Climate Change, Adaptation, and Sovereign Risk

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October 2025

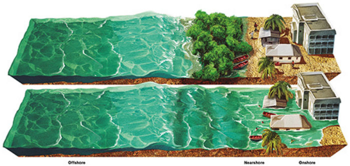
Motivation: Adaptation and Sovereign Risk

Climate change is projected to increase the frequency and severity of natural disasters

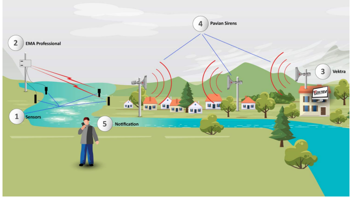
- Climate Policy attention turning towards adaptation: adjusting to this ‘new normal’
- Adaptation can limit damages, but it is costly

Cyclone Adaptation

Grey Infrastructure: Sea Wall



Green Infrastructure: Mangroves



Early Warning Systems

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- Climate change likely to increase borrowing costs further: climate defaults?
- Calls for ‘debt relief for climate resilience’

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This paper:

1. How does sovereign risk affect the adaptation motive?
2. Could debt relief help?

Takeaways

- Analytical Model: Sovereign default + natural disasters, endogenous adaptation
  - Default risk constrains adaptation of emerging markets: Adaptation Trap

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  - Adaptation increasing in exposure + ratings (1 SD $\rightarrow$ \$250m)
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  - Hurricane causes default prob $\uparrow$, driven by low adaptation economies

- Quantitative Model: long term debt, adaptation capital
  - Counterfactual: no default option
  - Adaptation investment / GDP in Caribbean is 13% lower
  - GDP effects of hurricanes are 10% higher - increases with climate change
  - Debt relief can help: interest free loan, adaptation linked bond

Relation to the Literature

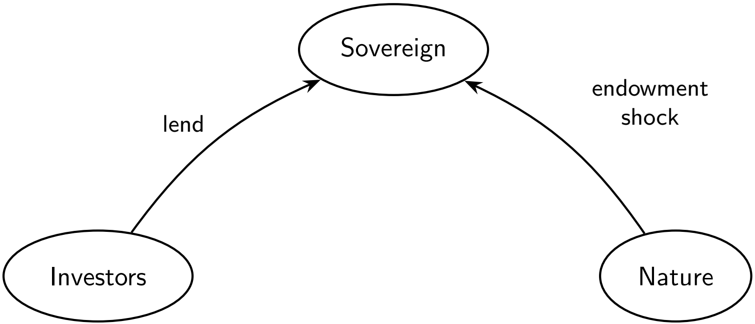
- Climate Change and Sovereign Risk
  - Change exacerbates fiscal vulnerabilities (Mallucci, 2022; Phan + Schwartzmann, 2023)
  - Contribution: Endogenous Adaptation
- Climate Change and Adaptation
  - Hong et al, 2023; Fried, 2021; Lane, 2024
  - Latent approach: (e.g. Burke et al, 2024). Direct: (e.g. Balboni et al, 2025; Grover and Kahn 2024)
  - Contribution: Default risk affecting aggregate adaptation
  - Contribution: Direct measure of aggregate adaptation
- Disaster Risk
  - Matters for asset prices and dynamics (e.g. Barro 2009, Gourio 2012)
  - Contribution: Additional feedback: protective capital

Outline

1. Simple Model
   - Analytical Results: spreads, climate change, and adaptation
2. Data
   - A new measure of adaptation
   - Validating the model
3. Quantitative Model
   - Calibration using adaptation measure
   - Quantitative Results: the adaptation trap
   - Debt Relief Counterfactuals

A Model of Sovereign Default

Objective: max U
choices: default, borrowing



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

$s = \Pr(\text{default}_{t+1})$

Sovereign Risk and Climate Risk

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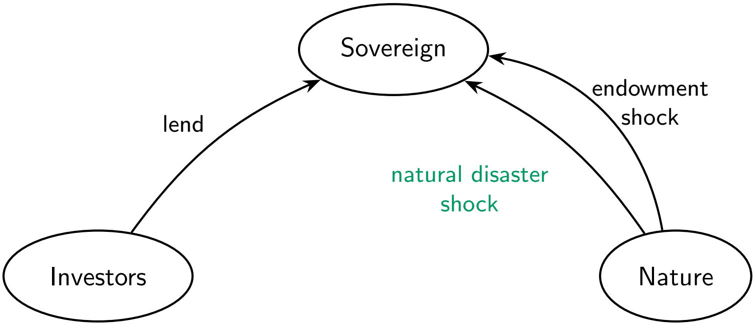

