Section 5 reports quantitative results. Section 6 examines disaster clauses. Finally, section 7 concludes.

2 Sovereign Defaults and Extreme Weather: Narrative Evidence

An inspection of recent default episodes shows that extreme weather has often played a prominent role. This is especially true for small agricultural countries where extreme weather events are particularly disruptive to the economy and affect a vast portion of the territory.[4] Moldova, Suriname, and Ecuador offer three clear examples of the nexus between sovereign risk and extreme weather. Moldova and Suriname defaulted in 1992 and 1998 respectively following severe droughts that weakened the production of agricultural export goods (International Monetary Fund, 1999b; Vos et al., 2000). Ecuador defaulted in 1997 just a few months after floods caused major power shortages (Sturzenegger and Zettelmeyer, 2007).

The nexus between sovereign vulnerabilities and natural disasters is especially visible in Caribbean economies, which are the main focus of this paper. Caribbean countries are vulnerable to natural disasters as they are small and are regularly hut by hurricanes and tropical storms.[5] The cases of the Dominican Republic, Antigua y Barbuda, and Grenada are worth highlighting. On September 22 1998, the Dominican Republic was hit by hurricane

[2] Hatchondo and Martinez (2010) and Alessandria et al. (2019) also investigate the role of non-economic factors in shaping default risk, studying the impact of political risk and migration on default risk.

[3] Other related papers are Belasen and Polachek (2008) focusing on the impact of hurricanes on wages and employment; Deryugina et al. (2018) and Gallagher and Hartley (2017) focusing on the impact of hurricanes on household income and finances; and Roth Tran and Wilson (2019) focusing on impact of hurricanes on local economies.

[4] Or in larger countries like Thailand and Indonesia, where the economic activity is concentrated in small areas that are prone to extreme weather events.

[5] Table 6 in the Appendix reports the chronology of major hurricane hits in a sample of 7 Caribbean countries.

Georges. The devastation brought by the hurricane was so extensive that the Dominican government had to seek support from the IMF and other official lenders (International Monetary Fund, 1999a) in that very same year. Similarly, the government of Antigua y Barbuda began to accumulate arrears and ultimately defaulted after a series of hurricanes devastated the country in the late '90s. Finally, the case of Grenada (Asonuma et al., 2018) is also emblematic. Between 1999 and 2002, Granada's fiscal position deteriorated sharply and the debt-to-GDP ratio increased from about 35% to 80%. Grenada's weak fiscal position ultimately became unsustainable when hurricane Ivan hit the island in September 2004, causing damages estimated at $900 million, equivalent to about 150% of Grenada's GDP. Tourism and agriculture, the two major sources of export earnings, were especially hit as the hurricane damaged tourism infrastructure and wiped out the entire nutmeg crop. By the end of 2004, Grenada debt-to-GDP ratio stood at 130%, forcing the government to restructure its debt.[6]

Sovereign risk and natural disasters are so interwoven in the Caribbean, that governments have become to consider issuing bonds which entail disaster clauses. Such clauses aim to provide liquidity relief during catastrophic events, as they allow government to delay debt servicing payments. The government of Grenada led the way. In 2013, Grenada's debt was restructured for the second time in a decade to address underlying solvency problem. A key feature of the restructuring event is that new bonds included a hurricane clause, allowing governments to delay debt servicing for up to two payment periods, in the event of a hurricane causing damages evaluated at least US $15 million. Grenada's decision to introduce a hurricane clause was endorsed by the Paris Club and other countries, including Mexico and Barbados, have followed Grenada's example. More broadly, the introduction of disaster clauses has been gaining support among policy makers, especially in light of IMF's emphasis on incorporating natural disaster risk as a component of macroeconomic risk management.

3 Model

In this section, I lay down the workhorse models that I adopt to study the impact of extreme weather and climate changes on sovereign risk. The model is similar to the one proposed by Arellano (2008) with one key modification: The economy is subject to disaster risk.

The world economy is composed of one small open economy and international lenders. The small open economy is inhabited by a continuum of identical risk-averse households and by a government. Households receive an exogenous stream of income y and are subject to a disaster shock h. The government is benevolent and maximizes the welfare of the representative household.

[6] For an excellent review of the Grenada restructuring refer to Asonuma et al. (2018).

The choice problem of the government is identical to Arellano (2008).[7] When the government has access to international financial markets, it can choose to default on external debt or repay. If it defaults, the government loses access to markets. If it repays, the government decides on the amount of assets to issue in the current period. The state variables are the stock of government debt b, the realization of the endowment process y, and the realization of the disaster shock h.

Government's optimal default decision d, conditional on the country having access to the financial market, solves

$$V = \max_{d} \left\{ (1-d)\, V^{nd} + dV^{d} \right\}. \tag{1}$$

Where V^{nd} and V^{d} are household's value functions in the non-default and in the default scenarios and where d is an indicator taking the value of one when the government decides to default.

The value function V^{nd} is the solution to the following maximization problem:

$$V^{nd}\,(y, h, b,) = \max_{c,b'}\; u\,(c) + \beta \mathbb{E}\left[V\,(y', h', b')\right] \tag{2}$$

$$\text{s.t. } \; c = y(1-h) + qb' - b, \tag{3}$$

$$q = \frac{E\,(1-d')}{(1+r^{f})}, \tag{4}$$

Equation (3) is the resource constraint of the model economy. Endowment y and the hurricane shock h interact to determine final endowment after hurricane damages $y(1-h)$. Consumption equals final endowment plus net imports from abroad.

