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CAMA Working Paper 26/2024
April 2024

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Abstract

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Keywords

sovereign credit rating, climate change, counterfactual analysis, climate-economy models, sovereign debt, physical risks, fiscal policy, transition risks, Latin America, Caribbean

JEL Classification

C33, C53, G10, G18, H63, O44, O54, Q51, Q54

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ISSN 2206-0332

Climate Change and Sovereign Risk: A Regional Analysis for the Caribbean*

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March 17, 2024

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Climate change is an existential threat to the world economy, with complex, evolving and nonlinear dynamics that remain a source of great uncertainty. There is a bourgeoning literature on the economic impact of climate change, but research on how climate change affects sovereign risks is limited. This paper provides forward-looking regional analysis of the effects of climate change on sovereign creditworthiness, probability of default and the cost of borrowing for the Caribbean economies. Our results indicate that there is substantial variation in the sensitivity of ratings to climate change across the region which is due to the non-linear nature of ratings. Our findings improve the identification and management of sovereign climate risk and provides a forward-looking assessment of how climate change could affect the cost of accessing international finance. As such, it leads to a suite of policy options for countries in the region.

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* We are grateful to Raul Jimenez and Cloe Ortiz de Mendivil and seminar participants at the Inter-American Development Bank (IDB) for helpful comments and suggestions. The views expressed in this paper are those of the authors and do not necessarily represent those of the IDB or its policy.

1. Introduction

Climate change is an existential threat to the world economy, with complex, evolving and nonlinear dynamics that remain a source of great uncertainty. There is a bourgeoning literature on the economic impact of climate change, but research on how climate change affects sovereign risks is limited (IMF, 2020).

This paper provides a bespoke regional analysis of the effects of climate change on sovereign creditworthiness, credit ratings, probability of default and the cost of borrowing for the following countries: The Bahamas, Barbados, Guyana, Jamaica, Suriname, and Trinidad and Tobago[1]. The methods build on the world's first climate-adjusted sovereign credit rating by Klusak et al. (2023), but has been adapted to reflect the unique economic, geographic, and policy contexts within the region. This study can improve the identification and management of sovereign climate risk and provides a forward-looking assessment of how climate change could affect the cost of accessing international finance. As such, it leads to a suite of policy options for countries in the region.

As the physical and transition-related impacts of climate change become increasingly urgent, policy interest in understanding how they translate into macroeconomic and financial risks is growing. Globally, central banks have established the Network for Greening the Financial System, , and business leaders have established Taskforces on Climate- and Nature-related Financial Disclosure (TCFD and TNFD, respectively). Enthusiasm for 'greening the financial system' is welcome, but the fundamental challenge of mapping climate science onto real-world financial risks remains. As a result, climate risk is often mispriced, mismanaged, or ignored altogether by financial markets, regulators, and policy makers. Furthermore, the Bridgetown Initiative, led by the Government of Barbados seeks to reform the finance and trade by redesigning the International Financial Architecture by proposing the creation of new instruments enabling climate resilience action and the attainment of the Sustainable Development Goals (SDGs), while accelerating private sector investments. For example, it promotes the inclusion of "hurricane clauses", which have proven to be a relief and have been considered by the IDB since 2020.

The Regional Climate Change Platform of the Ministries of Economy and Finance of Latin America and the Caribbean supports finance ministries in aligning the public finances with climate objectives. Established by the Inter-American Development Bank in 2022, the Platform facilitates knowledge sharing, coordination, dialogue on best-practice, and expertise to support the pursuit of sustainable growth and fiscal sustainability across the region. Research shows that by 2030, changing temperatures could push 3 million people a year into extreme poverty in Latin America and the Caribbean (Jafino et al., 2020). But it also shows that by 2030 a green transition could create 15 million net new jobs in areas such as plant-based food production, renewable energy, and construction. Serving as Technical Secretary for the Platform, the IDB supports nations in navigating these risks and opportunities.

The consequences could be especially severe for the Caribbean region, characterised by extreme vulnerability, both to the physical impacts of climate change and the economic consequences of the low-carbon transition. Caribbean small island developing states (SIDS) and coastal states are highly

[1] The Country Department Caribbean (CCB) at the Inter-American Development Bank is responsible for the promotion and development of Bank country strategies and programming in The Bahamas, Barbados, Guyana, Jamaica, Suriname, and Trinidad and Tobago and via the Caribbean Development Bank (CDB), the countries of the Organization of Eastern Caribbean States (OECS).

exposed to storms, sea level rise, extreme temperatures, species loss, and water stress, with direct effects on key industries such as tourism, agriculture, and fishing (Eckstein et al., 2019; IPCC 2022a-b; IDB 2014). The area of cultivated land is expected to fall due to rising temperatures and increasingly variable rainfall (Rhiney et al., 2016). Climate change is already affecting Caribbean economies. Out of 511 natural disasters which hit the states with population smaller than 1.5 million worldwide since 1950, 324 occurred in the Caribbean (IMF, 2018). More than 27% of population in the Caribbean live in coastal areas with 6-8% classified as high or very high risk (WMO 2021). An estimated 22 million people in the Caribbean live below 6 meters elevation (IPCC 2022b). The US National Climate Assessment (USGCRP 2018) found that economic losses incurred by the Caribbean region due to hurricanes such as Irma and Maria in 2017 reached between $27 and $48 billion and have long-term consequences for state budgets and infrastructure supporting the most disadvantaged. Natural disasters have cost Jamaica alone an estimated $1.2bn from 2001 – 2010, with Hurricane Ivan costing US$350mn (World Bank 2021). Annual losses from catastrophic climate events in the Caribbean are estimated at USD 3 billion dollars and are expected to rise as climate change intensifies (ECLAC 2020). The IPPC (2022b, p2046) notes that even under a global temperature scenario of 1.5C, "the reduced habitability of small islands is an overarching significant risk".

Fiscal health across the region will be determined by both the impacts of climate change on economies and the ambition of decarbonisation policies. Caribbean countries were already highly indebted prior to the pandemic and having spent between 1-4% of GDP on COVID-19 response efforts has left the region with an average debt to GDP ratio of 99% (IDB 2022). But whilst moving towards a resilient, carbon-neutral economy by 2050 will require an annual expenditure of between 5-16% of GDP by 2030, recent research suggests the economic benefits will outweigh the costs[2] (Beating et al., 2022).

The region will need to diversify its tax base to compensate for falling revenues from fossil fuel production and consumption. Currently, taxes on fossil fuel production and consumption generate significant revenues for governments in the region (OECD et al., 2022). For example, in Barbados, taxes on petroleum products are estimated to generate about 2.4% of total revenue for FY2022/23. Although fuel and carbon taxes may generate revenues in the short run, these can be expected to fall through the transition as economies substitute away from fossil fuels. For instance, with a target of reducing fossil fuels by 49%, Barbados has an ambition for 100% electrification of all buses and the public vehicle fleet by 2030 (Viscidi et al., 2020). The shift to electric vehicles will reduce receipts from fuel duties, with direct repercussions finance ministries. Although a reduction in oil imports will enhance the current account and foreign exchange reserves, the taxes on fuel sales comprise an important source of revenue which will disappear once the target is reached. As renewables increasingly out-compete fossil fuels on price, finance ministries that fail to plan for this transition will be left with a fiscal hole.

The Caribbean also faces substantial transition-related risks, particularly around energy prices and tourism. The global surge in energy prices since the Covid-19 pandemic and exacerbated by Russia's war in Ukraine has brought about varying impacts across the Caribbean. Guyana, Trinidad and Tobago, and Suriname have benefitted from higher oil and gas prices, whereas The Bahamas, Barbados, and Jamaica have suffered (IDB 2022). Further, indirect effects may be expected as tighter carbon regulations abroad drive-up flight prices, impacting tourism revenues. In this context a just transition strategy is adamant to minimize and address impacts in different spheres such as labour markets,

[2] Galindo, Miguel, Hoffman, B., Vogt-Schilb, A. (2022) How much will it cost to achieve climate change goals in Latin America and the Caribbean? IDB Working paper 1310.

work, resilient agriculture, and social equity, among others to protect livelihoods. Decarbonization strategies in the Caribbean requires a sensitive management of an adamant shift, and will need to include active stakeholder participation, innovative skills development, and a reform of the existing safety nets.

Climate-driven GDP losses will also affect sovereign credit ratings, default probabilities, and the cost of borrowing. There is strong evidence that climate change has already raised the average cost of debt in vulnerable developing countries (Kling et al., 2018; Buhr et al., 2018; Volz et al., 2020; Beirne et al., 2021). However, credit ratings agencies do not yet formally incorporate future climate projections into creditworthiness assessments (Klusak et al., 2023).[3] This means current credit assessments for the region understate the effect of climate on public debt, and therefore the incentive to invest in adaptation and resilience.

Although the Caribbean is considered the most indebted region of the world with most indebted countries being Barbados, Suriname and the Bahamas the sovereign credit histories vary substantially across the region. For instance, Trinidad and Tobago has been considered investment grade for over 20 years, whereas The Bahamas and Jamaica hover just below the investment grade threshold, and Barbados and Suriname have both defaulted within the past five years. Trinidad and Tobago's investment grade reflects a favourable external profile and stable democracy. The rating also reflects solid government financial assets which mitigate the effects of economic cycles on fiscal and external performance. The hydrocarbon sector will continue to support Trinidad and Tobago's economy despite some softening in prices this year from high levels in 2022 (S&P 2023). It is the least dependent on the petroleum imports in the region with 0.3% as a share of GDP. Some of the highest are Saint Lucia (21.1%) and Bahamas (12.9%) followed by Guyana (9.8%), Barbados (6.2%) and Suriname (3.3%) (Viscidi et al., 2020). Climate-driven economic losses can be expected to deteriorate the public finances and credit assessments of all these countries even further.

Many global-scale climate and economic models struggle to provide detailed regional analyses for use in guiding policy.[4] The result is that bespoke regional analyses are needed to translate the physical and transition related risks presented by climate change into sovereign risk assessment and fiscal strategy in the region. Indeed, this is the only approach that can reflect the diversity of physical geography, natural capital endowments, economic structures, default risk and history, and policy priorities across the Caribbean. Physical risks include the direct physical damages to property, infrastructure, homes, human health, and agricultural land resulting from climate extremes.[5] Transition risks typically include asset stranding, skills obsolescence and resulting un- or under-employment, loss of competitiveness, and reductions in fiscal revenues from declining industries. Both physical and transition risks vary across regions, countries, and economic sectors. In the Caribbean, physical risks to transport and tourism-related infrastructure may combine with transition risks, if global demand for long-haul flights wanes or emissions taxes make flying prohibitively expensive, or

[3] Moody's notes that climate change might affect Economic Strength, however it is an "unusual" occurrence (Moody's 2019). Although S&P (2015a,b) estimate the effect of extreme weather and natural disasters on ratings of 38(48) sovereigns, respectively, it is not included in their standard methodology. They measure direct damages up to 2050 (2020) which would arise from 1-in-250 year disasters (earthquakes, tropical storms, floods, winter storms). Our study differs significantly from theirs as we are not restricted by narrow selection of perils but the overall aggregate effect of climate change which has not been considered before (see section 3.2.1 and 4.1).

[4] E.g in IPCC AR6 (2021), the Caribbean is often excluded from calculations due to the small number of full land grid cells.

[5] The global models, including the IAMs reviewed by the IPCC typically lack the spatial resolution and geographic/economic specificity to facilitate convincing country-level conclusions.

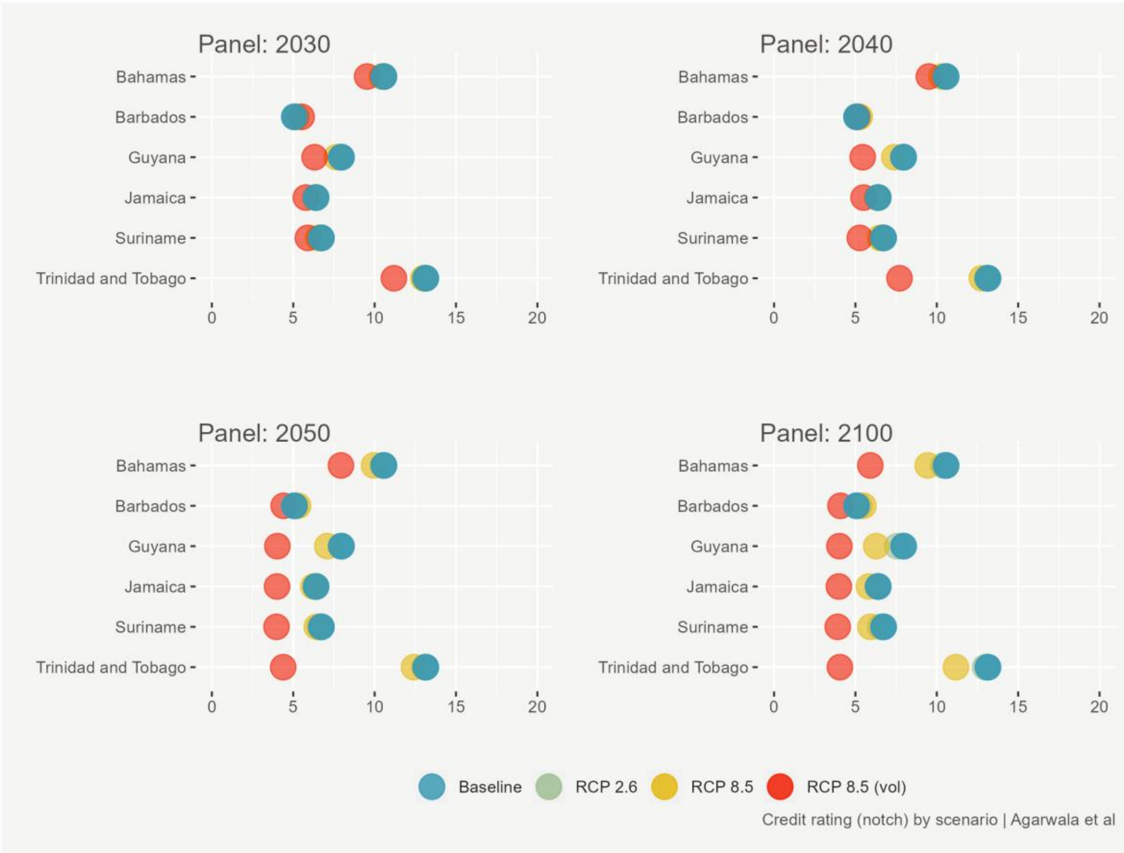
if changing temperatures and weather extremes shorten the peak season. For fossil-fuel rich economies, a global transition towards renewables will mean a shrinking export market and a reduction in the expected value of reserves.

The unique advantage of our approach is that it is inherently forward-looking. Empirical assessments of the effect of climate change on sovereign ratings and bond yields typically adopt a backwards-looking strategy, examining historical data to determine whether past climate change has affected current bond yields. But the climate science is clear: the past is a poor model for assessing future impacts. Economic analyses of climate change that rely solely on past data cannot tell us much about future risks and impacts. On the downside risk, even the severe climate impacts already experienced across the region in recent years would understate the likely consequences of unabated climate change. On the upside, estimates could overstate the consequences of future climate impacts if they rely on worst case scenarios that are ultimately avoided by successful global decarbonisation. In contrast, our approach is forward-looking, incorporating leading climate and economic models to investigate the climate-ratings-cost of capital relationship into the future under a range of warming scenarios. This is clearly a more useful analysis for guiding future policy and developing forward-looking fiscal strategies.

We used AI to simulate the effect of climate change on sovereign debt across the region under varying warming scenarios. Our results indicate that:

- Under a high emissions scenario, all studied countries could expect downward pressure on their sovereign credit ratings by 2050 (see Figure 1).
- Climate change is expected to increase annual borrowing costs across the region by 2050, under both high ($310 million) and low ($270 million) emissions scenarios.
- This could rise to over US$1 bn per year under a worst-case scenario that encompasses high global emissions, a loss of tourism revenues, and the economic consequences of rising temperature volatility.
- There is substantial variation in the sensitivity of ratings to climate change across the region. For instance, Barbados has a B- (highly speculative, non-investment grade) rating. Whilst climate change will lead to a deterioration of economic conditions, it is not expected that this will substantially affect the rating before 2030. In contrast, at BBB- (lower medium, investment grade), Trinidad and Tobago faces downgrades within the decade under the worst-case scenario.

Figure 1: Predicted Future Sovereign Credit Ratings by Climate Scenario



Notes: Simulated sovereign credit ratings under baseline, Paris compliant (RCP2.6), unmitigated climate change (RCP 8.5), and RCP 8.5 with temperature volatility included (RCP 8.5 vol) scenarios, at 2030, 2040, 2050, and 2100.