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Model

$$y_t = y_{t-1}^{\rho}(1 - \underbrace{x_t}_{\text{disaster indicator}} \underbrace{d_t}_{\text{disaster intensity}} F(\lambda_{t-1}))\epsilon_t$$

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

where $d_t \overset{iid}{\sim} F_d(d)$, $log(\epsilon_t) \overset{iid}{\sim} N(\mu_\epsilon, \sigma_\epsilon^2)$

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Sovereign maximizes utility:

$$U = ln(C_1) + \beta \mathbb{E} ln(C_2)$$

$$C_1 = y_1 + qB - \overset{\text{adaptation investment}}{\boxed{\lambda_1}}$$

$$C_2 = \begin{cases} y_2 - B & \text{if } D_2 = 0 \\ y_2 - \phi(y_2) & \text{if } D_2 = 1 \end{cases}$$

Model: Default

Sovereign chooses to default if: $B > \phi(y_2)$.

Assume simple procyclical default costs (Aguiar et al)

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

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Assume simple procyclical default costs (Aguiar et al)

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

Therefore, default if the disaster adjusted growth rate is below an endogenous default threshold:

$$\underbrace{g + \frac{1}{1+\psi} \ln(1 - x_2 d_2 F(\lambda_1))}_{\tilde{g}} < \underbrace{\frac{1}{1+\psi} \ln\left(\frac{B}{\bar{l} y_1^{\rho}}\right)}_{\bar{g}(B)}$$

Spread

Continuum of risk neutral investors implies:

$$q = \frac{1-s}{1+r} \qquad\qquad s = \mathbb{P}(D_2 = 1) = \mathbb{P}(\tilde{g} < \bar{g}(B))$$

Analytical characterization:

$$s(B,\lambda) = (1-p)\Phi_g(\bar{g}) + pE_{d'}\left[\Phi_g\left(\bar{g} - \frac{1}{1+\psi} ln(1 - d_2 F(\Lambda_2))\right)\right]$$

Climate Change, Adaptation, and the Spread

Proposition 1: The Spread is Increasing in Climate Change

$$\frac{\partial s}{\partial p} > 0 \qquad \hat{\Phi}_d \overset{\text{fosd}}{\geq} \bar{\Phi}_d \Rightarrow s(\cdot, \cdot | \hat{\Phi}_d) \geq s(\cdot, \cdot | \bar{\Phi}_d)$$

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Proposition 2: Spread decreasing in adaptation

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

Adaptation with Sovereign Risk

The optimal choice of adaptation trades off benefits and costs

- Counterfactual: no default option $\rightarrow$ MC $=$ MB damage reduction
- Now, additional effect through the spread

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FOC(λ):

$$\underbrace{\frac{1}{\boxed{C_1}}}_{\text{MC}} = \underbrace{\beta\mathbb{E}\left(\frac{y_2'(\lambda)}{C_R} - s(\lambda)\frac{y_2'(\lambda)B}{y_2 C_R}\right)}_{\text{MB damage reduction}} + \underbrace{\beta\mathbb{E}\left(s'(\lambda)(u(C_D) - u(C_R)\right)}_{\text{MB reduced default prob}} \underbrace{-\frac{\frac{1}{1+r}s'(\lambda)B}{C_1}}_{\text{MB lower spread}}$$

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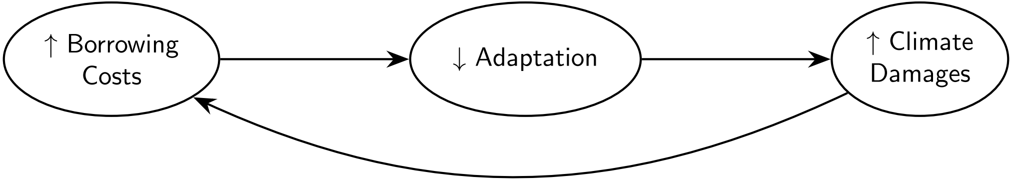
$\lambda^* \gtrless \lambda_c^*$ depends on the relative strength of these channels