If the government chooses to default, or lacks access to financial markets, the economy suffers an output cost of exclusion. In this setting, the country's endowment is reduced to $\delta(y)$, where $\delta(y) \leq y$. The government can re-gain access to financial markets with the exogenous probability λ. The value function in case of default is:

$$V^{d}\,(y, h, 0) = u\,(c) + \beta \mathbb{E}\left[(1-\lambda)\, V^{d}\,(y', h', 0) + \lambda V\,(y', h', 0)\right] \tag{5}$$

$$\text{s.t. } \; c = (1-h)\delta(y), \tag{6}$$

where equation (6) is the resource constraint of the economy under autarky.

[7] I briefly describe here the key equations of the model. Refer to the original paper for a more thorough treatment.

3.1 International Investors

International investors have deep pockets and are risk neutral. They purchase government bonds and have access to a risk-free asset that pays the return r^{rf}. The price of government bonds is determined by arbitrage:

$$q(y', h', b') = \frac{E(1 - d')}{(1 + r^f)}, \tag{7}$$

The price of government bonds is decreasing in the risk of default which is a function of the endowment, the debt level, and the hurricane shock.[8]

4 Calibration and Functional Forms

The model is calibrated to reproduce the quantitative properties of a set of Caribbean countries–Antigua y Barbuda, Belize, Dominica, the Dominican Republic, Grenada, Honduras, and Jamaica–from 1980 to 2019, at the annual frequency. Households' utility function takes the standard constant relative risk aversion (CRRA) form:

$$U(c) = \frac{c^{1-\gamma}}{1-\gamma}, \tag{8}$$

where the parameter γ determines the degree of risk aversion.

Following Arellano (2008), I assume that output costs of default are asymmetric and increasing in the endowment realization in a piecewise-linear fashion:[9]

$$\delta(y) = \begin{cases} y & \text{if } y \leq \delta \\ \delta & \text{if } y > \delta \end{cases}.$$

As it is standard in the literature, it is assumed that the endowment follows a log-normal AR(1) process, $log(y_t) = \rho_y y_{t-1} + \epsilon_t^y$, where $E[\epsilon_t^y] = 0$ and $E[\epsilon_t^{y,2}] = \sigma_y$.

The stochastic process h_t for hurricanes is modeled as follows. With probability p_h, the economy is hit by a hurricane, which causes an output loss ϵ_t^h. Output losses are normally

[8] The formal definition of the model equilibrium is reported in the appendix.

[9] Arellano (2008) shows that asymmetric default costs are crucial for the model to deliver a realistic debt-to-GDP ratio.

distributed with mean μ_h and variance σ_h. The stochastic process reads:

$$h_t = \begin{cases} 1 - \epsilon_t^h & p_h \\ 1 & 1 - p_h \end{cases} \tag{9}$$

Of note, it is assumed that the endowment process evolves independently from hurricane shocks and, thus, hurricanes have no persistent impact on the endowment. This assumption is grounded on the consideration that the model is calibrated at the annual frequency and that a significant fraction of hurricane damages is the temporary loss of crop.

Table 1, reports parameter values that are used in the calibration exercise. Panel A reports standard parameters that are the calibrated to the same value for each country. Households' discount factor β is set equal to 0.82, which corresponds to the quarterly value of 0.953 used in Arellano (2008). Risk-aversion parameter γ is set equal to 2 as it is standard in the literature. The re-entry probability λ is set equal to 0.33 which is consistent with the average re-entry time found in Richmond and Dias (2009).

Panel B, reports parameters that are calibrated to different values for each of the seven countries. Parameters above the line are calibrated independently. Parameter δ below the line is determined using the method of moments and targeting the average spread between the US T-Bills and the corresponding asset in each country.[10] Parameters ρ_y and σ_y are calibrated using GDP data.[11]

Parameters for the stochastic process of hurricanes come from the data collected by the National Oceanic and Atmospheric Administration (NOAA). Table 6 in the Appendix reports the chronology of major hurricane hits since 1871.[12] The probability p_h of hurricanes is set equal to the frequency of major hurricane hits since 1980. Parameter μ_h is set to replicate average GDP contraction in each country in the years countries were hit by hurricanes.[13]. Antigua y Barbuda and Jamaica are the two countries that are hit by hurricanes more frequently, as they are hit by major hurricanes every 7.2 and 9.7 years respectively. On the opposite side of the spectrum, Dominica has been hit only once by hurricanes in the last 39 years. Finally, the standard deviation of the hurricane shock σ_h is set equal to 0.40 for all countries and is estimated as the standard deviation of the average GDP loss associated with hurricanes in the sample.

[10] For Antigua y Barbuda, Dominica, Grenada, and Jamaica I use the spread between 3-months T-Bills and the corresponding 3-months US T-Bills. For Dominican Republic and Honduras I use the EMBI spread. For Belize I use the spread between 1-year T-Bill and the corresponding 1-year T-Bill.

[11] Parameters ρ and σ for Granada were computed using GNI data, which is believed to be a more accurate measure of wealth creation for small countries. GDP and GNI data come from the World Bank database. To separate income shocks from hurricane shocks, parameters for the endowment process are estimated on the subsample of years before a major hurricane hit. Such estimates are then used to predict the GDP value for the hurricane year. Finally, parameters from the income process are re-estimated using the full sample and replacing data for hurricane years with the GDP estimates obtained in the previous step.

[12] Major hurricanes are those classified category three or higher.