Our research have revealed a series of key policy implications:

- **Investing in statistical infrastructure and data gathering** will support improved economic analysis, including of the impacts and opportunities created by a transition to a low-carbon economy. Regular data collection and consistent publication will support efforts to identify and navigate specific climate-related risks and opportunities, including the potential to diversify into less climate-exposed sectors. It will also support macroeconomic strategy and planning across the board, including beyond the management of climate change.
- **Global climate scenarios can understate the actual climate risks faced by Caribbean economies** and should be augmented by bespoke, national and regional studies. Global scenarios are biased towards long-term economic risks that arrive along 'smooth' functions (Trust et al., 2023). This is a poor reflection of the reality of climate change in the region, which is already creating extreme, discrete hazards such as Hurricane Maria. Understanding the economic consequences of increasingly frequent and intense storms requires that these are modelled directly, as discrete, near-term events.
- **Innovative finance mechanisms may help plug the finance gap, but they are not a panacea.** Catastrophe bonds, sustainability linked bonds, disaster clauses, and similar green financial innovations can help smooth access to finance, but poor design can also erode incentive

compatibility and support greater risk taking. Extreme caution is needed to ensure that green finance supports investments in adaptation and resilience.

- **Diversification away from oil and gas,** with the goal of reorienting foreign investment towards growth industries in other sectors may help create alternative sources of fiscal revenues. Government revenues from oil and gas production as well as fuel duties and carbon taxes are expected to fall as economies decarbonise. Alternative revenue sources must be sought to avoid a deterioration in public finances as fossil fuels are phased out, as well as consider a just transition while designing decarbonization strategies.
- **Better quantification of the economic costs of climate change throughout the region can support demands for greater action at international climate summits and agreements.** A strong scientific and economic evidence base is needed to underpin negotiations relating to loss and damages as well as access to the green climate fund.

The remainder of this paper is organized as follows. Section 2 sets the scene, describing the physical and transition risks facing the Caribbean region and how these relate to sovereign debt markets. Section 3 discusses the role sovereign ratings play in managing risks and access to finance. Section 4 provides a non-technical description of the AI method we developed to assess the effects of climate change on sovereign credit ratings, borrowing costs, and default probabilities. Section 5 presents the empirical findings. Section 6 provides concluding remarks including key implications for finance ministries and economic decision makers. Finally, Section 7 provides further technical details of the modelling exercises.

2. Setting the scene: Why climate-related risks matter for sovereign debt

2.1. Climate change is already affecting Caribbean economies

Small island developing states including the Caribbean are considered the most vulnerable to climate change (Eckstein et al., 2019; Stennett-Brown et al., 2019; Nurse et al., 2014). In recent years, the region has already faced increasing frequency and intensity of extreme rain events, longer dry spells, higher and more volatile temperatures, and rising sea levels.[6] The key risks for the region include:

Sea-level rise: The Caribbean region is especially vulnerable to sea-level rise, which threatens to inundate coastal areas, disrupt tourism and fisheries, and increase the frequency and severity of coastal flooding. It is estimated that one meter sea level rise in the Caribbean region would place 49 – 60% of tourist resort properties at risk of beach erosion, and 29% would be partially for fully inundated. Losses of over 50% of coastal properties would be likely in Barbados, Bahamas and Trinidad and Tobago amongst others (Scott et al., 2012).

[6] Up to 2007 when Fourth Assessment Report (AR4) by IPCC was published sea level rise dominated vulnerability and impact studies of small island states. Mimura et al., (2007) mention lack of independent studies on the effects of climate on the region between 2001-2007 when Third and Fourth Assessment reports were published in comparison to the earlier period 1995-2001 when Second and Third reports came out. Since 2007 the literature deals with the issue in a multidimensional manner.

Coastal erosion and SLR: The combination of sea level rise, erosion, and growing populations place increasing pressures on coastal land use and related ecosystems (Gero et al., 2011; Mycoo, 2011). The result is a high concentration of infrastructure and human populations in vulnerable locations. More than 27% of the Caribbean population lives in coastal areas, with 6-8% classified as high or very high risk (WMO 2021). Approximately 14 million persons in the Caribbean currently live below 3m elevation and 22 million below 6m (Cashman and Nagdee, 2017).

Extreme weather events: The Caribbean is also prone to hurricanes and tropical storms, which are becoming more frequent and intense due to climate change. These events can cause widespread damage to infrastructure, crops, and homes, and result in billions of dollars in losses. Such events are more costly for smaller island states as they represent bigger proportion of the territory and greater per capita losses compared to larger countries (Anthoff et al., 2010). Amongst the most severely affected countries and territories in weather-related loss events of 2017 were Puerto Rico (63% loss in GDP) and Dominica (215% loss in GDP) (Eckstein et al 2019; IMF 2021). And these events have long lasting impacts; hurricanes in the Caribbean have a downward impact on unemployment, with lagged impacts of up to four years after a disaster strikes (ILO, 2021).[7]

Drought: Drought conditions are increasingly common in the region, leading to reduced crop yields, water scarcity, and increased competition for resources. The IPCC projects that a 1C increase in temperature from 1.7 – 2.7C of warming could result in a 60% increase in the number of people experiencing severe water stress from 2043 – 2071 (IPCC 2022b). Additional warming by 0.2°–1.0°C in the Caribbean could lead to a predominantly drier region with 5-15% less rain than the present day, impacting agricultural production and yield.

Coral reef degradation: Coral reefs are critical habitats for marine species and tourism, and amongst the most vulnerable to climate change. Warming waters and ocean acidification are causing widespread coral bleaching and death, with significant impacts on tourism and fishing industries. Reef surveys surrounding Barbados revealed that approximately 70% of corals have been affected by bleaching (Oxenford 2008). Resource degradation such as beach erosion or coral bleaching will have serious repercussions on tourism in Barbados. ECLAC (2011) estimated that the loss of coral reefs in Barbados could reduce tourism revenues by up to US$ 1.3bn by 2050. When combined with sea level rise and other climate impacts, lost tourism revenues could rise to US$ 7.6bn.

Human health impacts: Tropical areas are favourable to the transmission of diseases. For example, Caribbean region is amongst the most endemic zones for the leptospirosis. Trinidad and Tobago, Barbados and Jamaica face the highest annual incidences, which is tied to climatic as well as anthropogenic factors (Pappas et al. 2008). Moreover, outbreaks of Dengue in Trinidad and Tobago have been correlated with rainfall and temperature (Chadee et al., 2007). Climate change is also likely to increase the risk of vector-borne diseases such as dengue fever and chikungunya, as well as air pollution and heat stress, with negative impacts on public health.

The costs of these impacts can be significant, with some estimates suggesting that the Caribbean could face losses of up to 4% of its GDP by 2050 if no action is taken to mitigate the effects of climate change. The economic and environmental challenges faced by small island states are well documented (Eckstein et al 2019; Briguglio et al., 2009; Bishop 2012) with the Eastern Caribbean region considered amongst "most disaster-prone in the world" (IMF 2004). Economic vulnerability often lies outside control of the small island sovereign states as they depend on narrow range of exports and wide range of imports such as food and fuel (Briguglio et al., 2009). The risk and volatility in these economies is

[7] https://www.ilo.org/static/english/intserv/working-papers/wp026/index.html#ID0EZC

exacerbated by their small geographic size and low populations, which drive up costs per capita. The concentration of economic activity in a narrow set of climate vulnerable sectors such as tourism, fishing, and agriculture, means adaptation and diversification will be key to climate resilience.

Box 1. The Physical and Transition Risks of Climate Change in Caribbean

Climate change poses a range of physical risks to the Caribbean, including:

1. Increased frequency and intensity of hurricanes, tropical storms, and flooding.
2. Rising sea levels, leading to coastal erosion and saltwater intrusion into freshwater sources.
3. Coral bleaching and ocean acidification, which threaten marine ecosystems and fisheries.
4. Droughts and water scarcity, affecting agriculture, tourism, and human health.
5. Heat waves and extreme temperatures, leading to heat-related illnesses and death and increased energy demand.

These risks can cause damage to infrastructure, homes, and businesses, disrupt supply chains, and harm human health and wellbeing leading to reduced labour productivity and slower growth.

To mitigate these risks, governments, business, and markets are beginning to transition away from fossil fuels towards a low-carbon economy. This represents the largest deliberate transformation of the global economy in human history and the process introduces risks of its own. The transition risks of climate change in the Caribbean include:

1. Stranded assets in the fossil fuel industry, as the world moves towards renewable energy sources, rendering investments made in traditional energy sources obsolete.
2. Decline in tourism revenues due to the loss of coral reefs, a shortened season, and loss of tourism-related infrastructure (including resorts).
3. Financing costs of public and private investments to decarbonise energy, transport, buildings, and food.
4. The potential loss of export markets for carbon-intensive goods, or the introduction of border taxes.
5. Financial market risks, including exposure to high-carbon investments or carbon-intensive assets, which may lose value as the global economy transitions to a low-carbon future.
6. Pressure on the public finances owing to increased expenditure on disaster relief and recovery, or investments in adaptation and resilience. Additionally, tax revenues may change as climate reduces aggregate output and as transition to low-carbon alternatives reduces fuel levies and carbon taxes, specifically.

Despite these physical and transition risks, the economic consequences of unmitigated climate change and a failure to adapt are expected to be far worse, both in terms of economic damages and the human toll, which may include loss of life. Both the physical and transition risks can be minimised through dedicated progress towards emissions reductions, diversification, and investments in adaptation and resilience.

2.2. Link between climate change and sovereign debt

Climate change is considered 'the biggest market failure the world has seen" (Stern 2008), with wide-ranging implications for stability along multiple dimensions, including financial, economic, political, social, and environmental. Leading estimates place the economic losses from climate change at 2% - 22% of global GDP by 2100, though these will be highly unequally distributed (Dell et al., 2012; Burke et al., 2015; Kahn et al., 2021; Mohaddes et al., 2023). This paper extends cutting-edge analysis on how climate risks will impact sovereign debt markets to the Caribbean.

Sovereign debt is the world's largest asset class, and widely acknowledged as the 'safe asset' to which investors turn in times of turmoil. But because climate change reduces macroeconomic performance, even this safe asset is at risk from climate change. Reduced economic performance makes it harder for governments to service their debt or make productive investments. Volz et al. (2020) identify six interdependent channels through which climate change can amplify sovereign risk (see Section 2.2.1).[8] Ultimately, this can be expected to increase the riskiness of sovereign debt.

Credit rating agencies are beginning to take note, conducting internal analyses of the effects of climate on ratings factors. Meanwhile, investors are increasingly concerned with the climate exposure of their portfolios, and searching for environmental as well as financial returns. As sovereign ratings give information about the ability and willingness of sovereigns to service their debts, they are immediately linked with the cost of borrowing of governments. Sovereign downgrades increase the cost of both public and private debt, affecting overall economic performance and business conditions across sectors.

Empirical evidence shows that climate change is already increasing sovereign borrowing costs, especially for climate-vulnerable countries (Buhr et al., 2018; Kling et al., 2018,2021; Battiston and Monasterolo 2019; IMF 2020; Beirne et al., 2021; Mallucci 2022; Volz et al., 2020). Estimates of the effect of climate on sovereign borrowing costs vary depending on the sample of countries, specific definitions of climate vulnerability, and the time horizon under consideration. But the trend is clear. Climate change has already increased borrowing costs in the most climate-vulnerable economies by 117 – 275 basis points (Buhr et al., 2018; Bierne et al., 2021). IMF (2020) research extends the sample to 67 economies, including Barbados and Trinidad and Tobago, finding that a one percentage point increase in climate vulnerability is associated with a 0.69 percent reduction in creditworthiness in emerging markets. The cumulative effects of climate vulnerability have increased borrowing costs among the most affected economies by US$ 40bn – 62 bn over a 10-year period (Buhr et al., 2018; Kling et al., 2018). Focusing on seven Caribbean countries, Mallucci (2022) finds that disaster risk reduces governments' ability to issue debt and that climate change further restricts government's access to financial markets. In a scenario in which the frequency of high-category events increases by 29.2% and their intensity increases by 48.5%, debt-to-gdp ratios decline by at least 12% and spreads increase by at least 30%. Finally, the effects of climate on debt are not limited to government bonds. In an analysis of 15,265 firms across 71 countries between 1991-2017, Kling et al. (2021) find that climate vulnerability increases the cost of corporate debt by up to 0.68%.

These studies demonstrate that climate change is already adversely affecting bond yields, creditworthiness, and ultimately the public finances of climate-vulnerable countries. But these studies all depend on observed relationships between historical climate indicators and historical economic outcomes. But if there is a single, overarching lesson from climate science, it is that the future will not be like the past. The macroeconomic consequences of future warming cannot be proxied merely by examining recent history. Understanding the economics of climate change requires looking forward, through climate and economic modelling, to assess future risks and opportunities.

We build on recent research that integrates projections of future climate change into sovereign creditworthiness assessments (Klusak et al., 2023). However, this paper also entails several important extensions for the region. First, we go beyond sovereign ratings to assess impacts on default

[8] These include: 1) Fiscal impacts of climate-related natural disasters, 2) Fiscal consequences of adaptation and mitigation policies, 3) Macroeconomic impacts of climate change, 4) Climate-related risks and financial sector stability, 5) Impacts on international trade and capital flows and 6) Impacts on political stability.

probabilities. Second, we employ a more rigorous, market-based method for estimating the effects of ratings changes on the cost of borrowing allowing for greater alignment with financial market practice. Finally, we incorporate region-specific impacts, particularly around changes in the tourism sector.

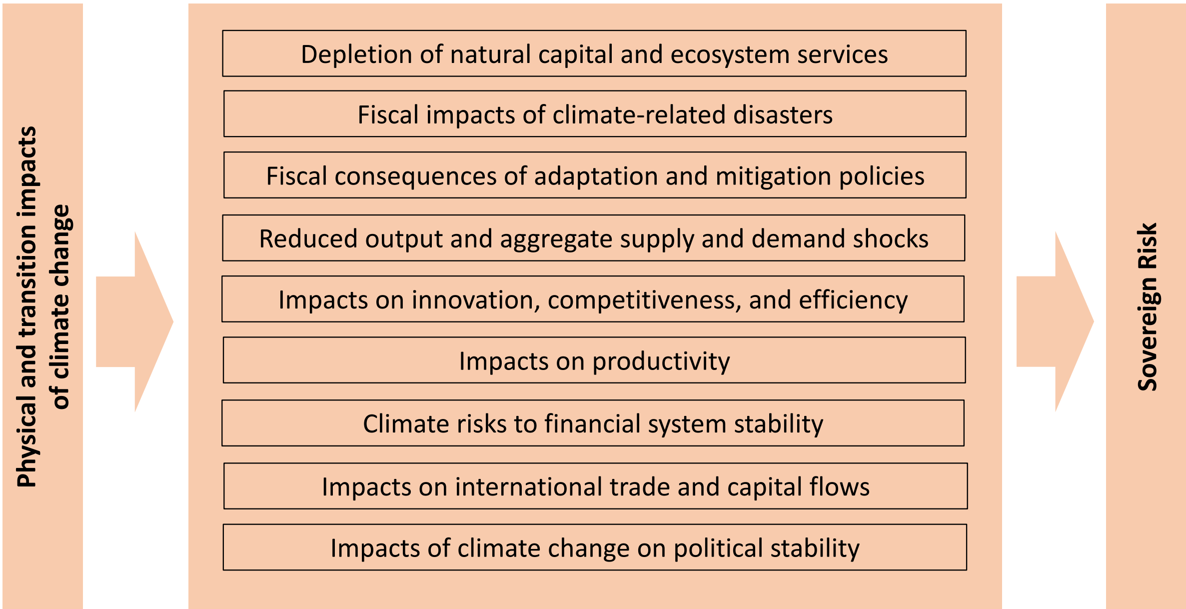
2.2.1. Physical and transition impacts of climate change

Whilst the direct physical impacts of climate change are increasingly understood, the links between climate risk and sovereign borrowing may be less familiar. Volz et al. (2020) and Agarwala et al. (2021) describe multiple channels through which climate risk might impact sovereign debt markets (see Figure 2). As Box 1 suggests, the fiscal consequences of climate change and the policy responses to it are not limited merely to the direct physical damages. Indeed, significant *near-term* impacts on aggregate output and public finances will derive from the climate transition, in addition to the physical risks from climate change itself.