For emerging markets: $\lambda^* < \lambda_c^*$

numerical intensive

Adaptation Trap



Roadmap

1. Simple Model
   - Analytical Results: spreads, climate change, and adaptation
2. **Data**
   - A new measure of adaptation
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   - Quantitative Results: the adaptation trap
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Measuring Adaptation

No data on aggregate adaptation across countries

Macro literature: latent variable approach. Infer adaptation if (conditional on disaster size):

- High hazard exposure $\rightarrow$ lower damages
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Adaptation is inferred, not observed

- Don't know what actions are taking place
- Panel variation and low power $\rightarrow$ can't compare across countries

Here: direct measure utilising data from government budgets

- Rich source of information on spending by purpose.
- Generate a dollar amount spent.

Measuring Adaptation: Keyword Discovery

Approach: transfer learning

1. Supply list of initial keywords unambiguously describing adaptation ▸ keywords
2. Build auxiliary corpus of adaptation related text ▸ sources
3. Construct word embeddings in that corpus ▸ word embeddings
4. Identify terms with high semantic similarity to at least one of the initial keywords ▸ example
5. Search for instances of the final set of keywords in budgets and record monetary value

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Sample: Rated economies in Latin America and the Caribbean with

- English or Spanish budgets
- Machine readable budgets

▸ sample

Measuring Adaptation

Spend on average **0.31%** (1.1%) of GDP (Total expenditure) on adaptation.

	N	Mean	St. Dev.	Min	Max
Adaptation Total / GDP	163	0.31%	0.0031	0.001	0.0187
Adaptation Total / Expenditure	163	1.1%	0.0100	0.0038	0.0538

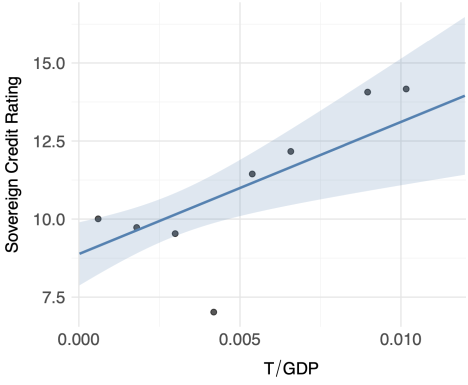
Table: Panel of 19 Latin American and Caribbean countries 2014-2025.

Adaptation Expenditure is:

1. Increasing in disaster exposure exposure
2. Trending upwards over time trend

Possible to disaggregate measure by action disaggregate line items

Adaptation Expenditure is Increasing in Rating



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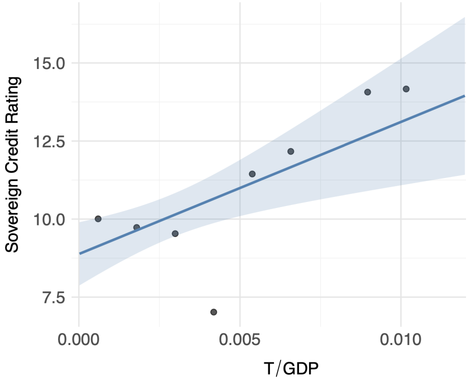

	adapt	
sovrate	67,554,921***	30,964,525***
	(16,647,312)	(9,241,031)
gdp	0.0022***	0.0069***
	(0.0002)	(0.0018)
exposure	143,757,032**	
	(62,519,154)	
government effectiveness	121,350,937**	
	(48,299,257)	
Country Fixed Effects	No	Yes
Year Fixed Effects	Yes	Yes
Observations	98	105
R-squared	0.95	0.84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

▸ data ▸ robustness

Cyclones and Sovereign Risk

Data:

- International Best Track Archive: hurricane location at 6-hourly intervals
- Map to country units:
- $D_{it} = 1$ if country i experiences at least category 1 hurricane in month (year) t
- Credit Default Swap spreads (36 countries)
- Default indicators (80 countries)

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

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Contribution:

- Physical disaster data rather than EMDAT (selection bias)
- Combine with adaptation data

Cyclones cause sovereign risk to increase ...