[13] The average GDP decline is computed as the difference between the actual realization of GDP and the predicted GDP obtained from the estimates of the stochastic process for the endowment

Table 1. Calibration

Panel A: Common Parameters

Moment		Value	Source/Target Statistic
Discount factor	β	0.82	Quarterly discount of 0.953
Relative risk aversion	γ	2	Standard
Readmission probability	λ	0.33	Richmond and Dias (2009)

Panel B: Country-Specific Parameters

Moment		Antigua	Belize	Dominica	Dominican Rep.	Grenada	Honduras	Jamaica	Source/Target
Endowment autocorr.	ρ_y	0.88	0.97	0.92	0.87	0.91	0.85	0.95	GDP World Bank
Endowment st. dev.	σ_y	0.052	0.039	0.038	0.047	0.046	0.030	0.028	GDP World Bank
Hurricane freq.	p_h	0.138	0.077	0.026	0.051	0.051	0.051	0.103	NOAA
Hurricane mean loss	μ_h	0.091	0.042	0.113	0.040	0.089	0.056	0.019	Mean GDP declines
Hurricane st. dev.	σ_h	0.040	0.040	0.040	0.040	0.040	0.040	0.040	s.d. of GDP declines
Output cost	δ	$0.865\mathbb{E}(y)$	$0.7\mathbb{E}(y)$	$0.86\mathbb{E}(y)$	$0.895\mathbb{E}(y)$	$0.875\mathbb{E}(y)$	$0.93\mathbb{E}(y)$	$0.91\mathbb{E}(y)$	Mean spread

Panel A reports parameter values for standard parameters that are calibrated to the same value in every country and the associated target statistics. Panel B reports country-specific parameter values that are used for the calibration of the model and the associated target statistics.

5 Quantitative Analysis

In this section I first compare moments in our model economy with those in the data. Next, I evaluate the impact of hurricane risk and climate change on government policies.

Moment Matching Exercise

The comparison between Panel A in Table 2, that reports key moments from the data, and Panel B, that reports key moments form the model, shows that the model fits the data fairly well. Spreads observed in the data, are closely replicated by the model. At the same time, default frequency predicted by the model are similar to those observed in the data. As it is standard with sovereign default models, the model under-predicts debt levels. The debt-to-GDP ratio is on average 50% percent smaller in the model than in the data. That said, the models reproduces well countries' ranking according to their debt levels. Belize and Dominica are the two countries with the highest debt-to-GDP ratio both in the data and in the model. Similarly, the Dominican Republics and Honduras are the two countries with the lowest debt-to-GDP rations both in the data and in the model. Finally, the model replicates well the incidence of hurricanes and the average GDP loss associated with them.

Sovereign Risk and Hurricanes

How much does hurricane risk affect government policies? To answer this question I solve a version of the model that eliminates hurricane risk setting the probability of the hurricane shock p_h equal to zero. Figure 2 in Appendix 8.3, shows that borrowing terms improve when hurricane risk is eliminated. As reported in Panel C of Table 2, better borrowing terms translate into higher debt-to-GDP ratios. Governments take advantage of the low rates and issue more debt. In equilibrium debt-to-GDP ratios increase on average 10%, while spreads are little changed. Countries that are more frequently hit by hurricanes benefit the most from the elimination of hurricane risk. According to the model simulations, the debt-to-GDP ratio in Antigua–the country in our sample that is most frequently hit by major hurricanes–would be 20% higher without hurricane risk. On the opposite side of the spectrum, the debt-to-GDP ratio of Dominica–the country the is least frequently hit by major hurricanes–would only increase 4%.

Climate Change

Finding trends in either the number or intensity of hurricanes is complicated because reliable records only date back as far as complete global satellite observations. Nevertheless, scientists have found evidence that hurricanes have already become stronger and more destructive,

Table 2. Quantitative Analysis

Panel A: Moments from the Data

Moment	Antigua	Belize	Dominica	Dominican Rep.	Grenada	Honduras	Jamaica
Average Spread	448	109	366	483	493	411	519
Default Frequency	0.051	-	0.026	0.051	0.051	0.026	0.051
Ext. Debt/GDP ratio	0.36	0.78	0.56	0.25	0.53	0.35	0.49
Hurricane Frequency	0.138	0.077	0.026	0.051	0.051	0.051	0.103
Default—Hurricane	0.25	0	0	0.5	0.5	0	0
ΔGDP— Hurricane	-0.091	-0.042	-0.113	-0.040	-0.089	-0.056	-0.018

Panel B: Simulated Moments

Moment	Antigua	Belize	Dominica	Dominican Rep.	Grenada	Honduras	Jamaica
Average Spread	456	126	356	477	489	429	479
Default Incidence	0.038	0.012	0.030	0.040	0.040	0.037	0.040
Ext. Debt/GDP ratio	0.15	0.68	0.23	0.13	0.17	0.09	0.16
Hurricane Frequency	0.139	0.064	0.027	0.043	0.051	0.047	0.073
Default—Hurricane	0.10	0.03	0.15	0.08	0.12	0.14	0.10
ΔGDP— Hurricane	-0.078	-0.050	-0.109	-0.048	-0.083	-0.060	-0.034

Panel C: Simulated Moments - No Hurricanes

Moment	Antigua	Belize	Dominica	Dominican Rep.	Grenada	Honduras	Jamaica
Average Spread	436	109	338	489	497	416	395
Default Incidence	0.037	0.011	0.029	0.040	0.041	0.034	0.039
Ext. Debt/GDP ratio	0.18	0.71	0.24	0.14	0.19	0.10	0.17

Panel A reports key moments from the data for each of the seven Caribbean countries. Panel B reports moment obtained simulating the model economy for 9,500 periods. Panel C reports moment obtained simulating the modified model economy without hurricanes.

amid rising global temperatures. In particular, while the overall frequency of hurricanes has remained stable since 1975, the incidence of category 3-5 hurricanes, which according to NOAA are responsible for 85% of all damages from hurricanes, has increase between 25 and 30 percent (Holland and Bruyere, 2013).