The 'transition' reflects the process of decarbonisation and reorientation of national economies away from a fossil fuel-based energy system towards a low-carbon, climate resilient economy. Transition risks include those associated with changes in policy, consumer preferences, litigious actions, and technological development that accompany the drive to reduce emissions. In addition to decarbonisation, the transition includes investments to support resilience and adaptation, as warming and associated impacts are now unavoidable, even under the most ambitious transition pathways. Thus, 'transition risk' is a broad concept and represents the challenges associated with the structural transformation of the economy. Associated to this concept, a "just transition" is also a key dimension to consider as the challenges associated with transitioning to a more sustainable and low-carbon economy will also generate new pressures on the communities given their dependencies to tourism, fossil fuels, and imports. In Latin America and the Caribbean, a study from the IDB assessed that aligning infrastructure and social spending will represent 7% to 19% of annual GDP, representing from US$470 billion to US$1,300 billion in 2030. Nonetheless, it is important to underline that the benefits of this reallocation of resources will exceed its costs as it will avoid the worst impacts of climate change and generate economic, social, fiscal, and environmental benefits.

The physical impacts of climate change will deplete natural capital and undermine ecosystem service delivery, particularly with respect to fishing and agriculture. Substitution away from oil and gas will reduce fiscal revenues for fossil fuel producing economies such as Trinidad and Tobago, Guyana, and potentially Suriname. But it will also reduce revenues from fuel levies in countries such as The Bahamas, Barbados, and Jamaica. Moreover, early progress on mitigation and adaptation investments may require an expansion of public debt, for instance through green bonds. These changes will affect sovereign creditworthiness.

Figure 2: Climate change to sovereign risk: a review of impact pathways



Sources: Adapted from Agarwala et al. (2021) and Volz et al. (2020).

Sovereign debt markets also present opportunities for financial innovation, spurring a green recovery that builds forward toward a more sustainable and resilient future (Agarwala et al. 2021). First, public debt is an important means through which economies can invest in themselves and their futures. It enables governments to crowd-in private investment in key industries such as renewable energy, and low-carbon infrastructure. This is especially important as such industries are characterised by high up front capital costs, for instance in constructing wind farms, followed by long-term low production costs. Green public debt can also signal to financial markets that the government is committed to sustainability. This signalling effect can be important because the returns to many green investments accrue over long time horizons, meaning that regulatory uncertainty and changes in government priorities can become substantial obstacles to private investment. Finally, green public debt can stimulate growth in the financial services sector by creating a new asset class of green bonds, encouraging the growth of green investment funds, and creating jobs in monitoring and reporting, which provides an additional benefit of improved transparency.

Box 2. Contingent Credit facility for Natural Disaster Emergencies

In 2009, the IDB created The Contingent Credit Facility for Natural Disaster Emergencies (CCF) as one of its main tools to help countries develop effective strategies for natural disaster financial risk management.

The CCF offers contingent loans that are prepared in advance but are disbursed after the IDB has verified the occurrence of a disaster event in terms of type, location, and intensity. This is part of the IDB's effort to help countries move from a primarily after-the-fact approach to managing disaster and climate risks to one that includes greater prevention, mitigation, and preparedness measures taken before disasters strike.

The CCF's objective is to provide countries with cash following a natural disaster of severe to catastrophic proportions for humanitarian relief and to restore basic services. Proceeds from CCF Loans are used to cover extraordinary government expenditures incurred six months after the disaster. Examples of eligible expenditures include emergency sanitation equipment, medications and vaccines, temporary shelter equipment and installations, water and foodstuffs for displaced or distressed populations, and debris removal, among others.

All IDB's borrowing member countries are eligible to receive financing through the CCF, provided they have in place a Comprehensive Natural Disaster Risk Management Program (CDRMP) approved by the IDB. The CDRMP includes measures on governance, risk identification, risk reduction emergency preparedness and response, and financial protection and risk transfer. The CDRMP has measurable output and annual indicators to allow regular monitoring.

The coverage limit of the CCF per country is up to US$300 million or 2% of the borrowing member country's GDP, whichever is less.

The country, through the project executing agency, submits to the IDB a Request for Verification of Eligibility of the disaster event. The IDB will then apply a previously agreed calculation methodology to produce an Eligibility Verification Report.

If the assessment concludes the event is eligible for disbursement, the IDB will include in the Eligibility Verification Report the maximum disbursement amount. The borrowing country must confirm in writing its intention to disburse.

Box 3. The hurricane clause

Given the frequency and destruction caused by these extreme weather events, Caribbean countries have been demanding climate-resilient debt instruments and other innovative means to build financial resilience. The IDB has introduced for this purpose the hurricane clause which also considers similar disaster-linked clauses in their loan agreements.

The hurricane clause is designed to provide cash flow relief at the crucial period after a natural disaster event, when financing needs are high and new sources of funding are limited. By embedding "hurricane-linked clauses" in debt contracts, countries can tap into extended maturity periods in the event of a natural disaster. As part of IDB loans, a country hit by a predefined disaster can chose to defer principal payments for two years. In the region, Barbados has recently included this clause in its loans. When well-managed, such clauses can offer crucial relief and support economic stability in times of turmoil.

Box 4. How catastrophe bonds can help reduce vulnerability

Catastrophe bonds, also known as "cat bonds," are a type of insurance-linked security that allows countries to transfer the risk of natural disasters, such as from hurricanes and tropical storms, to investors. They are typically issued by insurance or reinsurance companies, or multi-lateral development banks.

One example is the World Bank's 2021 US$185 million cat bond to provide Jamaica with disaster relief insurance against named storms over three hurricane seasons ending in December 2023.* The World Bank issued a bond to investors with a fixed yield, which is paid by Jamaica. For Jamaica, this is like an insurance premium. In the event of a named storm that meets the pre-arranged criteria, the cat bond is triggered and the bond principal is reduced by the amount of the pay-out.

The benefits to Jamaica are that much-needed finance is quickly released in the event of a disaster, without increasing Jamaica's public debt. The benefits to investors are a higher yield than would typically be available in traditional bond markets. However, if a qualifying catastrophic event occurs and triggers the policy, the bond may be partially or completely written down, and the investors lose some or all of their investment. All parties benefit from the World Bank's AAA credit rating and access to international financial markets, reducing the risk premia and associated transaction costs.

*The World Bank's first-ever cat bond was issued in 2014 to insure 16 Caribbean nations against earthquake and cyclone risk. In 2021, Jamaica became the first government in the Caribbean region and the first of any small island state to independently sponsor a cat bond.

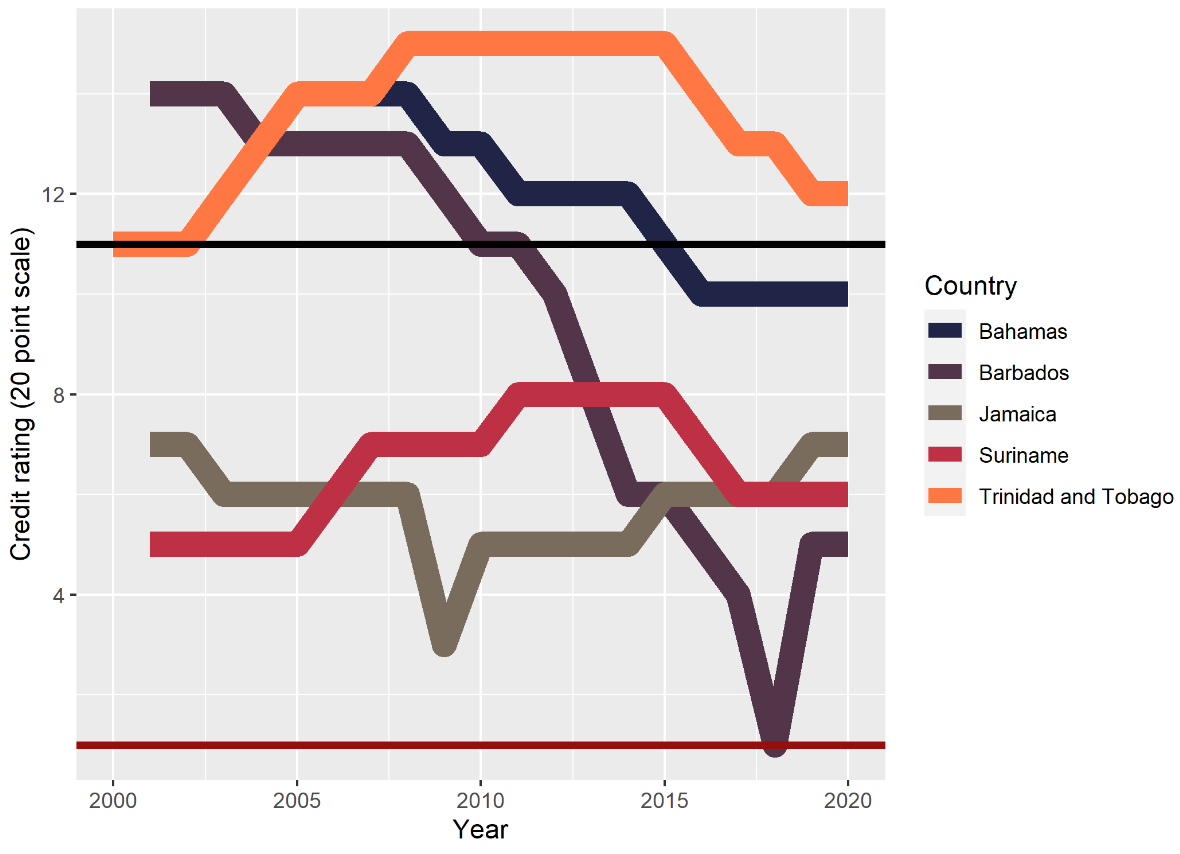
There are of course risks involved in expanding green public debt. If stringent reporting criteria are not enforced, 'green' investments are not selected on the basis of scientific evidence, or debt is used to subsidize current consumption rather than investments in long-term productive capacity then there is a risk of greenwash and a severely disruptive market correction. Mallucci (2022) warns that when green financial instruments are poorly managed, they can reduce financial incentives to mitigate and adapt to climate change and induce governments to take excessive risks, including borrowing more. Even with well-managed green debt, it remains a real possibility that investments in adaptation and resilience cannot keep pace with climate risks if international climate targets are not met. That is, green debt can be a useful tool to accelerate the transition and increase adaptation and resilience, but only if it is complemented by successful global emissions reductions and adherence to international climate agreements. Whilst some of these concerns can be addressed within the region through good governance, others require the active participation of the global community.

Ultimately, market and public opinion are shifting such that investors and financial institutions are increasingly determined to 'green' their portfolios. With little fiscal space remaining, governments must crowd-in private finance to stimulate growth- and resilience-enhancing investments. Many governments started tackling this issue by releasing climate and nature-linked bonds (Volz, 2020).

2.2.2. Historical ratings of the Caribbean region

Sovereign credit ratings vary substantially across the region, with direct repercussions for the cost of public borrowing. Trinidad and Tobago consistently falls within the investment grade range, whereas all other countries operate within the speculative grade (see Figure 3).

Figure 3: Sovereign Ratings 2000 – 2020 (S&P)



Sources: S&P Ratings Direct. Authors own calculations.
Notes: Guyana is excluded from the figure since it has never been rated by S&P. The black and maroon lines represent the investment grade and default rating thresholds, respectively. The investment grade threshold is equal to or above BBB- and translates to 11 on the 20-notch scale. The extremely speculative risk and default is observed with 1 point on the rating scale.

Although Barbados and The Bahamas held investment grade ratings until 2010 and 2015, respectively, our modelling exercise focuses on the years 2015 – 2020[9], as in (Klusak et al., 2023). Trinidad and Tobago is the only sovereign that maintained an investment grade rating for the duration of our sample period (2015-2020) with 13 notches, or BBB+. The second highest rated sovereign on average is The Bahamas with 10 notches, or BB+. During the study period, one sovereign (Barbados) defaulted on its foreign currency obligations in 2018 and is amongst the lowest rated sovereigns in the sample. Barbados received rating of 4 notches, or CCC+, on average. Table 1 presents the distribution of historical credit ratings for the sample of 5 sovereigns over the period 2000-2020.

Table 1: Rating distribution of the sample 2000-2020

Country	Obs	Mean	Std. dev.	Min	Max
The Bahamas	18	12.1667	1.6539	10	14
Barbados	21	9.7619	4.1341	1	14
Jamaica	21	5.8095	0.9284	3	7
Suriname	21	6.4286	1.1650	5	8
Trinidad and Tobago	21	13.5238	1.5040	11	15

Notes: This data provides historical sovereign long-term foreign currency ratings issued on 5 Caribbean sovereigns in the period 2000-2020 by S&P. Guyana is not shown because it has not been rated by S&P. Data available from Ratings Direct.

Additionally, this exercise faces a number of limitations, including the unavailability of credit ratings for many countries, as well as their low variability (i.e., See Figure 3) during the analysis period. Therefore, our results should not be extrapolated outside the sampled countries, and even in those countries, they should be taken with caution as such data limitations could imply that some relevant information in the formation process of credit ratings may not be fully captured. Yet, it is also worth emphasizing that this paper has been originally motivated precisely by the lack of data regarding Caribbean countries. Further, even in the presence of the observed low variability, our results do suggest that climate risks would increase risk premiums for countries that already face high costs of debt.

3. The role of ratings in managing risks and accessing finance

3.1. Sovereign ratings and their methodology

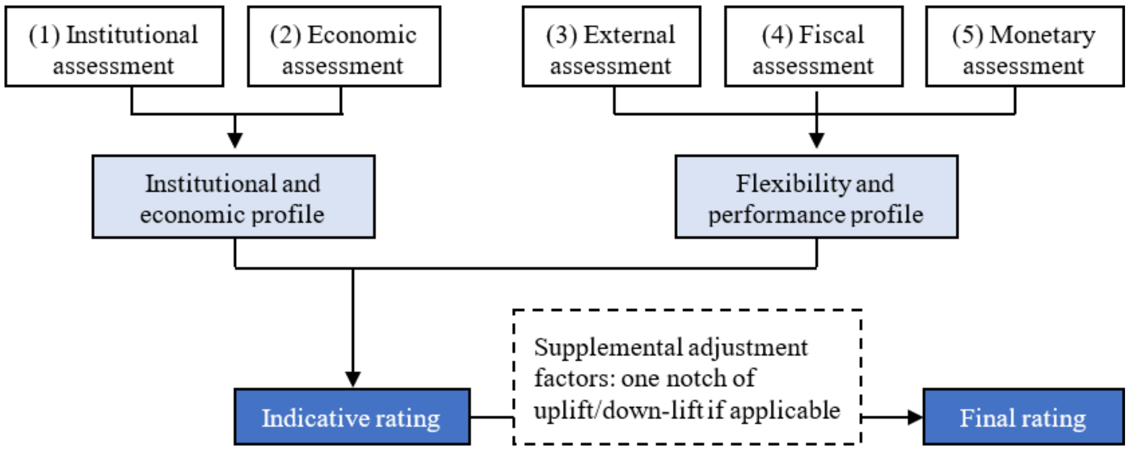
As key intermediaries between the supply and demand for finance, credit ratings agencies (CRAs) play a central role in markets by providing standardised information about the creditworthiness of national economies. Sovereign ratings combine objective data with subjective assessments of the ability and willingness of sovereigns to service their debt. Although several agencies issue sovereign ratings, we use S&P's because they have the widest country coverage over the assessment period and their ratings

[9] This is because the ratings prediction model provided the strongest predictive accuracy over this period. Extending the sample period introduced noise from the 2008-2009 financial crisis and the subsequent Euro crisis, which ultimately undermined model performance.

actions have the strongest own-country stock market impact (Almeida et al 2017; Brooks et al 2004; Kaminsky and Schmukler 2002).

According to the sovereign rating methodology published by S&P—a leading rating agency — ratings are based on five key determinants: (1) institutional assessment, (2) economic assessment, (3) external assessment, (4) fiscal assessment, and (5) monetary assessment (Figure 4). These five factors are measured on a six-point scale based on quantitative factors and qualitative considerations (S&P 2017). An institutional and economic profile is constructed by averaging the scores in (1) and (2), and a flexibility and performance profile calculated as the average of scores in (3), (4), and (5). The resulting profiles are then merged using a matrix to assess the indicative rating, which is typically adjusted depending on additional adjustment factors (S&P 2017).

Figure 4: Sovereign Issuer Criteria Framework



Sources: Standard & Poor's Global (2017).

Although CRAs make their ratings methodologies publicly available, the subjective inputs mean that sovereign ratings are not perfectly replicable by outsiders.[10] Empirical researchers have attempted to 'hack' sovereign ratings methods, using publicly available macroeconomic and governance indicators to 'reconstruct' sovereign ratings based on objective data, thus eliminating the subjective component and making ratings replicable.