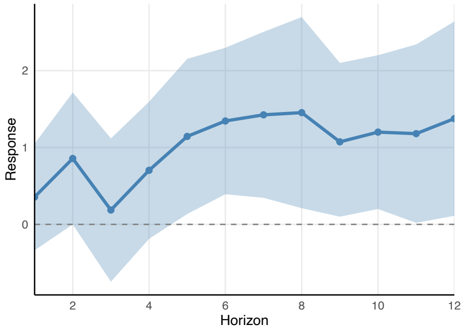

Figure: Impulse Response Function of CDS spreads to a cyclone shock over a horizon of twelve months. 90% confidence bands are shaded in blue.

… mostly for low adaptation economies

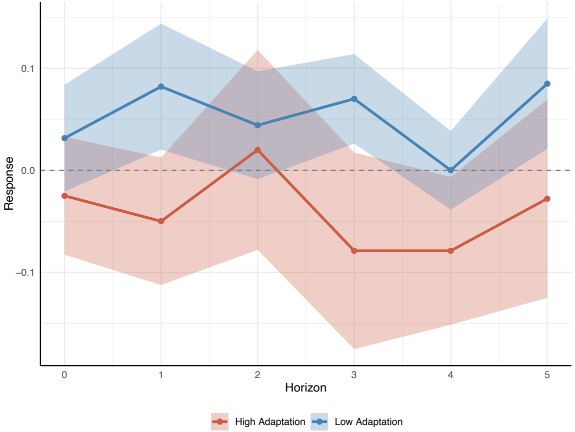

Figure: IRF of Sovereign Crisis dummy to a cyclone shock. 90% confidence bands are shaded.

Taking Stock

1. Governments invest in adaptation
2. The level of adaptation is increasing in exposure
3. The level of adaptation is declining in sovereign risk
4. Cyclones increase sovereign risk, attenuated by adaptation

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How quantitatively important is this sovereign risk - adaptation channel?

- What does it mean for the welfare effects of disasters? and climate change?
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Infinite horizon extension of model

- Long term debt, adaptation capital

Quantitative Model

Law of motion for adaptation:

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

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Bond issued at t promises an infinite stream of coupons, which decreases at a constant rate ψ.

Resource constraint:

$$C_t = \begin{cases} y_t + q_t(b_{t+1} - (1-\psi)b_t) - b_t - \lambda_t & \text{if } D_t = 0 \\ y_t - \phi(y_t) - \lambda_t & \text{if } D_t = 1 \end{cases}$$

Regain access w.p. η.

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Bond price:

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

Functional Forms

Quadratic costs of default:

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

CRRA utility:

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

Adaptation benefits:

$$F(\Lambda_t) = exp\left(-\alpha \Lambda_t^{1/\alpha}\right).$$

Calibration Strategy: Population Weighted Caribbean

1. Standard parameters: η, γ, δ

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2. Calibrated externally from data: r, ψ, p, ρ, μ_ϵ, σ_ϵ, σ_d
   - Estimate:
   $$\log(y_t) = \rho \log(y_{t-1}) - \xi x_t + \varepsilon_t$$
   - Model counterpart:
   $$\xi_t = F(\Lambda_t) d_t$$

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3. Jointly calibrated to target moments:
   - μ_d: mean GDP loss from disaster, ξ
   - α: adaptation investment to GDP ratio
   - β: debt to GDP ratio
   - d_0: mean spread
   - d_1: std dev spread

▸ calibration

Model Performance

	Model	Data
Targeted		
Adaptation Investment/GDP	0.003	0.003
Debt/GDP	0.401	0.414
GDP loss | Cyclone	0.052	0.050
Mean Spread	502	526
Std. dev Spread	352	374
Untargeted		
Default Frequency	0.048	0.051
Median Spread	121	143
Spread Increase | Cyclone	0.015	0.01
Adaptation Capital/GDP	0.029	
Percent Damages Avoided	0.45	
Market Value Debt/GDP	0.37	
Welfare Loss		
	5.1%	

Sovereign Risk Restricts Adaptation

Simulated Moments: Caribbean		
Moment	Model	No Default Counterfactual
Adaptation Investment/GDP	0.003	$+13\%$
GDP loss per Hurricane	0.05	-10%
Welfare loss from Hurricanes	5.1%	4.62%

- GDP loss from a hurricane is 10% larger due to the sovereign risk- adaptation channel
- This gap increases to 13% with a projected increase in frequency and severity by end of century
  - 29.1% increase in p, 48.5% increase in μ_d

Sovereign Risk Restricts Adaptation

Split sample: high and low sovereign risk

- Re-calibrate debt parameters: β, d_0, d_1
- Keep climate and adaptation parameters

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	Low Risk		High Risk	
	Model	Data	Model	Data
Adaptation Investment/GDP	0.38%	0.39%	0.29%	0.27%
Debt/GDP	0.49	0.51	0.37	0.38
Mean Spread	460	442	573	559

Model accounts for differences in adaptation expenditure across economies with differing sovereign risk.