Going forward, scientists expect the frequency of high-category hurricanes to increase even further as hurricanes become stronger and more powerful. Bender et al. (2010), for instance, project that the frequency of category 4 and 5 hurricanes will increase more than 90% by the end of the twenty-first century. In a related paper Bhatia et al. (2018) estimate the frequency of major cyclones will increase at least 30% in the Atlantic by 2081-2100, with the frequency of category 5 storms jumping 136%.

Not only will high-category hurricanes become more frequent, they will also become more intense. A number of studies project rainfall to increase (Emanuel, 2017), winds to pick up (Bhatia et al., 2018), and hurricanes' forward speed to decline (Kossin, 2018) by the end of the twenty-first century. Bhatia et al. (2018), in particular, find that tropical cyclones will more routinely reach wind speeds that are well above the category 5 threshold, hinting that the SaffirSimpson scale might need to be extended to include higher categories. With tropical cyclones becoming more intense, rising sea level, and increasing population in the coastal areas, the economic damages caused by hurricanes are bound to increase sharply. Nordhaus (2010) studies the economic cost of hurricanes in the Atlantic coastal United States and finds that a 2.5°C increase of global temperatures, will cause a 113% increase of the economic costs associated with hurricanes, as hurricanes will become more intense. Similarly, Mejia (2016) estimates that the economic cost of hurricanes will increase between 20% and 77% due to the increase of wind speed.

In this paper I examine the scenario in which, due to climate change, the frequency of high category hurricanes increases 90% as projected by Bender et al. (2010) and, at the same time, hurricane damages double as high-category hurricanes become more intense causing more damages as projected by Nordhaus (2010). Panel A of Table 3 reports simulated moment for the seven Caribbean economies in the climate-change scenario. Default risk, captured by sovereign spreads, is little changed, but debt-to-GDP ratios are smaller suggesting that governments need to reduce their borrowings to keep interest rates in check. Debt-to-GDP ratios declines on average 16%. Yet, there is substantial heterogeneity across countries. In Antigua, where hurricanes are already frequent and intense, the debt-to-GDP ratio declines 40% while in Belize and Honduras, where hurricanes are far less frequent and violent, the debt-to-GDP ratio only declines roughly 5%.

Panel B and C of Table 3 unpack the impact of climate change. Panel B looks at the case in which the frequency of high-category hurricanes increases, but their intensity is unchanged. Panel C looks, on the contrary, at the case in which the frequency of high-category hurricanes stays the same, while their intensity increases. Broadly speaking, frequency and intensity have the same impact on government borrowing policies. In both cases, debt-to-GDP ratios decline as governments reduce borrowings to maintain borrowing costs low.[14] Yet, increasing the frequency of hurricanes has a bigger impact on government policies. Debt-to-GDP ratios decline 6% as the frequency of hurricanes increases 90%, while they only decline 4% when the intensity of hurricanes doubles.

[14] Results in section 6, show that this is not the case with hurricane clauses.

Table 3. Climate Change

Panel A: 1.9x Hurricanes' Frequency - 2x Hurricanes' Damages

Moment	Antigua	Belize	Dominica	Dominican Rep.	Grenada	Honduras	Jamaica
Average Spread	417	141	377	505	526	410	585
Default Incidence	0.033	0.013	0.031	0.040	0.041	0.034	0.045
Ext. Debt/GDP ratio	0.09	0.65	0.20	0.12	0.14	0.07	0.14
Hurricane Frequency	0.265	0.145	0.051	0.099	0.098	0.097	0.174
Default—Hurricane	0.08	0.05	0.20	0.10	0.15	0.13	0.10
ΔGDP— Hurricane	-0.131	-0.071	-0.213	-0.071	-0.160	-0.098	-0.044

Panel B: 1.9x Hurricanes' Frequency

Moment	Antigua	Belize	Dominica	Dominican Rep.	Grenada	Honduras	Jamaica
Average Spread	467	133	377	512	540	432	517
Default Incidence	0.038	0.013	0.031	0.041	0.043	0.036	0.042
Ext. Debt/GDP ratio	0.12	0.66	0.22	0.12	0.16	0.08	0.15
Hurricane Frequency	0.270	0.132	0.050	0.086	0.095	0.092	0.14
Default—Hurricane	0.08	0.03	0.14	0.08	0.12	0.11	0.09
ΔGDP— Hurricane	-0.065	-0.043	-0.107	-0.042	-0.080	-0.053	-0.035

Panel C: 2x Hurricanes' Damages

Moment	Antigua	Belize	Dominica	Dominican Rep.	Grenada	Honduras	Jamaica
Average Spread	438	131	375	515	536	440	577
Default Frequency	0.036	0.012	0.031	0.041	0.042	0.036	0.046
Ext. Debt/GDP ratio	0.13	0.67	0.22	0.13	0.16	0.08	0.16
Hurricane Frequency	0.142	0.077	0.026	0.051	0.049	0.053	0.091
Default—Hurricane	0.12	0.05	0.22	0.12	0.17	0.16	0.12
ΔGDP— Hurricane	-0.156	-0.077	-0.217	-0.074	-0.170	-0.107	-0.048

Panel A reports moments obtained simulating the model economy for 9,500 periods assuming that the frequency of hurricanes increases 90% and the intensity of the damages double. Panel B reports moments obtained simulating the economy and assuming that the frequency of hurricanes increases 90%, while their intensity stays constant. Panel C reports moments obtained simulating the economy and assuming that the intensity doubles, while their frequency stays constant.