Traditional approaches to modelling credit ratings often rely on parametric estimation. However, due to the unique nature of ratings (the fact that they are captured by incremental scale) it is difficult to model them this way. Incremental shifts through the rating scale do not represent equally meaningful changes in creditworthiness. For instance, if Country A moves from one high grade rating to another, this change would not be as significant as if Country A moved from a lower medium grade to a non-investment grade. Second, sovereign credit ratings are not characterised by the same distributional properties we may observe in other variables. There are typically far more observations at the top-end of the ratings scale than throughout the rest of the rating categories. These features make linear modelling of credit ratings difficult and subsequently lead to error. Therefore, researchers have considered non-parametric approaches to model sovereign ratings. The central benefits associated

[10] One of our authors of Klusak et al. (2023) served as Global Chief Rating Officer, Sovereign Ratings at S&P (2013 – 2018).

with these approaches are much better handling of non-linear outcomes in the data and the potential for superior fit. Because sovereign ratings may be subject to thresholds in country-level predictors, such as GDP per capita (S&P 2017), methods capable of handling non-linearities are essential.

To mitigate these issues and ensure the reliability of our estimates, we employ machine learning approaches to predict credit ratings for the Caribbean region. Please refer to section 4.1. for non-technical summary of our method or Appendix 7.1-7.3 for the technical description.

3.2. Why are sovereign ratings important?

We focus on sovereign ratings for several reasons. First, they are readily interpretable and familiar indicators of creditworthiness that are already used by investors, portfolio managers, financial institutions, and regulators in a range of decision contexts. For instance, ratings are 'hardwired' into decisions over which securities investors can hold: institutional investors may be committed by their charter not to hold debt below a certain rating (Fuchs and Gehring 2017). Similarly, under Basel II rules, ratings directly affect the capital requirements[11] of banks and insurance companies (Almeida et al 2017). Moreover, sovereign debt, which was expected to top $92 trillion in 2021 (IIF, 2021) is by far the world's largest asset class. It is the safe haven to which investors flee in times of turmoil, and its sustainability is what determines the capacity of nations to weather shocks, from Covid-19 to climate change. As measures of the creditworthiness of this debt, sovereign ratings act as 'gatekeepers' to global markets, significantly influencing the cost and allocation of capital across countries (Cornaggia et al 2017). Sovereign downgrades increase the cost of both public and private debt, influencing overall economic performance and with potentially significant implications for business across all sectors (Chen et al., 2016). If the economic effects of climate change reduce sovereign creditworthiness, there could be indirect impacts on other asset classes. One potential mechanism is

Box 5: The role of sovereign ratings in sovereign debt markets

Investors and market actors interested in 'greening the financial system' face a fundamental challenge: despite growing evidence of the economic consequences of climate change, there is still no agreed strategy for translating environmental degradation into material risks for investors.

Credit ratings agencies (CRAs) work to identify, assess, and quantify risks, offering investors an 'inside-look' into the creditworthiness of sovereign issuers. They help translate relevant information into material risk assessments, and the ratings they assign affect both the cost and allocation of debt finance around the world.

Although sovereign ratings assess the creditworthiness of governments, their influence also impacts private debt markets. The well-known 'ceiling' and 'spillover' effects describe how sovereign ratings effectively impose a cap on ratings in other asset classes, and how sovereign downgrades often trigger corporate and financial institution downgrades (Almeida et al 2017). Such ratings are part of the DNA of global debt markets, affecting banks' capital requirements and determining which bonds institutional investors (pension funds) can hold.

[11] Basel II 'hardwires' ratings into the capital requirements imposed on banks and insurance companies holding specific sovereigns or firms. The rating bins on sovereign claims and their corresponding risk weights are as follows: AAA to AA− (0%), A+ to A− (20%), BBB+ to BBB− (50%), BB+ to B− (100%), and below B− (150%) (Almeida et al., 2017).

the 'sovereign ceiling effect,'[12] whereby sovereign ratings implicitly place an upper bound on ratings in other asset classes (Adelino and Ferrera 2016). A second and closely related mechanism is the observed 'sovereign spill-over effect', whereby sovereign downgrades are quickly followed by downgrades in other asset classes (Augustin et al., 2018). Because both the ceiling and spillover effects are more pronounced for firms and financial institutions whose ratings are closest to the sovereign's, any climate-induced downgrades are likely to have a greater impact on the highest rated firms.

A further motivation for focusing on sovereign ratings is the observation that climate change does not just affect firms individually, it affects countries and economies systemically. Narrow, firm-level assessments that ignore broader climate impacts are necessarily incomplete. For instance, major floods, storms, and fires have impacts across sectors rather than just hitting individual firms. Combined, the sovereign ceiling, spillovers, size of the sovereign bond market, and the indiscriminate nature of climate change means no corporate climate risk assessment is complete without also considering the effect of climate on sovereigns. Finally, because sovereign ratings impact bond yields (i.e., the cost of public borrowing), understanding how they might be affected by climate change is central to long-term fiscal sustainability.

3.2.1. Climate change - a gap in current rating methodology

Existing ratings methodologies do not explicitly incorporate climate-related risks[13]. The methodologies published and applied by leading CRAs largely focus on governance, economic, external, monetary, and fiscal factors, but do not explicitly incorporate climate and nature-related risks, and recent changes have rather taken a broader ESG approach than a climate specific focus. However, it is possible that environmental factors could indirectly affect ratings through their impact on the factors already included in the ratings model. For instance, there is strong evidence that climate change has already raised the average cost of debt in vulnerable developing countries (Kling et al., 2018; Buhr et al., 2018; Volz et al., 2020). Ratings agencies do however recognise that climate change and environmental risks CRAs recognise that climate and environmental factors "could have significant implications for sovereign ratings in the decades to come… [although they] pose a negligible direct risk to sovereign ratings in advanced economies for now, on average, ratings on many emerging sovereigns (specifically those in the Caribbean or Southeast Asia) will likely come under significant additional pressure" (S&P 2018).

Conceptually, incorporating climate- and nature-related risks into sovereign ratings is no different from incorporating geopolitical or other highly uncertain risks. All sovereign methodologies include

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[12] For example, following a sovereign downgrade of Italy on the 28th April 2020, Fitch downgraded four Italian banks: UniCredit S.p.A.'s, Intesa Sanpaolo's (IntesaSP), Mediobanca S.p.A.'s , and Unione di Banche Italiane S.p.A.'s (UBI). https://www.fitchratings.com/research/structured-finance/covered-bonds/fitch-downgrades-four-italian-banks-following-sovereign-downgrade-12-05-2020. Similarly, Moody's downgraded 58 sub-sovereign entities after UK's sovereign action 16th October 2020. https://www.moodys.com/touupdated.aspx?isAnnual=true&lang=en&cy=global&ru=%2fresearch%2fMoodys-has-taken-rating-actions-on-58-sub-sovereign-entities--PR_434579

[13] There is some debate over this point. Notably, CRAs claim to have incorporated climate risk into sovereign ratings already. It is conceivable that climate concerns may affect subjective assessments, or that as climate change reduces GDP (e.g. due to catastrophic storms) this GDP loss places downward pressure on ratings. However, this would be a backwards looking analysis and is only capable of telling an economy that the catastrophic hurricane they've just faced is bad for business. Fundamentally, climate risk is not reflected in mainstream credit ratings. Indeed, ESMA, the financial regulator, has not supported the integration of climate risk into sovereign ratings.

efforts to quantify potential liabilities that are hard to anticipate in either scope or timing. For example, contingent liabilities related to bailing out a failing financial sector or strategic or state-owned enterprises are part of the standard repertoire of sovereign risk factors. Similarly, assessing the vulnerability to geopolitical risk is a common feature of established sovereign methodologies. In some cases, a negative adjustment is made to a sovereign's rating for outsized exposure to geopolitical risks, even if those risks have not materialised for many years or decades. CRAs use specific proxies, or simply judgement, to incorporate those risks into the final ratings profile of a sovereign.

A common excuse for excluding climate and nature-related risks from credit risk assessments is that the scientific uncertainty is allegedly too high. In fact, that uncertainty is not fundamentally different from the uncertainties surrounding issues of geopolitical risks or contingent liabilities. What is different, however, is that nature-related risks have emerged only more recently. Methodologies have not yet caught up with this new trend. But that is no valid reason to ignore these emerging risks. At least one leading rating agency has recently acquired a company specialising in assessing cyber risk, another superficially amorphous risk. This research is aimed at helping CRAs to make similar steps into the hitherto underappreciated field of climate and nature-related risks.

The omission of climate and nature risks in sovereign assessments is no small matter. Some estimates suggest that almost half of the world's value added is 'moderately or highly dependent' on nature and its services to humanity (World Economic Forum 2020). That share can be significantly higher for individual countries. Some developing countries are particularly dependent on natural capital. According to World Bank estimates (Johnson et al., 2021), the cost of national GDP loss following a hypothetical collapse of the services hitherto provided for free by nature would exceed the GDP loss caused in 2020 by the Covid-19 pandemic in around half the countries for which data is available. In other words, a collapse of biodiversity would in many instances have a more severe economic impact than what has been arguably the biggest global economic shock in living memory. The pandemic has also been the biggest single trigger for an unprecedented wave of sovereign downgrades during 2020 (Tran et al., 2021). A pandemic is impossible to predict for rating agencies, both in epidemiological and geographical scope. It would therefore be unreasonable to expect a quantification of pandemic risk in sovereign risk methodologies to be applied to individual issuers. The risk of climate change, on the other hand, can be more precisely quantified and geographically localised. Given the potential size of the related economic risk for individual sovereigns, overshadowing anything so far observed in peace times, the inclusion of nature risks into sovereign risk frameworks is not only expedient, but inevitable.

4. Incorporating climate change into sovereign ratings in the Caribbean

4.1. Sovereign ratings estimation

The effect of climate change on sovereign ratings is likely to be mediated through a weaking of the fundamental factors which determine sovereign creditworthiness, "including economic, external, fiscal, monetary and institutional assessments" (S&P 2015a). The available evidence on the effects of climate change on sovereign creditworthiness is that high climate vulnerability and low resilience increase sovereign borrowing costs, especially for lower income countries (Beirne et al., 2021; Kling et al., 2018). But rising costs are also found in developed countries (Painter 2020; Zenios 2021).

IMF (2020) use OLS and ordered response models to regress past sovereign ratings on climate vulnerability, resilience, and the usual macroeconomic indicators for a panel of 67 countries between 1995 and 2017. They find a positive statistically significant effect of climate resilience on ratings, but only mixed results for vulnerability. We advise caution in interpreting these results for several reasons. Many of the countries in their sample were not rated by CRAs until the mid-2000s and may not have many ratings events in the panel. Moreover, the effect of climate change over the period 1995 – 2017 is likely to be small compared to what is expected over the coming decades. It could therefore be difficult to identify an appropriate signal of climate-specific impacts on ratings in the past. More importantly, their approach only considers the effects of climate change on ratings through climate vulnerability and resilience, but ignores the effect of climate change on GDP per capita, GDP growth, or indeed any of the other macroeconomic variables in their model.

One of the first forward looking pieces (S&P 2015b) highlighted that "sovereigns most vulnerable to natural hazards are likely to be small island states with next to no 'geographical diversification' and a narrow economic base. Countries in the Caribbean are thus among the most disaster-prone in the world in terms of incidence, percentage of population affected, and relative extent of damage" (p.4). Subsequent simulations showed that the effects of natural perils such as tropical cyclones (storm surges) and floods on the economic activity ad credit of the Caribbean are amongst the most severe (S&P 2015a). The study finds potential direct economic damages of over 1 percentage point increase in value compared to non-climate scenario for sovereigns such as The Bahamas, Barbados, and Jamaica. The projected additional negative ratings impact for these sovereigns up to 2050 was estimated at almost 0.3 notches compared to the non-climate-change scenario (p.11).

Our approach differs in two ways from S&P's studies. Firstly, we do not focus on a narrow selection of natural perils, but instead estimate the wide-ranging effects of climate change on macroeconomic aggregates such as GDP per capita, growth, and other governance performance indicators which take part in the rating assessment. By applying the most up to date scientific modelling approaches, we can translate the changes in temperature and precipitation into the expected changes in GDP outcomes across nations under various climate scenarios. This allows us to simulate future credit ratings with scientific rigour. Secondly, we are able to provide simulated results for any year from 2030 – 2100, meaning the research can be used for economic analysis in the short- and long-run. Finally, our modelling approach enables us to incorporate economies that have never been studied before in climate and credit ratings research. For example, we are the first to not only project ratings, probabilities of default, cost of financing due to climate for all six Caribbean sovereigns in the sample, but for the first time estimate the sovereign rating for Guyana.

4.1.1 Non-technical description of the method

In this section we outline the methodology for estimating the impact of climate change on sovereign credit ratings of the Caribbean. Our conceptual framework builds on that of Klusak et al. (2023) and focuses on 'soft-linking' climate science with climate economics, leading sovereign credit rating methods which are then translated into additional costs of interest on public debt. Our goal is to remain as close as possible to climate science, economics, and real-world practice in the field of sovereign credit ratings. To the best of our knowledge, Klusak et al. (2023) were the first to simulate the effect of future climate change on sovereign credit ratings, and our approach enables us to evaluate these impacts under various policy and warming scenarios. This process is summarised in Figure 5.

Our model makes use of a machine learning technique referred to as random forest classification. Our modelling approach is split into three steps. In step 1, we collect macroeconomic data for a range of countries and their associated credit ratings released by S&P between 2015-2020[14]. In this step we try to 'hack' the ratings model by training an algorithm on the past ratings to maximise its predictive accuracy. Our ratings prediction model is parsimonious, incorporating just six macroeconomic indicators[15]. This approach is motivated by a desire to avoid overfitting, and most importantly, to ensure our model inputs remain as close as possible to the underlying climate science and economic models. This process enables us not only to replicate the past ratings with high accuracy but gives high predictive capacity to make predictions about credit ratings with new data in step 3. Thanks to the learning capacity of our algorithm and a big data history globally we are able to estimate ratings of sovereigns which previously have not been rated (e.g., Guyana).

In step 2, we combine climate economic models and S&P's own natural disaster risk assessments to develop a set of climate-adjusted macroeconomic data (government performance variables) to feed the ratings prediction model created in step 1. First, we adjust our macroeconomic data, which is considered crucial in predicting credit ratings historically, to account for climate change using climate economic models. This step involves a complex macro econometric modelling approach described in Kahn et al. (2021). Kahn et al. (2021) link deviations of country-specific climate variables (temperature and precipitation) from their historical norms to growth in real output per capita. Their approach reveals country-level climate impacts and explicitly model changes in the *distribution* of weather patterns (that is, not only *averages* of climate variables, but also their *variability*). For these reasons, we utilise their results to adjust two of the ratings factors in our model for climate change: GDP and GDP growth. The detail available in Kahn et al. (2021) enables us to provide details results under three warming scenarios (known as Representative Concentration Pathways, or RCPs). First we consider RCP 2.6, which describes a future that largely aligns with meeting the goals set out in the Paris Climate Agreement and limits warming to less than 2°C. Second, we consider RCP 8.5, which describes a future characterised by higher emissions and warming of about 4.5-5°C by 2100. Finally, we acknowledge and incorporate recent climate and economic research which demonstrates: (i) that as the average temperature rises, so does the volatility of temperature, and (ii) that the economic costs of climate change rises even more as temperature becomes more volatile. This enables us to consider a third scenario, RCP 8.5 + volatility, which describes a high emissions world with rising average temperature and rising variability of temperature. Refer to Appendix 7.3 for technical description.

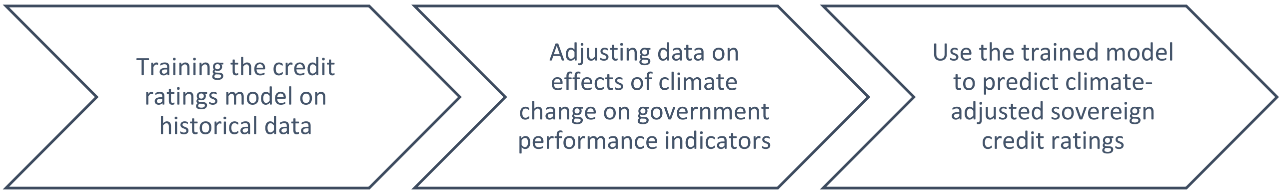
Of course, sovereign ratings encompass more information than simply GDP level and its growth. They incorporate a wide range of objective macroeconomic data and subjective assessments by rating agencies. For example, sovereign ratings include a range of government performance indicators including net general government debt/GDP, narrow net external debt/current account receipts, current account balance/GDP, and general government balance/GDP. Although the science, economics, and politics of climate change are widely studied, we do not have a reliable source of information on how climate change will impact every variable included in the sovereign ratings methodology. To construct climate-adjusted versions of the four government performance variables, we construct statistical models based on data from S&P's own assessments (see Appendix 7.4 for details).

[14] This time horizon excludes the 2008-2009 financial crisis, the subsequent European debt crisis, and the Covid-19 pandemic. This is deliberate. It is precisely because these events had significant impacts on sovereign ratings and debt markets that we want to exclude them from our sample. Including them would confuse their turbulence with that which can be attributed to climate change. At this point in the modelling exercise, our sole objective is to maximise the predictive accuracy of the model. The procedure is explained in Klusak et al. (2023), including the fact that including 'noisy' years in the model *reduced* predictive accuracy.

[15] There are three core criteria for inclusion in our model. Variables must be: (i) relevant to sovereign credit ratings, (ii) there must be a scientific and economic evidence base for adjusting the variable to reflect climate risk, and (iii) data must be available for a broad range of countries. These three criteria exclude some potentially important ratings factors, including default history (in this instance because there is no scientific or economic explanation of how default history changes with climate).

Finally, in step 3 we feed our newly created climate-adjusted macroeconomic indicators to our sovereign ratings model to simulate the effect of climate on ratings. For comparability with the literature and to demonstrate the effect of strict climate policies that are consistent with meeting the Paris Agreement, we present results under four warming scenarios: RCP 2.6, RCP 8.5, and both of these are estimated in different time horizons starting from 2030 up to 2100.

Figure 5: Model building and prediction process

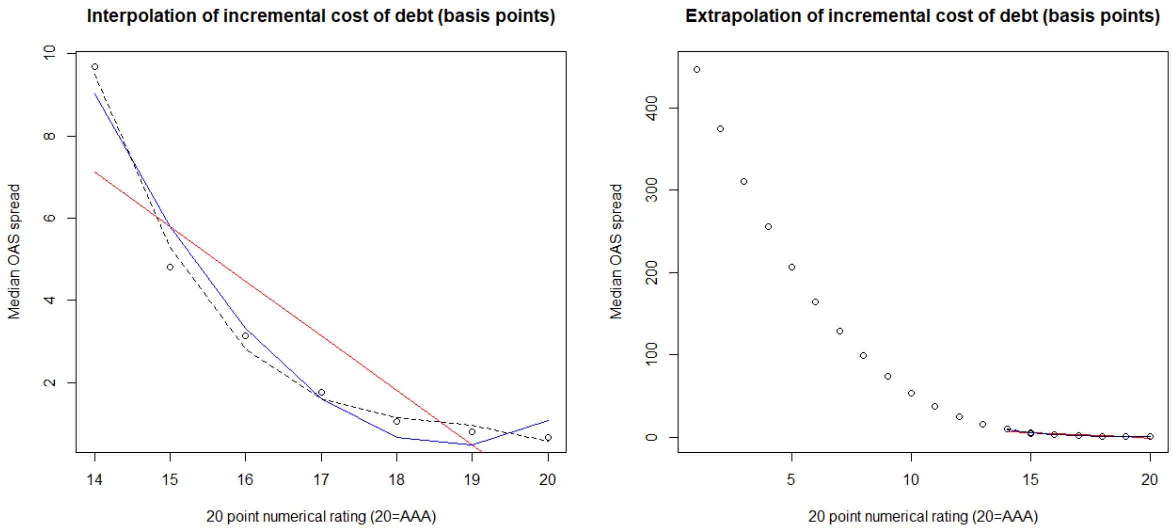


4.2. Cost of debt

Once we obtain the climate-adjusted credit ratings we can translate them into additional costs of borrowing of sovereigns and corporates. Our method of calculating cost of debt relies on option-adjusted spreads. This data provides the interest cost for each rating category applicable to sovereigns, over and above the risk-free rate. This data, taken from the Federal Reserve, provides us with the additional interest cost for AAA through to CCC. Here we take the spread increase for the downgrade we estimate in an earlier step and multiply it through by gross sovereign debt. For the spreads we take the median spread for the ratings given (which vary between AAA to CCC), which allows us to use a value slightly lower than the mean, revealing a lower bound. We then interpolate the data to produce a function which will be the best at describing a relationship between ratings and spreads (namely we fit a 3rd level polynomial; see the left panel of Figure 6). Once that function is established, plug in the relevant estimated downgrades under each scenario.[16] Finally, we calculate the difference in spreads between the scenarios, which represent an increase in the cost of debt due to climate change. Cost of debt amounts to the change in the spread divided by 10,000 and multiplied by the amount of outstanding debt. Additionally, since sovereigns impose a direct ceiling and spill over onto other assets classes incorporated in the country (banks, corporations), we are able to translate the effect of sovereign changes into corporate cost of debt. Taking data on outstanding corporate debt accessed through the Bank of International Settlements (BIS), we produce a similar calculation for the impact these downgrades could have on corporate debt within the country.

[16] Note, we extrapolate the values of the ratings scale which are not observed in our dataset using this function (Figure 6 to the right).

Figure 6: Interpolation and extrapolation of incremental cost of debt



Notes: This figure presents how we interpolate (extrapolate) the cost of debt function using our data. The left panel plots median OAS spreads (vertical axis) against each rating level (horizontal axis). We fit polynomials of increasing order until we find a function that best describes the spreads. The right panel plots the exponential incremental rise in the OAS spread as we move down the ratings scale (from right to left).

4.3. Probability of default

The relatively low ratings found across our sample (see Section 2.2.2) suggest that our results should be considered lower-bound estimates. Ratings are an ordinal rather than a cardinal ranking of credit risk. Credit risk does not rise and fall proportionately as we move along the rating scale.[17] Instead, as ratings move down the scale, default probabilities rise exponentially. For historical reasons (initially only highly creditworthy issuers sought ratings) there is far more granularity at the top of rating scale than at the very bottom. In other words, a sovereign with a very low rating in the B category does not have much further to fall, even if credit fundamentals deteriorate (for numerical interpretation of ratings scales see Appendix 7.5). That is why ratings tend to be stickier in the B category.[18] It takes a bigger shift in fundamentals to move these rating categories than others. This can explain why sovereigns starting off in the B category might appear to be better shielded from downgrades.

To partly correct for this technical bias that underestimates the impact on creditworthiness for lower-rated sovereigns, we convert the alphabetical ratings into empirically observed probabilities of default (PD). Rating agencies publish on an annual basis default and transition statistics for all asset classes, including sovereigns. In those publications the agencies described how the ratings have performed over time. In doing so they apply different time horizons, with five and 10 years being the most commonly used.

[17] This implies that the creditworthiness does not move linearly with the probability of default. Therefore, if Country X is downgraded by one notch it does not infer an equivalent effect on probability of default to what Country Y might experience.

[18] According to transition data by S&P Global (2021b, Table 39) spanning 1975-2020, 17.1% of all sovereigns rated B-, B, or B+ still had the same rating 10 years later. That proportion is lower for sovereigns rated in other categories except for the ones at the top of the scale. The corresponding numbers for BB, BBB, and A are 10.2%, 15.8% and 14.3%, respectively.

4.4. Data sources

This section outlines the data sources used to simulate credit ratings, default probabilities, cost of borrowing, and tourism losses. Where the project team has estimated or simulated data, the technical description of these processes is available in Section 7. We begin by describing the ratings data used to construct and calibrate the ratings prediction model (Section 4.4.1) based on Klusak et al. (2023). Section 4.4.2 describes how these data are adjusted to reflect the physical and transition risks from climate change in the region, based on Kahn et al. (2021), S&P (2015), Klusak et al. (2023), and the authors' own calculations.

4.4.1 Credit ratings data

Historical sovereign long-term foreign currency ratings are obtained from S&P's Ratings Direct. Following the procedure developed by Klusak et al. (2023), we use six macroeconomic indicators to reconstruct ratings:

- Current account balance / GDP
- Net general government debt / GDP
- General government balance / GDP
- Narrow net external debt / current account receipts (CARs)
- Real GDP growth
- GDP per capita

All six variables have been collected from Ratings Direct Sovereign Risk Indicators platform for The Bahamas, Barbados, Jamaica, Suriname, and Trinidad and Tobago between 2015-2020.

One exception to this procedure is the production of results for Guyana. Guyana is currently un-rated and access to data on their performance variables is limited. All variables except Narrow net external debt to CARs are collected from the IMF WEO database.[19] For General government balance to GDP, we take General government revenue, and subtract General government total expenditure to GDP using IMF data. Because the IMF does not provide a measure of Narrow net external debt to CARs for Guyana, we use random forest imputation. This technique leverages the methodology we employ for predicting credit ratings in our model to predict missing values in our dataset. The process constructs a random forest model from the complete data and uses this to predict the missing values. We make use of the algorithm designed and discussed by Stekhoven (2012).

5. Results

5.1. The physical costs of climate change

As described in Klusak et al. (2023), country-specific projections of climate-adjusted GDP and GDP growth rates under varying warming scenarios are taken from Kahn et al. (2021). They develop a stochastic growth model that links deviations of country-specific climate variables (temperature and precipitation) from their historical norms to real output per capita growth. Analysing data between 1960 and 2014 across 174 countries, they find that persistent deviations of temperature from the country's historical norm reduces per capita output growth, amounting to around 7% reduction in gross world product by 2100 in the absence of mitigation policies. However, these losses are unevenly distributed across countries. These results can be considered a lower bound estimate of the country-specific physical costs of climate change that can be expected under a range of warming scenarios.

[19] World Economic Outlook Database: October 2021 (imf.org)

The Kahn et al. (2021) model also enables us to go beyond temperature *levels* to examine how changes in the *volatility* of temperature – the height of the highs and depth of the lows – affects GDP losses by country. This is an important scientific innovation, because as temperature *levels* rise, so does this *volatility,* and with it, the physical costs of climate change. On average, incorporating the effect of the effect of increasing temperature volatility increases the global losses to 13% of gross world product by 2100.

We examine and report results for the GDP losses arising from the physical impacts of climate change under three warming scenarios, RCP 2.6, RCP8.5, and RCP 8.5 (Vol)[20]. The RCPs were developed by the IPCC and the international climate science community to facilitate benchmarking and comparison across models. In simple terms:

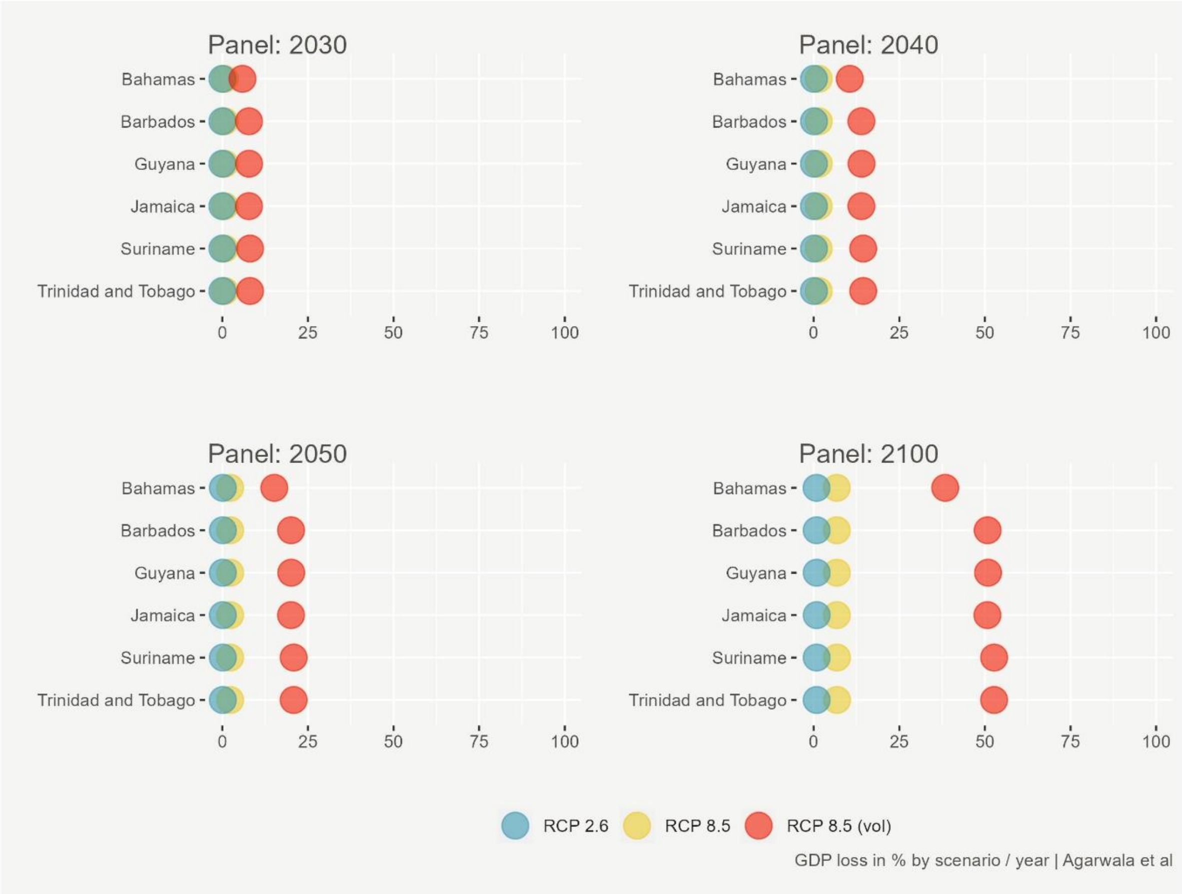
- **RCP 2.6** corresponds to a future in which the global community meets the commitments under the Paris Agreement and warming is limited to below 2°C over pre-industrial levels.
- **RCP 8.5** is often considered a 'worst case scenario' in which emissions continue to grow and warming rises to 4.5°C above pre-industrial levels by 2100.
- **RCP 8.5 (vol)** is a bespoke scenario created by Kahn et al. (2021) and Klusak et al. (2023). It is identical to RCP 8.5, except that it additionally allows for the volatility of temperature to rise commensurately with the level of temperature, and for the added costs arising from this volatility to be reflected in GDP losses, ratings changes, default probabilities, and the cost of sovereign borrowing.

Figure 7 shows the percentage loss of GDP by country arising from the physical impacts of climate change under each scenario, by 2030, 2040, 2050, and 2100 as estimated by Kahn et al. (2021). A notable feature is that if the global community meets the Paris Agreement and limits warming to below 2°C, the GDP losses associated with the physical damages of climate change will be relatively minor, especially over the long term. This does not mean that these economies are immune to the effects of 2°C warming. Indeed, Section 2 summarizes the economic consequences of climate change that have already occurred, at a level of only 1.11°C compared to the 19th century average (NASA 2023). However, over the long-term it is expected that if no further warming were to occur, countries would increasingly adapt to past warming and the costs of these damages would fall over time. In stark contrast to RCP 2.6, near-term GDP losses are substantial under RCP8.5, especially as increased volatility (RCP 8.5 vol) is considered.

There are some important caveats to these figures. First, there is an ongoing debate within the scientific community over which scenarios are most likely. One school of thought is that the scale of investment in renewable energy is already so large that RCP 8.5 is an unlikely scenario for describing 2100. Indeed, some argue that researchers should stop reporting on it altogether. Another school of thought compares the emissions trajectories described in each scenario with the real-world emissions trajectories observed over recent years. This exercise reveals that the emissions trajectories described in RCP 8.5 are far closer to empirical observation over recent years (a difference of about 1%) than those described by RCP 2.6 (a difference of about 8%). We make no judgement over which scenario is 'most likely to occur'. One potential interpretation is that whilst RCP 8.5 may more closely describe the recent past, the purpose of transition is to bring the global economy more in line with RCP 2.6 over the medium term. Thus, the scenario that best describes today may not be the one that best describes the future.

[20] The abbreviation 'RCP' stands for Representative Concentration Pathway, and describes potential trajectories for the atmospheric concentration of greenhouse gasses. The numbers represent different degrees of 'radiative forcing' – a measure of the difference between the amount of energy entering Earth's atmosphere and the amount that leaves it.

Figure 7: GDP losses (%) by country under each warming scenario by 2030, 2040, 2050, and 2100



A further caveat is that these losses should be considered a lower-bound estimate of the costs of the physical damages from climate change. This is because the data describing the long-run relationship between temperature change and GDP that underpins their model covers 174 countries from 1960 – 2014. Whilst this coincides with a rapid increase in global average surface temperature, it cannot capture fully the potential consequences of future warming, especially relating to runaway sea level rise, political unrest, and mass migration of 'climate refugees'. Each of these would substantially increase the costs of climate change and associated impacts on sovereign debt markets, but cannot be accurately assessed on the basis of existing evidence. Ultimately, this means that both the GDP losses and all simulations of future credit ratings, default probabilities, and costs of borrowing reported here can be considered conservative estimates.

Moreover, the analysis in Kahn et al. (2021) relies on studying growth as a function of temperature deviations from baseline. Under their study, cold countries experience a greater growth impact as a result of temperature increase, because of the heightened rate at which these countries experience warming above their baseline. Therefore, the Kahn et al. (2021) study generally underestimates economic damages to countries that already have a high temperature baseline. The Caribbean region fall within this sample of countries. We address this issue by leveraging the rich data provided by Kahn et al. (2021) to train a K-nearest neighbour model which estimates economic losses given a combination of economic and spatial data. With this combination, relying on nearby countries and similarities of economic condition, we estimate economic damages.