6 Hurricane Clause

In 2013 Grenada introduced a "hurricane clause", that stipulates an immediate, yet temporary, debt moratorium when the country is hit by hurricanes causing damages over $15 bilion. Grenada's decision to introduce a hurricane clause was endorsed by the Paris Club. More broadly, disaster clauses have been receiving increasing attention in policy circles as they are often perceived as effective tools to adapt to climate change. In this section, I modify the baseline theoretical model to account for the hurricane clause, and I evaluate its impact on governments' policies.

6.1 Modeling the Hurricane Clause

Hurricane clauses allow governments to stop servicing debt when hurricanes hit. Hence, governments face three options when a hurricane strikes: default, repay, or activate the hurricane clause and receive debt-servicing relief. Government's optimal default and debt-servicing relief decisions solve:

$$V = \max_{d,rel} \left\{ \mathbb{1}_h \left((1-d-rel) V^{nd} + rel V^{rel} + d V^d \right) + (1-\mathbb{1}_h) \left((1-d) V^{nd} + d V^d \right) \right\}. \quad (10)$$

Where $\mathbb{1}_h$ is a dummy that is equal to one when the economy is hit by a hurricane and rel takes the value of one when the government decides to request the debt-servicing relief. V^{rel} is the value function when the government requests the debt-servicing relief, while V^{nd} and V^d are investors' value function in the non-default scenario and in the default scenario, defined in Section 3.

The value function V^{rel} is defined as:

$$V^{rel}(y, h, b,) = \max_{c,b'} u(c) + \beta \mathbb{E} \left[(1-\lambda_h) V^{rel}(y', h', b) + \lambda_h V(y', h', b) \right] \quad (11)$$

$$\text{s.t. } c = (1-h)y. \quad (12)$$

Where λ_h is the exogenous probability that the government resumes making payments.[15] Equation (12) is the resource constraint of the economy prescribing that consumption equals output net of hurricane damages. When the government requests debt-servicing relief, it stops paying maturing bonds and borrowing from abroad. Crucially, there are no output cost associated with the activation of the hurricane clause.

International investors price government bonds by arbitrage taking into consideration the

[15] In the quantitative exercise I set $\lambda_h = 0.5$ to reflect the fact that the hurricane clause in Grenada allows the government to stop payments for two consecutive periods.

existence of the hurricane clause. The asset pricing equation for government bonds becomes:

$$q\left(y', h', b'\right) = \frac{1}{1 + r^{rf}} E\left[\left(1 - d' - rel'\right) + \frac{\lambda_h rel' \left(1 - def' - rel'\right)}{r^{rf} + \lambda_h}\right]. \tag{13}$$

As it is standard in the literature, the price of government bonds depends on the risk-free rate and the default risks. Additionally, with the introduction of the hurricane clause, the price also depends on the risk that the government activates such clause, and a term that accounts for the expected discounted value of maturing bonds after the government resumes payments.[16]

6.2 Quantitative Analysis

6.2 Figure 1 compares the price function government bonds in the benchmark model and in the model with the hurricane clause.[17] With the disaster clause, the price function shifts to the right implying that, for any given level of government debt, borrowing terms improve. The improvement is due to a decline of credit risk.

Table 4 reports simulated long-run moments for the model economy with the disaster clause. A comparison with Panel B of Table 2 shows that the disaster clause allows governments to borrow more and sustain higher debt-to-GDP levels. On average debt-to-GDP levels are 20% higher in the model with the disaster clause relative to the baseline model. The increase of debt-to-GDP ratios is especially pronounced in Antigua, and Jamaica, the two countries with the highest frequency of hurricane hits.

Results in Table 4 show that, in equilibrium, credit risk is little changed relative to the benchmark economy, while spreads increase notably.[18] This result descends from the fact that governments expand their borrowings so much that credit risk rises back to the same levels observed in the benchmark economy. Yet, for the same level of credit risk, spreads are now on average 40% higher, as investors also need to be compensated for the risk that governments activate the disaster clause. Of note, governments are willing to pay higher spreads, as disaster clauses allow governments to push forward debt repayments reducing the effective cost of repaying the debt. In equilibrium, debt-to-GDP ratios and spreads increase notably.[19]

On net, results indicate that government engage in "gambling for debt-servicing suspension' behavior, when hurricane clauses are introduced. Governments are willing borrow more and

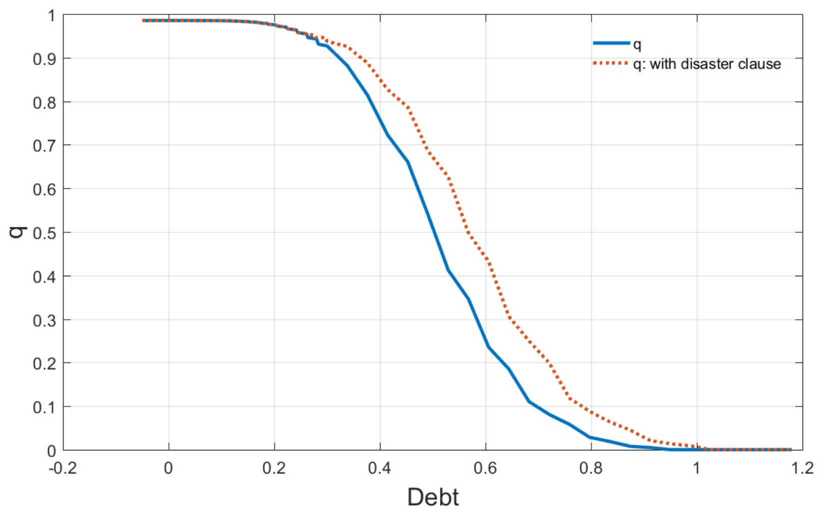
[16] Section 8.4 in the appendix formally derives equation (13).