Our estimates of the physical climate damages are given in Table 2. These damages reveal that even under high warming scenarios, climate damages are limited to roughly 2% across the Caribbean region on average. However, we also show that under an increased temperature variability scenario these losses could exceed 20% by 2050 across some jurisdictions.

Table 2: KNN estimated climate damages

Country	GDP losses (%) RCP 2.6	GDP losses (%) RCP 8.5	GDP losses (%) RCP 8.5 w/variability
Panel A: 2030			
Bahamas	0	-0.007	-0.059
Barbados	0	-0.007	-0.078
Jamaica	0	-0.007	-0.078
Suriname	0	-0.007	-0.081
Trinidad and Tobago	0	-0.007	-0.081
Guyana	0	-0.007	-0.078
Panel B: 2050			
Bahamas	-0.002	-0.023	-0.152
Barbados	-0.002	-0.023	-0.201
Jamaica	-0.001	-0.023	-0.201
Suriname	-0.001	-0.023	-0.208
Trinidad and Tobago	-0.001	-0.023	-0.208
Guyana	-0.001	-0.023	-0.201

Notes: This table presents estimated climate damages using a K-nearest neighbour algorithm under three scenarios. RCP 2.6, RCP 8.5 and RCP 8.5 with temperature volatility. Panel A(B) considers scenario up to 2030 (2050) respectively.

5.2. The transition costs of climate change

The transition risks associated with climate change are notoriously difficult to model. There are several reasons. First, a transition to net zero would so fundamentally transform the structure of the economy that any model capable of credibly describing today's economy cannot also credibly describe a net zero economy. That is, today's models cannot describe the destination we are moving towards. And models that can describe the destination cannot describe how we get there from here. This is largely due to the path dependencies, non-linearities, and tipping points – social, technological, and ecological – that such a transition would require.

A second challenge is that the costs of transition are endogenous to decisions made today. Early investment in decarbonisation and the roll-out of low carbon technologies and business practices can 'jump-start' a green innovation machine, unleashing the dynamics of 'learning-by-doing' that can rapidly reduce costs. One important example of this is the rapid deployment and reduction in costs of renewable energy generation, which have consistently outpaced modelled expectations for nearly a quarter century.

The result of these challenges is that there is no comprehensive economic model of the country-level transition risks associated with climate change. This means that the inclusion transition risks into our analysis necessarily entails stronger assumptions and due caution in interpreting the results.

The IPCC (2022, Ch 15) notes that many small island states are highly dependent on tourism revenues and are increasingly facing "crises associated with climate-related disasters and more recently COVID-19 disruptions of travel" (Sheller, 2020). Here, we exploit the natural experiment imposed by the

COVID-19 pandemic, associated lock-downs, and reductions in international travel to develop a proxy scenario for transition risk across the region. Our scenario is based on the potential impact of a reduction in tourism revenues associated with a combination of climate change, changes in consumer preferences, and the possibility that fuel taxes, 'flight shaming' and international policy lead to substantial reduction in the demand for flights and travel to the region.

There are several pathways through which climate transition risk might affect the region. First, extreme weather events including heat waves and a higher frequency and intensity of storms may shorten the tourist season or damage and ultimately reduce tourism infrastructure (including airports, ports, roads, and hotels). Second, climate change could damage key coastal and coral reef ecosystems that attract tourists. Over and above the direct costs of these damages, the potential shift in foreign demand for tourism away from the Caribbean represents a form of transition risk. Third, further demand reductions could arise due to changes in consumer preferences for long-haul flights, for instance due to 'flight shaming'. Fourth, international policies including carbon taxes or individual carbon budgets could make travel to the region more expensive, thus reducing demand. Finally, Caribbean economies for whom fossil fuel exports represent a significant share of output could see a reduction in resource rents, investment, and employment, as well as an increase in stranded assets.

It is beyond the scope of this research to model each pathway independently, but the turmoil associated with the COVID-19 pandemic offers some insight into the potential effects of a reduction in tourism revenues. Of the countries in the sample, all but one suffered severe economic contractions in the year 2020. Guyana is the outlier, which grew at an anomalous 43% in the year 2020, due to an unprecedented rapid expansion of oil production (World Bank 2023). GDP losses in 2020 are shown in Table 3.

Table 3: GDP losses in 2020, by country

Country	GDP loss
Barbados	14%
Bahamas	23.8%
Suriname	15.9%
Jamaica	10%
Trinidad and Tobago	7.4%

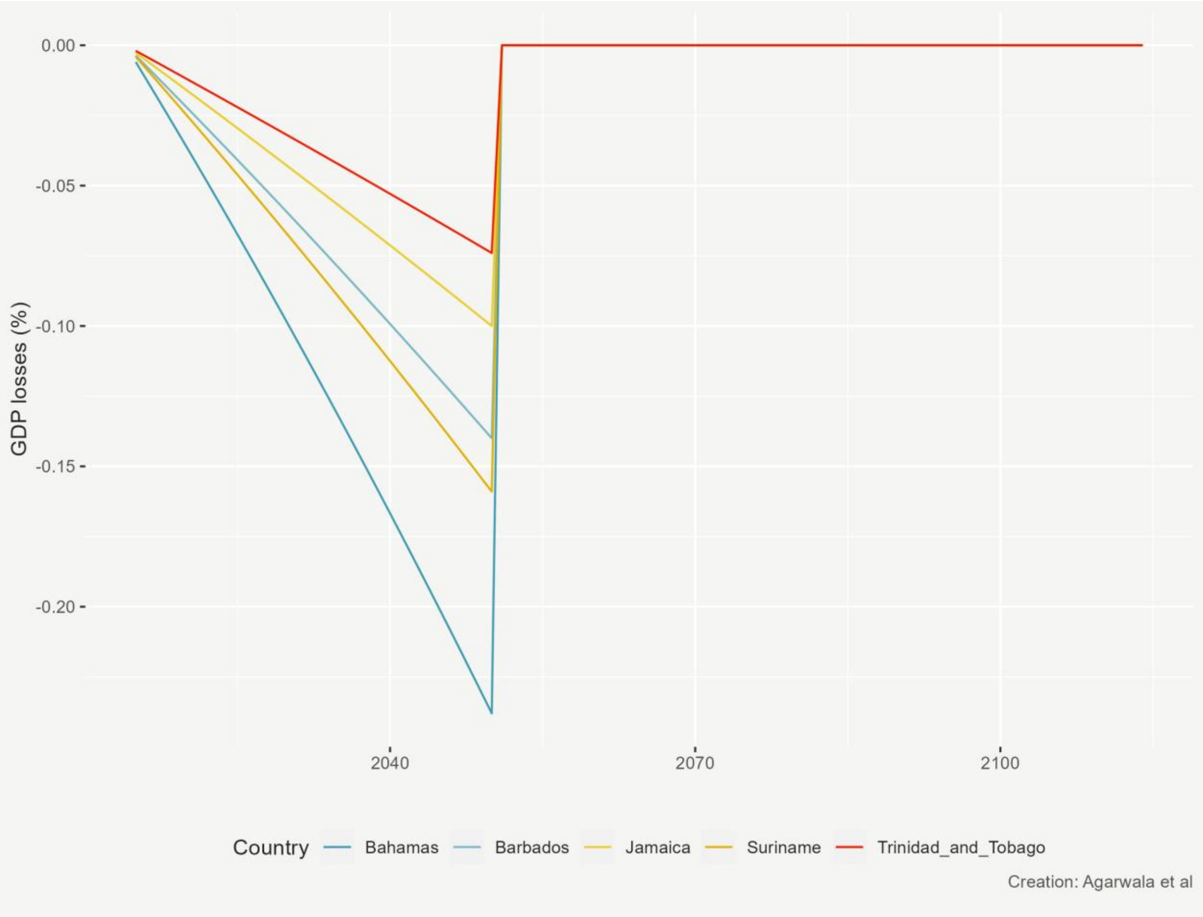
Sources: World Bank (2023).

The GDP losses described in Table 3 reflect the combined impact of COVID-19 across all sectors in 2020. To construct an 'upper-bound', worst case scenario, we examine how ratings would be affected if the impact of climate transition on tourism was equal to the impact of COVID-19 on the entire economy in 2020.

The next question is over what time horizon these losses would be realised. Whilst COVID-19 lockdowns and travel restrictions were imposed overnight, it is unlikely that climate policy, consumer preferences, and local conditions would change in such an instantaneous manner. It would therefore be an extreme assumption to impose the same magnitude of losses all in one year. A more reasonable assumption is that these transition risks would manifest over the course of the transition to net zero. We therefore assume that the by the year 2050, the percentage loss in GDP due to transition would equal that of the pandemic in 2020.

It is unlikely that the trend in GDP losses from a reduction in tourism would continue indefinitely. Economies would adapt, resources would be reallocated, and alternative industries or climate-friendly tourism practices would be developed. We therefore assume that beyond 2050, there is no further loss in tourism revenues. As the IPCC (2022) notes, "tourism system transitions can enable the sector to contribute to climate resilient development pathways through managing climate risks and improving ecological, economic and social outcomes for small islands (medium evidence, high agreement) (Loehr, 2019; Mahadew and Appadoo, 2019; Loehr et al., 2020; Sheller, 2020)." The adaptive capacity and innovations demonstrated by SIDS during COVID-19, moving beyond dependence on 'extractive' international tourism, demonstrate the potential benefits of diversified and sustainable economies (and ecologies) for the enhanced resilience of both human and ecological communities (Sheller, 2020). This scenario for GDP losses is depicted in Figure 8.

Figure 8: A scenario for transition-related GDP losses from tourism



Notes: This figure depicts one potential scenario describing transition-related losses in the tourism sector. It is assumed that transition away from carbon intensive tourism is increasingly costly as net zero policies are pursued to 2050, by which time each country's shortfall in GDP is equal to the 2020 impact of COVID-19. Beyond 2050, it is assumed that there is no further reduction in GDP due to tourism transition.

Prior to the year 2050, we assume tourism losses accumulate in a compounded fashion. We begin in 2015 to remain consistent with the model of Kahn et al. (2021). Some number, X, represents the annual tourism loss. This number is compounded for each period t. This is done in such a way that when we reach t=2050, the losses are equal to those experienced because of the Covid-19 pandemic.[21]

[21] The script for this process has been produced in R, and can be made available upon request to enable full scrutiny.

We justify this by arguing that the heightened physical risks across the region and potential reduction in aviation demand limits or makes tourism prohibitively expensive.

In Table 4 we show how the tourism scenario interacts with the physical risk GDP losses.

Table 4: GDP losses compounded with tourism scenario

Country	GDP losses (%) RCP 2.6 w/tourism	GDP losses (%) RCP 8.5 w/tourism	GDP losses (%) RCP 8.5 w/variability+tourism
Panel A: 2030			
Bahamas	-0.1	-0.106	-0.153
Barbados	-0.06	-0.067	-0.133
Jamaica	-0.043	-0.05	-0.118
Suriname	-0.068	-0.074	-0.143
Trinidad and Tobago	-0.032	-0.039	-0.11
Panel B: 2050			
Bahamas	-0.239	-0.255	-0.354
Barbados	-0.141	-0.16	-0.313
Jamaica	-0.101	-0.121	-0.281
Suriname	-0.16	-0.178	-0.334
Trinidad and Tobago	-0.075	-0.095	-0.267

Notes: This table presents GDP losses compounded by tourism scenario. In columns 1-2 we observe RCP 2.6 and 8.5 respectively, whereas in column 3 we observe RCP 8.5 with temperature volatility. Panel A(B) considers scenario up to 2030 (2050) respectively.

5.3. Sovereign ratings results

This section presents results describing how the tourism scenario interacts with each warming scenario to impact sovereign credit ratings, default probabilities, and the cost of debt across the region. Table 5 reveals estimates of the sovereign downgrades for 2030 and 2050 compounded by the tourism scenarios with RCP 2.6, 8.5 and 8.5 with temperature volatility. Countries' simulated downgrades are generally not parallel to their economic losses. This is because the impact on ratings is non-linear, and largely dependent on the starting point for each country. Thus, ratings impacts appear less severe for sovereigns at the lower end of the spectrum (i.e. non-investment grade). This observation does not suggest that the lowest rated sovereigns have little to worry about when it comes to depletion of their natural resources. As in section 4.3, sticky ratings at the low end of the scale do not imply lower economic or human impacts from climate change, merely that these impacts may not drive ratings.

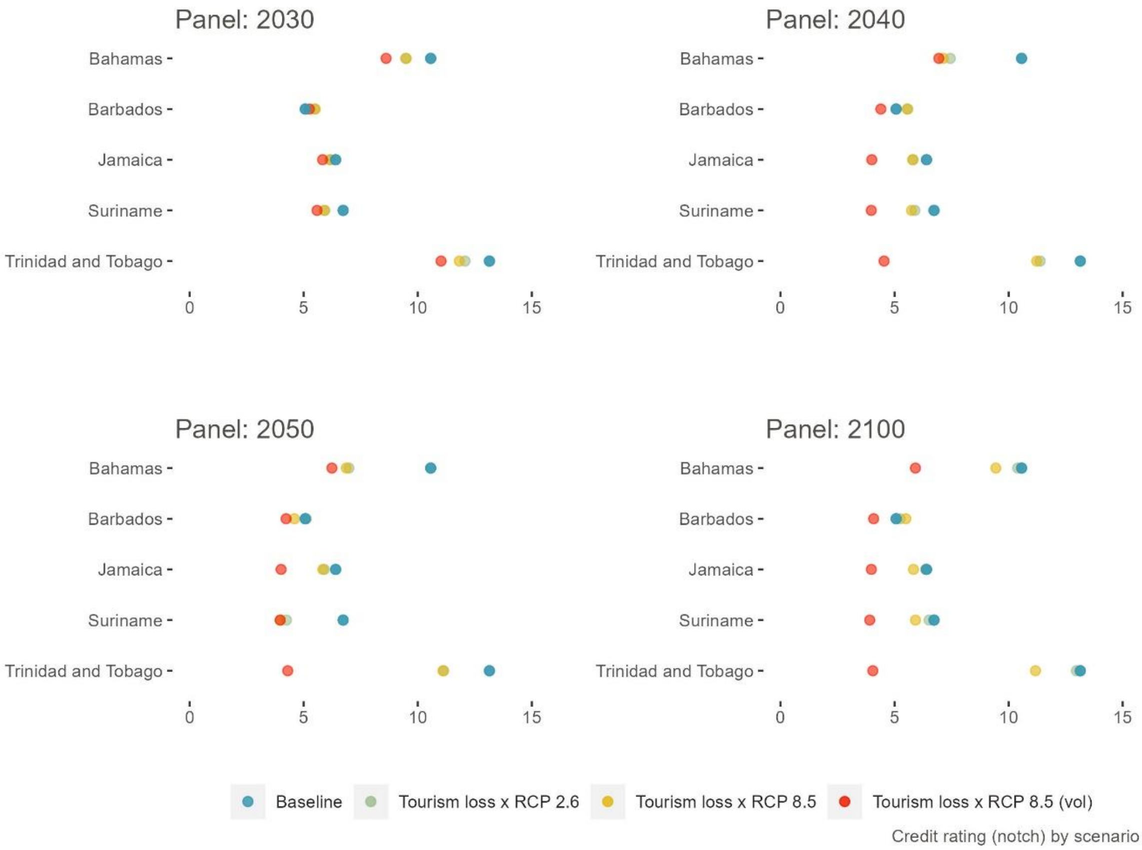
A corollary of this finding is that the countries that suffer the most severe downgrades are usually those that begin with the highest rating. Figure 9 makes this dynamic clearer by showing the country's starting point and estimated rating under given scenarios. Figure 9 shows that Trinidad and Tobago and the Bahamas generally suffer the worst outcomes from their associated economic damages in terms of their sovereign rating. Results become more severe under RCP 8.5 in 2050, especially for The Bahamas and Guyana. Adding increased temperature volatility (scenario RCP 8.5 +vol) reveals a marked shift in downgrades, with all sovereigns facing a deterioration of creditworthiness. Trinidad and Tobago is the most affected with a downgrade of nearly 9 notches, followed by Guyana with 4 notches, Suriname and Bahamas with nearly 3 notches and Jamaica with 2.4 notches. Although Barbados is the lowest rated sovereign in the sample is not spared and it will receive a downgrade approaching a notch.