[17] The graph reports the price function for the government debt of Antigua. Price functions of other countries are similar.

[18] The incidence of defaults conditional on hurricane hits fall to zero as the hurricane clause eliminates government incentives to default when hurricanes strike.

[19] Figure 3 reporting policy functions for government debt and for the price of government debt further clarifies the point.

Figure 1. Price of Government Debt



The blue line plots the price schedule for government bonds in the benchmark model. The red dashed line plots the price schedule in the model with the disaster clause.

pay higher yields as they anticipate that the hurricane clauses will reduce the effective cost of repaying the debt. Countries that are more frequently hit by hurricanes, have greater incentives to engage in "gambling for debt-servicing suspension" behavior, as the diaster clauses are activated more frequently in those countries. In Antigua and jamaica, the two countries that are most frequently hit by hurricanes, spreads increase 100% and 50%, repsectively.

Climate Change

in this section, I check how climate change impacts government policies when government bonds feature the hurricane clause. Panel A in Table 5 reports results obtained in our baseline scenario in which the frequency of defaults increases 90% and, at the same time, GDP losses associated with hurricanes increase 100% as hurricanes become more intense. I find that the hurricane clauses allows government to continue to issue the same quantity of debt. Debt-to-GDP ratios do not change much in response to the increase of the frequency and intensity of hurricanes. This result is in sharp contrast with those presented in Section 5, showing that climate change reduces government ability to issue debt, when government bonds do not entail the disaster clause.

Unlike debt-to-GDP ratios, borrowing terms are heavily affected by climate change. Spreads

Table 4. Hurricane Clause

Moment	Antigua	Belize	Dominica	Dominican Rep.	Grenada	Honduras	Jamaica
Average Spread	881	207	404	620	640	528	729
Default Incidence	0.041	0.013	0.032	0.042	0.043	0.035	0.040
Ext. Debt/GDP ratio	0.21	0.73	0.24	0.15	0.20	0.11	0.19
Hurricane Frequency	0.140	0.065	0.026	0.042	0.049	0.046	0.074
Default—Hurricane	0	0	0	0	0	0	0
ΔGDP— Hurricane	-0.078	-0.050	-0.108	-0.049	-0.085	-0.058	-0.039

This table reports moments obtained calibrating the model economy with the hurricane clause to each of the seven Caribbean economies in the sample, and simulating each economy for 9,500 periods.

increase on average more than 40% across countries and they almost double in Belize in response to climate change. The rise in yields is due to the fact that governments need to compensate investors for the higher risk that the hurricane clause gets activated. Even so, higher spreads do not restrict government's ability to borrow as the hurricane clause reduces the effective cost of repaying the debt. Once again, governments display a "gambling for debt-servicing suspension" behavior.

Panel B isolates the impact of increasing hurricanes' frequency on governments' policies. When hurricanes' frequency increases and the intensity of hurricanes stays constant, spreads increase notably. At the same time, debt-to-GDP ratios rise as their average level is, on average, 4% higher. This pattern can be, once again, explained by the "gambling for debt-servicing suspension" behavior identified in Section . As the frequency of hurricanes increases, the effective cost of repaying debt declines, as governments can invoke the hurricane clause more frequently. The decline of the effective cost of repaying debt offsets the increase of yields allowing governments to issue marginally more debt. Of note, results in Panel B re similar to those presented in Panel A, suggesting that hurricanes' frequency is the key factor driving the overall impact of climate change on governments' policies.

Panel C isolates the impact of increasing hurricanes' intensity on governments' policies. As the cost of hurricanes doubles, debt-to-GDP ratios decline marginally falling, on average, about 5%. At the same time, spreads and default rates are little changed. These results echo those presented in Section 5 and suggest that hurricane clauses do not protect the government from the consequences of rising hurricanes' intensity.

All told, results suggest that disaster clauses can be an effective tool to mitigate the impact of climate change on governments' policies. Disaster clauses reduce the effective cost of repaying the debt, thereby allowing governments to borrow from abroad in spite of the increasing frequency of natural disasters.

Table 5. Climate Change

Panel A: 1.9x Hurricanes' Frequency - 2x Hurricanes' Damages

Moment	Antigua	Belize	Dominica	Dominican Rep.	Grenada	Honduras	Jamaica
Average Spread	1617	400	444	771	758	653	1103
Default Incidence	0.038	0.012	0.032	0.042	0.044	0.037	0.036
Ext. Debt/GDP ratio	0.21	0.73	0.24	0.16	0.20	0.11	0.19
Hurricane Frequency	0.267	0.147	0.048	0.097	0.098	0.098	0.175
Default—Hurricane	0	0	0	0	0	0	0
ΔGDP— Hurricane	-0.132	-0.071	-0.215	-0.071	-0.160	-0.101	-0.044

Panel C: 1.9x Hurricanes' Frequency

Moment	Antigua	Belize	Dominica	Dominican Rep.	Grenada	Honduras	Jamaica
Average Spread	1630	400	454	773	759	668	1115
Default Frequency	0.038	0.013	0.031	3	0.044	0.038	0.036
Ext. Debt/GDP ratio	0.22	0.73	0.24	0.16	0.20	0.11	0.20
Hurricane Frequency	0.27	0.122	0.051	0.082	0.095	0.089	0.138
Default—Hurricane	0	0	0	0	0	0	0
ΔGDP— Hurricane	-0.065	-0.046	-0.108	-0.045	-0.080	-0.056	-0.037