Table 5: Sovereign downgrades

Country	Rating downgrade RCP 2.6 w/tourism	Rating downgrade RCP 8.5 w/tourism	Rating downgrade RCP 8.5 w/volatility+tourism
Panel A: 2030			
Bahamas	0.1	0.1	1
Barbados	-0.1	-0.1	-0.4
Jamaica	0	0	0.6
Suriname	0.1	0.2	0.8
Trinidad and Tobago	0.1	0.1	2
Guyana	0.1	0.3	1.7
Panel B: 2050			
Bahamas	0.1	0.6	2.6
Barbados	-0.1	-0.2	0.7
Jamaica	0	0.2	2.4
Suriname	0.1	0.3	2.8
Trinidad and Tobago	0.1	0.7	8.8
Guyana	0.1	0.9	3.9

Notes: This table presents sovereign rating downgrades associated with climate change under various scenarios. In columns 1-2 we observe RCP 2.6 and 8.5 respectively compounded by tourism scenario. In column 3 we observe RCP 8.5 with temperature volatility compounded by tourism losses. Panel A(B) considers scenario up to2030 (2050) respectively.

Figure 9: Simulated ratings by scenario



5.4. Probabilities of default results

Table 6 reveals significant increases in the probability of default (PD) across the spectrum of scenarios. The relationship between ratings and probabilities of default is non-linear (See Appendix 7.4). Countries generally experience minimal economic impact when downgrading from AAA to AA+, whereas in the sub-investment grade category, changes in default probability are very sensitive to changes in the rating. Guyana does not feature in the combination of transition and physical scenarios due to anomalous GDP growth (due to oil production) during Covid-19, meaning their experience is not appropriate for modelling transition risk in this manner. Suriname and The Bahamas face the greatest increases in default probability. Under the RCP 8.5 + vol scenario, combined with tourism losses all five sovereigns would experience increased PD of more than 10% by 2050.

Table 6: Increased probability of default

Country	Increased PD RCP 2.6 w/tourism	Increased PD RCP 8.5 w/tourism	Increased PD RCP 8.5 w/volatility+tourism
Panel A: 2030			
Bahamas	3.17	3.07	6.7
Barbados	-4.5	-4.81	-2.03
Jamaica	2.08	2.15	5.26
Suriname	7.03	7.26	10.42
Trinidad and Tobago	0.67	0.93	2.11
Panel B: 2050			
Bahamas	16.58	17.46	22.68
Barbados	-0.55	5.73	10.46
Jamaica	4.55	5.14	26.81
Suriname	26.28	30.02	30.1
Trinidad and Tobago	1.91	1.96	47.1

Notes: This table presents probability of default results arising due to climate change under various scenarios. In columns 1-2 we observe RCP 2.6 and 8.5 respectively compounded by tourism scenario. In column 3 we observe RCP 8.5 with temperature volatility compounded by tourism losses. Panel A(B) considers scenario up to 2030 (2050) respectively.

5.5. Costs of debt results

Returning to our estimates of sovereign downgrades, induced by physical and transition costs observed in Table 5, we calculate the additional costs of borrowing incurred by sovereigns. Table 7 presents the anticipated increase in interest payments following an option-adjusted spreads methodology (see Section 4.2). This approach reflects a higher cost of debt for an incrementally lower rating. For example, in case of Trinidad and Tobago, which faces a simulated downgrade of approximately 9 notches by 2050 (under RCP 8.5 + vol), the knock-on effect on its additional costs of borrowing will be approximately US $450mn. This is followed by Jamaica where a nearly 2.5 notch downgrade is associated with an increase in annual debt service costs of US$ 270mn. Although Suriname experiences slightly more severe downward pressure with nearly 3 notches, the country has significantly lower debt levels. Collectively, climate change will negatively affect borrowing costs across the region. Under the worst-case scenario (RCP 8.5 + vol and tourism losses) by 2050 it will increase interest payments by over US$ 1 bn per year. Although the effect without the volatility under RCP 8.5 is expected to be three times smaller with US$310 ml (Column 3) per year it is not much lower than the aggregate effect under RCP 2.6 (Column 2). This further sheds light on the importance of taking actions early to mitigate the effect of temperatures to align with Paris Agreement’s 2C limit, before borrowing costs rise.

Table 7: Increased interest payments

Country	Outstanding debt	Increase interest RCP 2.6 w/tourism	Increase interest RCP 8.5 w/tourism	Increase interest RCP 8.5 w/volatility+tourism
Panel A: 2030				
Bahamas	7.4	0.03	0.03	0.06
Barbados	5.2	0	0	0
Jamaica	11.2	0.02	0.02	0.06
Suriname	1.7	0.01	0.01	0.02
Trinidad and Tobago	9	0.02	0.02	0.04
Panel B: 2050				
Bahamas	7.4	0.14	0.14	0.18
Barbados	5.2	0	0.03	0.05
Jamaica	11.2	0.05	0.05	0.27
Suriname	1.7	0.04	0.05	0.05
Trinidad and Tobago	9	0.04	0.04	0.45

Notes: This table increased interest payments in US$ bn arising due to climate change under various scenarios. In columns 1-2 we observe RCP 2.6 and 8.5 respectively compounded by tourism scenario. In column 3 we observe RCP 8.5 with temperature volatility compounded by tourism losses. Panel A(B) considers scenario up to 2030 (2050) respectively.

6. Concluding remarks

It is likely that political leaders and economic decision makers are already familiar with the importance of credit ratings, the physical impacts of climate change, and transition risks, in isolation. The primary added value of this paper is to consider how these issues interact, and to provide scientifically and economically rigorous simulations of the financial consequences of those interactions. Our research and results lead to a range of important considerations for finance ministers, central banks, and economic policy makers across the Caribbean region.

A general concern across the region is that global scale models are likely to underestimate the economic consequences of climate change in our target economies. Global assessments tend to be biased towards long-term risks that arise along a smooth path with the main economic impacts accruing in the distant future (Trust et al., 2023). But this fairly benign view does not match the observed reality in the region, which is already facing a combination of slow growing risks (such as sea level rise), punctuated by catastrophic climate-related shocks (such as major storms). As a result, economic decision makers in the region may especially benefit from analyses of discrete hazard events, including sectoral impacts, as these could help identify potential priorities for resilience and economic diversification.

Turning specifically to the impacts of physical and transition risk, the results described in Section 5 reveal a challenging story for finance ministries. Even with these conservative, largely lower-bound estimates, the consequences across the region of a high global emissions scenario are severe. Beyond the human toll, the key implications for finance ministries across the region include:

1. **The importance of global progress on mitigation:** Many of the economies studied here are heavily dependent on tourism, agriculture, and related industries. These are heavily exposed to physical and transition risks from climate change. The increased frequency and intensity of extreme climate events can undermine the capital infrastructure, labour productivity, and global demand for these goods and services. The risks from the global crisis are especially acute in these economies, so championing international efforts to radically and swiftly reduce global emissions remains a primary objective.
2. **Capital markets, exchange rates, and inflationary pressures:** Sovereign downgrades, falling investor sentiment, and the risk of stranded assets arising from climate damages and reduced tourism demand can place pressure on foreign direct investment and foreign exchange earnings. Ultimately, this could lead to difficulties in maintaining currency pegs or lead to depreciation of free-floating currencies, and subsequently inflationary pressures on imports.
3. **Deteriorating investor sentiment and rising borrowing costs:** As investors and ratings agencies increasingly recognise the vulnerability of these economies to climate change, they may expect to extract higher interest rates to cover the additional climate-related risk premium. The combination of falling ratings, rising default probabilities, and increased yield spreads found under higher emissions scenarios can be expected to increase borrowing costs in all studied countries. Our results indicate that under a worst-case scenario, annual interest payments across the six economies we studied could rise by US$ 1 billion. However, this finding is sensitive to the effects of temperature volatility and assumptions regarding the potential decline in tourism revenues.
4. **Reduced fiscal capacity for investing in adaptation and resilience.** Increasing borrowing costs driven by climate change could undermine the ability of governments to invest in adaptation and resilience in the future. This provides further evidence that the net returns to such investments are higher in the near term, to avoid higher borrowing costs in the future.
5. **Diversification presents both opportunities and risks for Caribbean economies:** the transition away from fossil fuels both reduces emissions and improves air quality (with substantial benefits for human health and labour productivity). However, it also reduces important fiscal revenues from fuel duties, carbon taxes, and oil and gas production. Finance ministries should prepare for associated receipts to fall and seek alternative sources of revenue. Beyond carbon, diversification into climate-resilient sectors and industries will be key to reducing vulnerability.

One general lesson that arose during our research was the importance of data quality and availability across the region. Economic statistics are the lens through which we view the economy and are key inputs into sound economic strategy and management. International best practice requires that these should be compiled regularly by politically independent national statistical offices and made easily and publicly available. Doing so improves transparency and accountability, but also facilitates economic modelling and internationally peer-reviewed research. Throughout the project, we found on several occasions that mainstream macroeconomic indicators were unavailable and therefore had to be simulated. Sectoral data would enable economists to be more specific in the identification of risks and opportunities, and offer more targeted policy advice. Finally, these benefits are not limited merely to the management of public finances in the face of climate change. Investing in the statistical infrastructure of nations can benefit all areas of economic policy.

7. Appendix

7.1. Technical description of our method

Random forest algorithms are variously identified as the optimum machine learning technique in the application of credit rating prediction (Ozturk et al., 2016; De Moor et al., 2018; Agarwala et al., 2022; Klusak et al., 2023). Figure A.1 provides an overview of the mechanics of this algorithm. Random forests can be thought of as a collection of decision trees. Decision tree algorithms work through the construction a series of nodes represented by the circles in Fig. A.1. At each node, the algorithm selects the feature which provides the best split of the data. Once the data has been split on the first feature, it then attempts to split the data again such that the resulting splits are as different from the other split as possible, but as similar to each other as possible. This process continues until the data can no longer be split on the features provided.

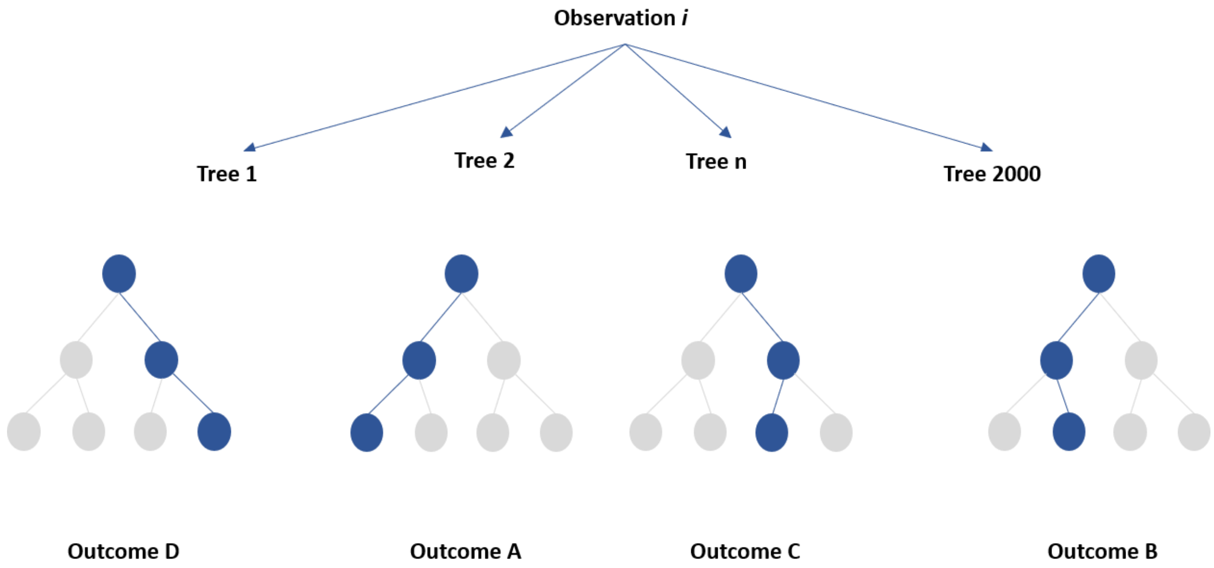
Random forest algorithms can be thought of as extensions of decision trees, but differ in two key ways. First, decision tree algorithms can be highly sensitive to the data on which they have been trained. Random forests improve upon this by enabling each tree within the forest to be trained upon a randomly selected sub-sample of the data, with replacement. Second, in an ordinary decision tree process, the algorithm selects the feature (from all available features) which provides the best split. A random forest algorithm enables the tree to select from only a random subset of features. The intuition behind each of these two modifications is that the prediction made by a forest is an average of the decision made by each tree, and consequently is much more reliable and robust as a collection.

Machine learning methodologies are becoming increasingly popular in the sovereign ratings literature. Research variously employs these techniques to model the impact of the informal economy (Markellos et al., 2016), predict sovereign debt crises (Fioramanti 2008), provide accurate predictions of credit ratings (Bennell, 2006; De Moor et al., 2018; Ozturk et al., 2016; Van Gestel et al., 2006) and explain variance in ESG ratings (Berg et al., 2022). Evidence across the literature supports the view that machine learning techniques outperform traditional parametric approaches in each of these applications. Furthermore, in applications of rating prediction, research reports an improvement of accuracy of approximately 30% above parametric approaches (De Moor et al., 2018; Ozturk et al., 2016). This research supports the use of random forest techniques in ratings prediction application.

This approach differs from the existing literature in one primary way. That is, our goal is to estimate sovereign credit ratings in various climate change scenarios. A common theme throughout the literature is the inclusion of a wide range of determining variables. Inclusive amongst these are economic indicators, trade relations, and measures of institutional quality. In our application, we only make use of variables which we can readily predict under climate change scenarios. As such, we sacrifice some predictive capacity in order to stay as close to the climate research as possible.

Since some of the metrics are not quantifiable and due to proprietary rights weights of the exact (numerous) variables are not known it is difficult to closely replicate the rating. Because sovereign debt has a pronounced economic and financial effect many researchers attempted to find an exhaustive suite of sovereign rating determinants using publicly available information to then mimic and forecast them into the future.

Figure A.1: Random forest classification process



There are four central benefits behind the implementation of a random forest model over other techniques. First, we implement the above-described process thousands of times with slightly modified versions of the original data set each making use of a varied pool of the original six variables. This means that our model, which we later use for prediction, will perform much better when presented with new data. This training of our model adds precision to our estimates that no parametric approach such as regression can offer. Second, this approach enables us to model non-linearities with greater ease. Rating data is peculiar as it is discrete in nature (alphabetical ratings are translated into numerical scale such as the one we are using AAA=20, AA+=19, SD=1; with the AAA being the highest creditworthiness to SD being the lowest). Incremental shifts through the rating scale do not represent equally meaningful changes in creditworthiness. For instance, if *Country X* moves from one high grade rating to another on the scale (e.g., AAA to AA+), this change would not be comparable to a situation where *Country X* moved from a lower medium grade to a non-investment grade (BBB- to BB+).[22] Machine learning ultimately captures the dynamics of our variables with great accuracy and realism. The third advantage of this approach relates to the fact that sovereign credit ratings are not characterised by the same distributional properties we may observe in other variables. The case is that often far more observations are found at the top-end of the ratings scale than throughout the rest of the rating categories. These features make linear modelling of credit ratings difficult and subsequently lead to error. Finally, ratings are not merely quantitative assessments and involve element of subjective component which are difficult to be modelled using traditional approaches. Therefore, using methodology which can handle distributional properties, non-linearities and qualitative components is essential.

7.2. Out of sample tests and sensitivity analyses

Prior to incorporating climate change, a necessary step is to determine the predictive accuracy of the ratings estimation procedure described in Sections 4.1 and 7.1. The core model that underpins this

[22] Note that there is a fine line between investment (BBB-) and non-investment grade (BB+). For a conversion of alphabetical ratings into 20-notch scale see Appendix 7.5.

research has been peer-reviewed and published in a world-leading academic journal as Klusak et al. (2023). This sub-section presents out of sample tests and sensitivity analyses contained in that paper.

Out-of-sample tests are a critical component of machine learning and are used to evaluate model the performance and generalisability. These tests involve assessing how well a model, trained on a particular dataset, can make accurate predictions on new, unseen data that it was not exposed to during training. The objective is to ensure that the model's predictive power extends beyond the initial training data, indicating its robustness and reliability for real-world applications such as our prediction of sovereign ratings.