Panel B: 2x Hurricanes' Damages

Moment	Antigua	Belize	Dominica	Dominican Rep.	Grenada	Honduras	Jamaica
Average Spread	853	208	399	613	639	512	723
Default Incidence	0.039	0.012	0.032	0.042	0.044	0.037	0.039
Ext. Debt/GDP ratio	0.21	0.74	0.24	0.15	0.20	0.10	0.18
Hurricane Frequency	0.138	0.077	0.025	0.051	0.050	0.051	0.093
Default—Hurricane	0	0	0	0	0	0	0
ΔGDP— Hurricane	-0.156	-0.076	-0.220	-0.075	-0.169	-0.105	-0.048

Panel A reports moments obtained simulating the model economy with the hurricane clause for 9,500 periods assuming that the frequency of hurricanes increases 90% and the intensity of the damages double. Panel B reports moments obtained simulating the economy with the hurricane clause and assuming that the frequency of hurricanes increases 90%, while their intensity stays constant. Panel C reports moments obtained simulating the economy with the hurricane clause and assuming that the intensity of hurricanes doubles, while their frequency stays constant.

7 Concluding Remarks

This paper investigates the impact of extreme weather on government's borrowing and default policies through the lens of a quantitative sovereign default model. In particular, I focus on a sample of small Caribbean countries that are exposed to hurricane risk. I find that extreme weather restricts government ability to issue debt. The impact of extreme weather on government policies is poised to become even more sizable in the coming years, amid rapid climate change. In the paper, I show that in a scenario in which the frequency of high-category hurricanes increase 90% and their intensity increases, debt-to-GDP ratios decline by more than 15%, on average, with some countries experiencing declines as large as 40%.

Next, I explore whether disaster clauses, that allow governments to suspend payments in the event of natural disasters, can facilitate government access to international financial markets. I find that disaster clauses reduce borrowing terms, allowing government to issue more debt. I also highlight that hurricane clauses induce governments to engage in "gambling for debt-servicing suspension" as they reduce the effective cost of repaying the debt. Finally, I show that hurricane clauses only protect governments against an increase in the frequency of extreme weather events, while they are less suited to protect governments against an increase in the intensity of extreme weather events.

Two of the modeling assumptions are worth discussing. Throughout the paper, it is assumed that the pool of investors that buy government bonds does not change after the introduction of the disaster clause. Yet, complex bonds that entail a disaster clause may only appeal to sophisticated traders. If this is the case, the potential pool of investors may become smaller and the benefits of disaster clauses may be smaller. The second assumption is about the design of the disaster clause. In the paper it is assumed that the activation of the disaster clause provides full debt-servicing relief. This assumption is consistent with the way disaster clauses are structured in the real world. Yet, results may change if the debt-servicing relief was only partial or proportional to the severity of hurricanes. In general, further research is needed to identify the optimal design of disaster clauses.

Concluding, this paper takes a first step in the direction of uncovering the unexplored relation between sovereign risk, weather events, and climate change. Several questions, however, remain open. In particular, additional effort should be devoted to investigate the role that official lenders and insurance schemes can play to support governments, amid natural disasters. This could certainly be an area for interesting future research.

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8 Online Appendix

8.1 Equilibrium

Equilibrium In equilibrium, the government sets the policy for default or repayment and for issuance or purchase of an asset, in order to maximize the welfare of the representative household, subject to the resource constraint of the small open economy and to the constraint implied by foreign lenders' pricing of debt. The equilibrium is formally defined below.

Definition 1. *A recursive equilibrium in the small open economy is characterized by*

- *a set of value functions for the representative household V, V_R, and V_D,*
- *government policies for default d and asset holdings b',*
- *a government debt price function q*

such that:

- *the debt price function is consistent with optimization by foreign lenders, (7),*
- *given the debt price function q, the value functions of the household and the policy functions of the government solve the maximization problem (1), (2), (5).*
- *the resource constraint of the small open economy is satisfied*

8.2 List of Hurricanes

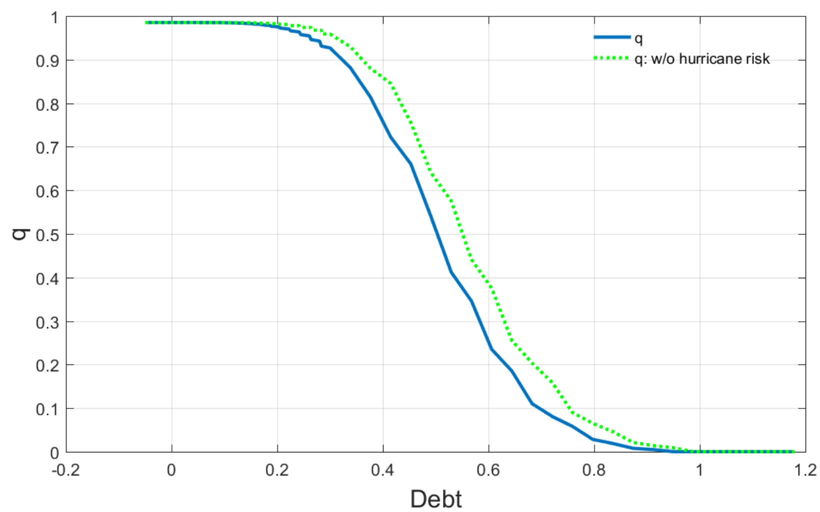
Table 6. Major Hurricanes Hits

	Dates	Frequency 1971 − 2019	Frequency 1980 − 2019
Antigua	1871, 1899,1928,1932, 1950, 1960, 1966, 1989, 1995, 1998, 2017	0.074	0.138
Belize	1931, 1955, 1961, 1974, 1978, 2000, 2001, 2010	0.054	0.077
Dominica	1883, 1891,1894,1899 1928, 1964, 1966, 1979, 2017	0.061	0.026
Grenada	1955, 1963, 2004, 2005	0.027	0.051
Honduras	1978, 1998	0.014	0.051
Jamaica	1903, 1912, 1944, 1951, 1980, 1988, 2004, 2007	0.054	0.10

Major hurricanes are those category 3 or higher. The first column reports the dates of direct hits. The second column reports the frequency of direct hits from 1871. The third column report the frequency of direct hits since 1980, which are also used in the calibration exercise.

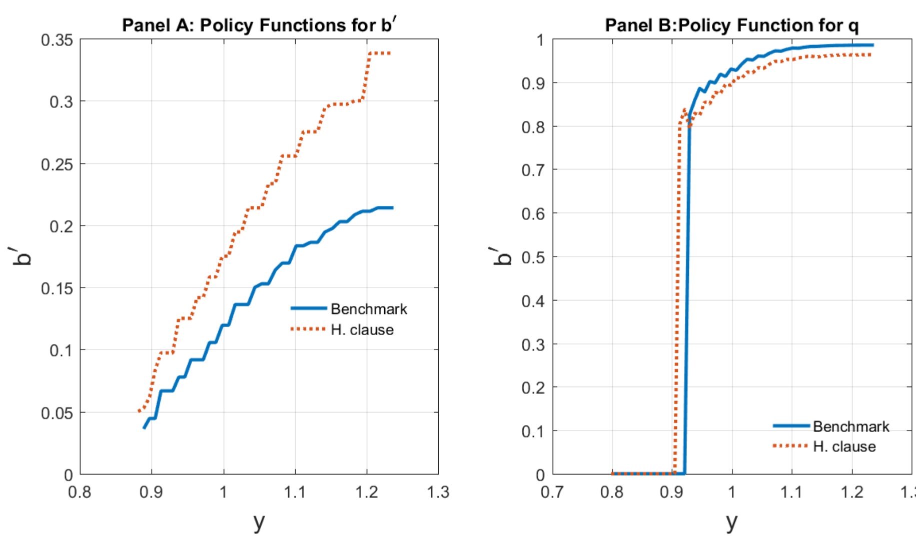
8.3 Additional Graphs

Figure 2. Price of Government Debt without Hurricane Risk



The blue line plots the price schedule for government bonds in the benchmark model. The green dashed line plots the price schedule in the model without hurricane risk.

Figure 3. Policy Functions in the Model with Hurricane Clause



Panel A compares the policy functions for government debt in an economy without disaster clause (blue line) and in an economy with the disaster clause (orange dashed lined). Panel B compares the policy function for the price of government debt in an economy without disaster clause (blue line) and in an economy with the disaster clause (orange dashed lined)

8.4 Investors' Maximization Problem with the Disaster Clause

Investors are risk neutral, have deep pockets, and hold two types of assets: risk-free bonds b_{rf} that pay r^{rf} in every period, or risky government bonds b_L. Investors are price takers hence, they take the state variables that define the price of government debt as given $s = \{y, b, x, rel\}$, where x is a dummy variable that summarizes market access and rel is a dummy variable that summarizes the activation of the disaster clause.

The maximization problem of investors is:

$$V_L(s, b_L) = \max_{c_L, b'_{rf}, b'_L} c_L + \beta_L \mathbb{E}\left[V_L(s', b'_L)\right], \tag{14}$$

$$\text{s.t. } c_L = (1 - d - rel)\left(b_{L,i} + (1 - x - rel)\, q_i b'_L\right) + (1 + r^{rf}) b_{rf} + b'_{rf}. \tag{15}$$

The first-order conditions of investors' maximization problem yield:

$$b'_{rf}: \ \frac{1}{1 + r^{rf}} = \beta_L \tag{16}$$

$$\begin{aligned} b'_L: \ q = \beta_L E\left[(1 - d' - rel') + rel\beta_L\left[\lambda_h (1 - d'' - rel'')\right.\right. \\ \left.\left. +(1 - \lambda_h)\beta_L\left[\lambda_h (1 - d''' - rel''') + (1 - \lambda_h)\beta_L[....]\right]\right]\right]. \end{aligned} \tag{17}$$

First order condition (17) equates the marginal cost q of purchasing government bonds to their marginal expected utility. Two factors determine investors' marginal utility associated with purchasing government debt. First, the expected utility investors receive next period if the government does not default and the hurricane clause is not triggered. Second, the utility that investors expect to receive if the hurricane clause is triggered. This second term depends on the probability that the government resumes payments in the future, the intertemporal discounting factor β_L, and the expected stream of income, once the government resumes payments.

Using the law of iterated expectations, equation (17) becomes:

$$q = \beta_L E\left[(1 - d' - rel') + rel\beta_L \sum_{j=0}^{\infty} \left(\lambda_h \beta_L\right)^j (1 - d'_j - rel'_j)\right]. \tag{18}$$

Plugging equation (16) in (18) and imposing that the decisions to default and activate the disaster clause are constant over time in equilibrium, I obtain:

$$q = \frac{1}{1 + r^{rf}} E\left[(1 - d' - rel') + \frac{\lambda_h rel\,(1 - def' - rel')}{r^{rf} + \lambda_h}\right]. \tag{19}$$