The steps include:

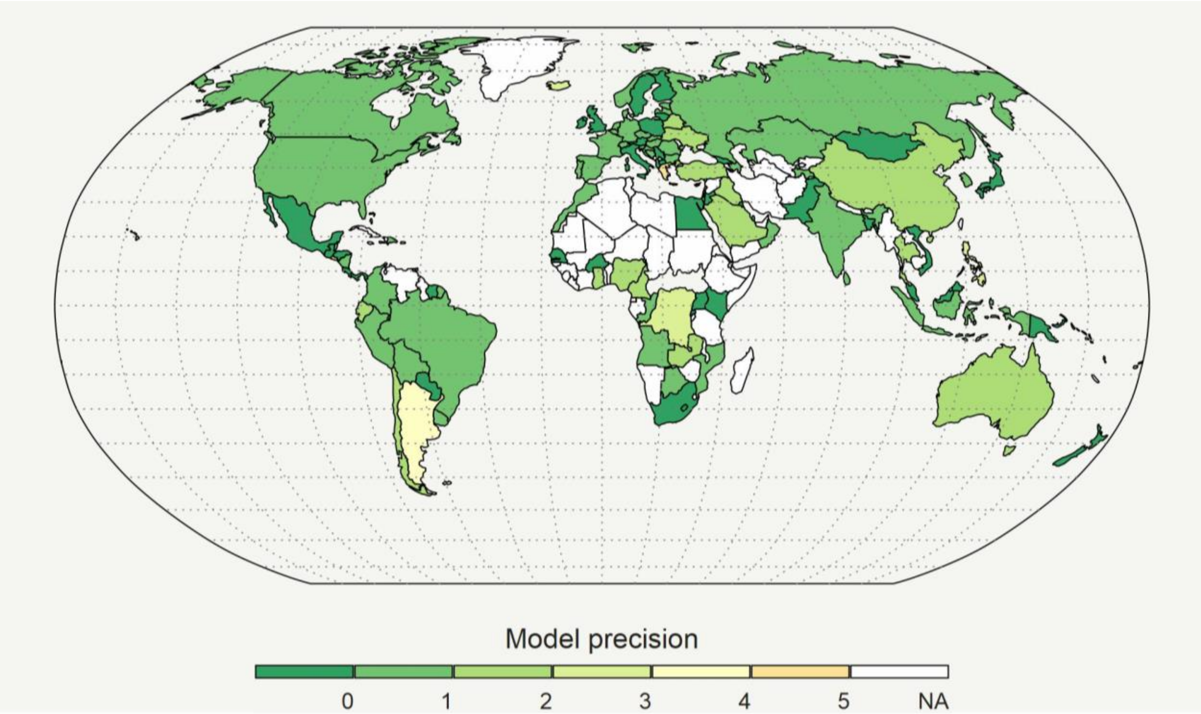
1. Splitting the original dataset into a *training set* and a *testing* or *validation* set. A common split (and the one we used here) is to use 80% of the data in the training set, reserving 20% for validation.
2. Use the training set to train the model, reserving the validation set for evaluating model performance.
3. Use the model developed with the training set to predict the outcomes that should found in the validation set.
4. Compare the model's predictions with the real-world observations found in the validation set.

Using the 80/20 split described above, Figure A.2 presents the headline results from our out of sample tests. Further results and details on model verification are found in Klusak et al. (2023). Recall that the objective here is to use 80% of the data to predict the remaining 20% of ratings, before making any adjustments for climate change. Also recall that the validation set contains observed ratings. The figure compares our predicted ratings against the real-world observed ratings. Dark green demonstrates a perfect match. Lighter colours indicate prediction errors of one, two, … , notches. The results indicate that there is strong predictive accuracy globally, including in hot and cold, developed and less developed, northern and southern, large and small, and coastal and land-locked economies.

In addition to out of sample tests, Klusak et al. (2023) also investigate the sensitivity of their results to the specific climate-economy model used in Step 1 (described in Section 4.1). For reasons described in Section 4.1 of this paper, and in further detail in Appendix C of Klusak et al. (2023), we use Kahn et al. (2021) as the baseline macroeconometric model. However, Appendix C of Klusak et al. (2023) also constructs results using alternative climate-economy models and varying time series of training data. These include models developed by Burke et al. (2015) and Kalkul and Wenz (2020). In both cases, results were qualitatively similar, though due to limitations of the underlying models, more restrictive assumptions were required. Despite this, T-tests indicated that results remained statistically significant at the 1% level. Further detail is available in Klusak et al. (2023) Appendix C. The conclusion from these investigations is that the results described here are broadly upheld even when using not just one, but three unique and independent climate-economy models, developed by different modelling teams, using different methods, and different samples. The stability of our results in the face of these sensitivity checks offers confidence in the appropriateness of our approach.

Validation sets, in the context of a Forest Model, are subsets of that sample of countries-rating used to evaluate project performance and, therefore, to find the parameters that optimize accuracy. 80% of the data is for training, and 20% of the data is for validation.

Figure A.2: Out of sample predictive accuracy of our sovereign ratings model



Notes: This figure 2 depicts out-of-sample predictive accuracy of our ratings prediction model. There is strong predictive accuracy across most of the world, including countries of varying size, latitude, coastal extent, political system, economic structure, and population. Some countries are not rated by S&P and so cannot be predicted.

The accuracy is evaluated in terms of the model successes to predict an observed rating. Therefore, an exact match (rating prediction equals the observed rating) is portrayed in dark green. A one-notch-off is portrayed in lighter green. The figure shows that, except for Argentina, the model does a good job in predicting the rating in all the sample countries.

7.3. Climate economy models

Macroeconomic climate models can be grouped into two categories: global integrated assessment models (IAMs) such as the DICE model for which Bill Nordhaus was awarded the 2018 Nobel Prize in Economics (for review see Diaz & Moore 2017), and a more recent strand of macroeconometric models to estimate the long-run impacts of changes in temperature and precipitation on aggregate output at the country level (Burke et al., 2015; Dell et al., 2014; Kahn et al., 2021). IAMs typically operate at the global scale and are used to evaluate economic impacts of various warming scenarios or climate policies, or to calculate the social cost of carbon for use in social cost-benefit analyses (Stern 2008). Although they have been useful in organising economists' thinking about climate-economic relationships, IAMs are notoriously sensitive to assumptions about discount rates, the shape and parameterisation of damage functions, the latency of greenhouse gases in the atmosphere, the degree of climate sensitivity, and the costs and efficacy of investments in mitigation and adaptation (Diaz & Moore 2017). Whilst some characterize such sensitivities as weaknesses (Pindyck 2013), others find their flexibility useful for integrating advances in economic theory and environmental science into climate policy (Bastien-Olvera & Moore 2020; Dietz & Stern 2015).

The primary limitation of IAMs for the current application – assessing the effect of climate on sovereign creditworthiness – is their high degree of spatial aggregation. Global analyses do not easily translate into country-level risk metrics.[23] For instance, using DICE, Dietz et al. (2016) estimate the representative 'climate value at risk' of global financial assets to be US $2.5 trillion, but do not comment on the distribution of value at risk across countries. While their results demonstrate that restricting warming to 2°C or less make financial sense for risk-neutral and institutional investors, DICE prevents them from making statements about sovereign risk.

A new body of research that combines climate science with long-run macroeconometric analyses of relationships between temperature and GDP growth at the country-level is emerging (Burke et al., 2015; Dell et al., 2012; Kahn et al., 2021). Such models are increasingly used to assess country-level impacts of climate change and identify country-specific social costs of carbon (Ricke et al., 2018). In an early contribution, Dell et al. (2012) constructed a 53-year, 125 country panel of weather and macroeconomic data to show that warming significantly reduces growth in poor countries by 1.3 percentage points for each 1C increase in temperature, but that the results are not significant in rich countries. Relaxing Dell et al's (2012) assumption of linearity, Burke et al. (2015) find more extreme and unequal values for the impacts of climate change, with substantial winners and losers from climate change, summing to a net 22.6% of gross world product by 2100. Whilst these models can produce estimates of the economic effects of climate change, their macro structure means they cannot comment on the mechanisms through which these impacts are found (Burke et al., 2015). In contrast, Kahn et al., (2021) develop a stochastic growth model that links deviations of country-specific climate variables (temperature and precipitation) from their historical norms to real output per capita growth. Using data between 1960 and 2014 and 174 countries, they find that persistent deviations of temperature from time-varying and country-specific historical thresholds (i.e., the historical norm) reduces per capita output growth, amounting to around 7% reduction in gross world product by 2100 in the absence of mitigation policies (with the global losses being significantly higher at 13% if the country-specific variability of climate conditions were to rise commensurate to temperature increases). Due to their ability to assess country-level climate impacts (and explicitly modelling changes in the distribution of weather patterns; that is not only averages of climate variables that the climate-macro literature focuses on but also their variability), our baseline model uses Kahn et al. (2021) to inform our assessment of the effects of climate change on sovereign ratings.

7.3.1. RCP scenarios

RCPs describe potential trajectories for the annual flow and overall stock of greenhouse gases (GHGs), aerosols, and chemically active gases in the atmosphere to 2100 (Moss et al., 2010). Each RCP is named according to its corresponding level of radiative forcing in 2100. For instance, RCP 2.6 refers to a world of stringent climate policy that results in an end-of-century increase in radiative forcing of 2.6 Watts/m2 and corresponds to temperature rise well below 2°C, relative to pre-industrial conditions. In contrast, RCP 8.5 refers to an end-of century increase in radiative forcing (8.5 Watts/m2) and temperature of 5°C, relative to pre-industrial levels.

In terms of policy, the Paris Climate Agreement pledged to limit average warming to 'well below 2°C' and corresponds most closely to RCP 2.6. In contrast, RCP 8.5 is described as the 'worst case' high emissions scenario (Hausfather & Peters 2020; van Vuuren et al., 2011). For comparability with previous literature, we report results for warming scenarios under RCP 2.6 and RCP 8.5.

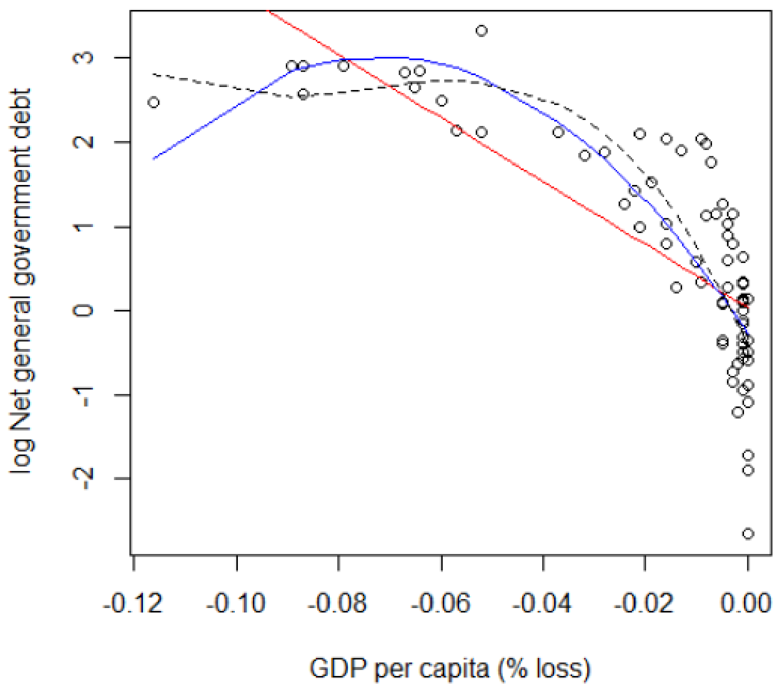
[23] Even the regional version of DICE (called RICE), aggregates to eight regions (Nordhaus & Boyer 2000).

7.4. Constructing climate-adjusted government balance variables

To construct climate-adjusted versions of the four government balance variables in our model, we extrapolate statistical models based on data from S&P (2015b). S&P produce estimates of the effect of various climate and natural disasters on our set of government balance indicators. For instance, using the scenario of a 1 in 250-year earthquake, they estimate the value of the damage caused in terms of impacts on GDP per capita. They repeat this analysis for tropical cyclones, floods, and winter storms. To make use of this data, we combine the tables in S&P (2015b) and assume homogeneity across the various events.

Figure A.3. illustrates the process. Data points combines values from tables in S&P (2015b) describing the relationship between disaster-induced losses in per capita GDP and the log of net general government debt (one of our four government performance variables). To adjust our government performance variables for the effect of climate change, we need a function describing the data in Figure A.3. To derive this function, we first fit a linear model (red line), followed by polynomials of increasing order until ANOVA tests indicate no further significance is achieved. Using the coefficients from the best fit polynomial, we apply GDP losses determined by Kahn et al. (2021) to derive climate-adjusted net general government debt for each country in the sample. We repeat the process for each government balance variable.

Figure A.3: Fitting models of the effect of GDP loss on government performance variables



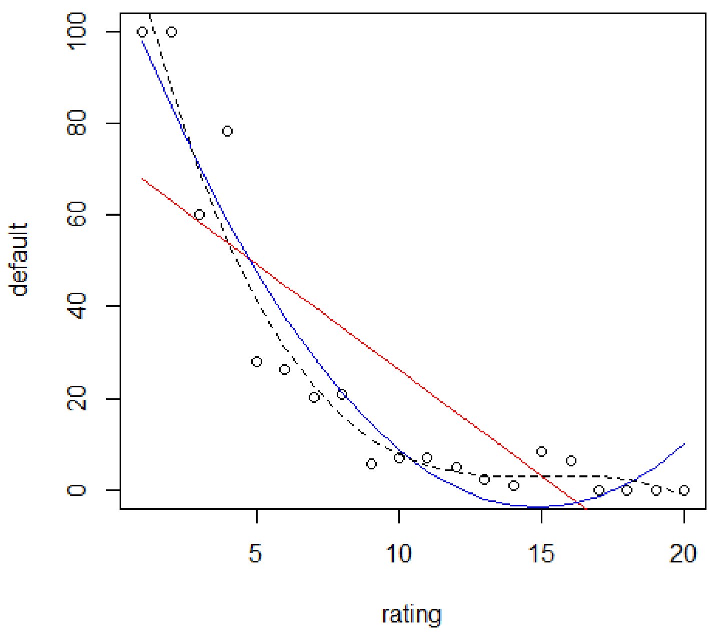
This approach is a simplification, as more sophisticated models of the effects of each type of disaster on GDP may be available. However, we believe this is justified for two reasons. First, in this step we are not interested in the effect of disasters on GDP, but rather the effect of the change in GDP on e.g. net general government debt. Our measure of the effect of climate on GDP comes directly from Kahn et al. (2021). Second, this approach provides practitioner evidence on the expected relationship between GDP losses and these macro indicators, keeping our approach as close as possible to real-world practice in CRAs. Finally, the approach enables us to continue to rely on the same direct links between climate science and climate economics that we use for adjusting GDP and its growth rate.

7.5. Probability of default

A transition table would follow the ratings changes off a static pool of ratings over the defined time horizon, say 10 years. For example, they look at all issues that were rated BBB on 1 January 1990. They then follow this static pool of BBB rated sovereigns to determine, which percentage has defaulted within the 10-year horizon. This exercise is repeated for every year, i.e. 1991, 1992, and so on. At the end they calculate the average of the percentage of defaulted issuers within the time horizon over all those static pools. This results in what is generally referred to as a BBB default probability. This default probability is not the ratio that rating agencies would deliberately target. Instead, it is the outcome of historical observations. Depending on the credit cycle, the percentage of defaulted sovereigns will vary between the different static pools. The BBB default probability is simply the average over longer time horizon. In the case of S&P, the average is calculated for the period 1975 to 2020. Ideally, the default probability would increase as the rating of different static pools declines. Given the relatively small universe of default observations for sovereigns, there are discreet jumps, however. This means that, against expectations, the probability of default could drop if we move down one notch. For classes with much larger number of issuers, such as corporates, such kinks are uncommon.

To correct for such outliers along the rating scale, we complete a best fit interpolation to create a monotonically rising probability of default as we move down the rating scale. Figure A.3. shows the rating on the x-axis and the default probability on the y-axis. The red, blue and dotted black line represent a linear, 2nd order and 3rd order polynomials, respectively. The third order provides the best fit and adding further terms does not provide a statistically significant 'better' fit. The equation representing the third order polynomial interpolation is then applied to assign smoothed (or 'unkinked') default probabilities to each rating level. It is important to understand that the change of the probability of default does not relate to the rating in a linear fashion. The probability of default increases exponentially as we move down the rating scale, and especially so once we cross into speculative grade ratings, i.e., ratings in the BB category or below. With this smooth default probability curve, we can then convert rating changes into changes of default probability at every rung of the rating ladder.

Figure A.4: Relationship between probability of default and ratings



7.6. Converting S&P's alphabetical scale to 20-notch numerical scale

Table A.1: Rating scale

Long-term foreign currency issuer rating symbol	**Numerical rating**	**Rating grade**	
S&P			
AAA	20	Prime high grade	Investment grade
AA+	19	High grade	
AA	18		
AA-	17		
A+	16	Upper medium grade	
A	15		
A-	14		
BBB+	13	Lower medium grade	
BBB	12		
BBB-	11		
BB+	10	Speculative	Non-investment grade
BB	9		
BB-	8		
B+	7	Highly speculative	
B	6		
B-	5		
CCC+	4	Substantial risks	
CCC	3		
CCC-	2		
CC	1	Extremely speculative	
C	1		
D/SD	1	In default	

Notes: This table presents S&P alphabetical categories translated into 20-notch scale based on S&P's Global Rating Definitions available from: https://www.standardandpoors.com/en_US/web/guest/article/-/view/sourceId/504352

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