Policy Counterfactual: Interest Free Loan

IMF Resilience and Sustainability Trust:

- New lending facility established 2022
- Long term funding for climate (and pandemic) preparedness

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Consider loan 10% of pre-loan output, 3 year grace period

- Default free due to seniority $\rightarrow$ at risk free rate

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

Policy Counterfactual: Interest Free Loan

Simulated Moments: Caribbean			
Moment	Baseline	No Default	Loan Counterfactual
Adaptation Investment/GDP	0.003	$+13\%$	$+5\%$
GDP loss per Hurricane	0.05	-10%	-4%
Welfare loss from Hurricanes	5.1%	4.62%	4.87%

Policy Counterfactual: Adaptation Bond

Increase in prevalence of ‘green bonds’

- Mostly corporate, and ‘use of proceeds’
- Now some mitigation outcome-linked bonds e.g. Chile

Policy Counterfactual: Adaptation Bond

Increase in prevalence of 'green bonds'

- Mostly corporate, and 'use of proceeds'
- Now some mitigation outcome-linked bonds e.g. Chile

Here consider an 'Adaptation Bond'

- c% coupon reduction if adaptation capital 5% larger

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

Policy Counterfactual: Adaptation Bond

Two countervailing effects on s:

1. $\downarrow$ Default risk $\rightarrow$ s $\downarrow$
2. State contingency $\rightarrow$ lenders require a premium

Spread minimizing $c = 2.2\%$

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Simulated Moments: Caribbean			
Moment	Baseline	No Default	Bond Counterfactual
Adaptation Investment/GDP	0.003	$+13\%$	$+10\%$
GDP loss per Hurricane	0.05	-10%	-8%
Welfare loss from Hurricanes	5.1%	4.62%	4.70%

Conclusion

Sovereign Risk restricts adaptation and increases the costs of disasters

- Theory: Framework integrating sovereign risk, climate risk, and adaptation
    - Adaptation Trap
- Data: New dataset of adaptation expenditures
    - Robust negative correlation between sovereign risk and adaptation
    - Adaptation attenuates sovereign risk effects of disasters
- Quantitative: Quantitative model matches Caribbean data
    - Hurricanes have a 10% larger effect through restricted adaptation
    - This wedge grows with climate change
    - Debt relief can help: adaptation bond, interest free loan

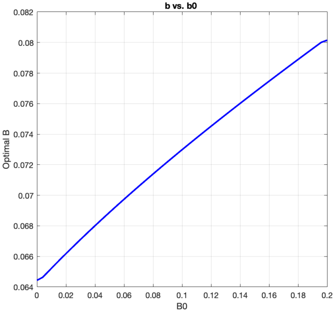
Adaptation Trap

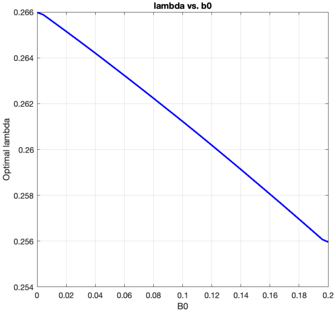
	$p = 0.1$, $\alpha = 2$	$p = 0.1$, $\alpha = 1.1$	$p = 0.5$, $\alpha = 2$	$p = 0.5$, $\alpha = 1.1$
$\bar{l}$ min	NA	0.91	NA	0.87
implied s (bps)	NA	21	NA	28

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

back

Sovereign Risk and Adaptation





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Initial Keywords

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

Adaptation Text: Sources

Adaptation specific text comes from a number of sources:

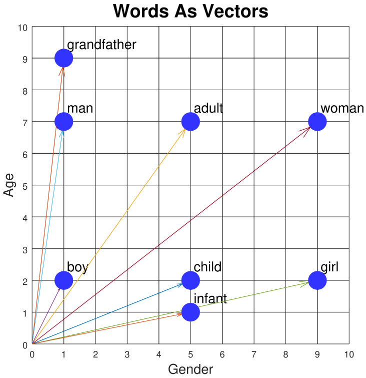
- Adaptation sections of Nationally Determined Contributions, as submitted to the UN
- National Adaptation Plans, as submitted to the UN
- UNEP Adaptation Gap Reports
- UNFCCC Adaptation related reports
- Adaptation Communications, as submitted to the UN
- Country Climate and Development Reports, from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

▸ back

Word Embeddings

Word embedding: real-valued vector representation of a word

- Words closer in the vector space are expected to be similar in meaning
- Use GloVe model from Stanford NLP group trained on my adaptation corpus



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Word Embeddings

Map co-occurrences of words into a meaningful space

Context of a term$w_{d,n}$ in a vocabulary V:

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

Co-occurrences are defined by a VxV matrix

- Entry $W_{i,j}$ is the number of times that term i appears within the context of j, and vice versa.
- Standard: $L = 10$, $K = 200$.

Each term is associated with a vector $\boldsymbol{\rho}_v$ in $\mathbb{R}^K$, chosen to solve:

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

$f(\cdot)$ is a non-negative, increasing, and concave weighting function.

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Keyword Discovery

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

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Sample

- Latin America: 18 sovereigns. Caribbean: 13 sovereigns
- Lose 2 due to language
  - Haiti, Brazil
- Lose 3 due to lack of rating
  - Saint Lucia, Antigua + Barbuda, Dominica
- Lose 7 due to lack of machine readability
  - Trinidad and Tobago, Cuba, Bolivia, El Salvador, Nicaragua, Paraguay, Venezuela
- Lose 74 country-year observations due to lack of availability

Final sample: Unbalanced panel of 19 economies 2014-2025

- 163 country-year observations

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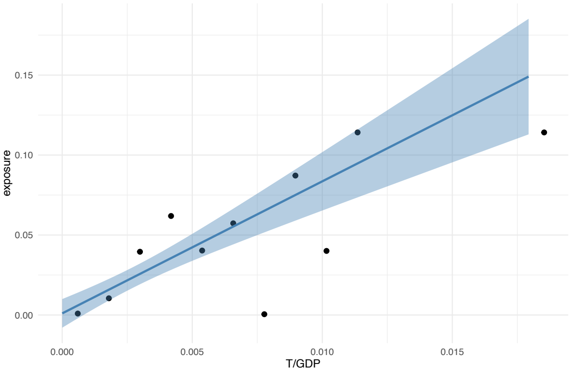
Exposure



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Exposure

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

Table: Regression Results: Adaptation and Climate Hazards

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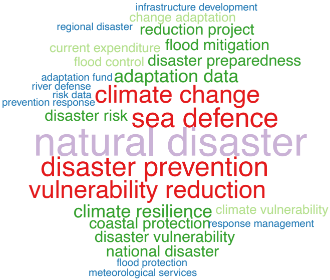
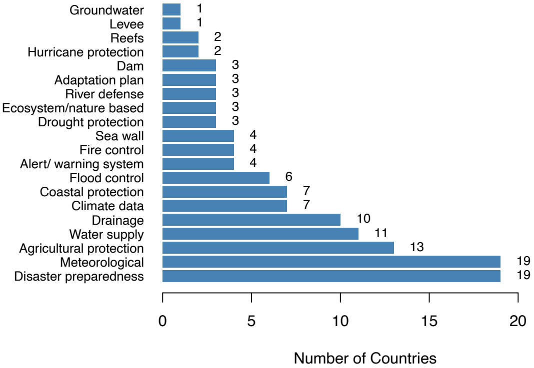
Adaptation Measure: Disaggregated





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Adaptation Measure: Map

Line Items: Descriptive Statistics

	N	Mean	St. Dev.	Min	Max
Line Items (country x year)	163	17.7	23.3	3	126
Line Items (country average)	19	20.33	23.4	4.9	75.4

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

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Expenditure Comparisons

	Mean
Adaptation/GDP	0.31%
Agriculture/GDP	1.3%
Health/GDP	3.4%

Table: Source: ELAC

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Official Debt: Share of Total

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

Table: Share of Official Debt in Total Public Debt (2018)

Data

1. sovrate:
   - Index from 0-21
   - From World Bank
2. exposure:
   - wind speed (maximum yearly), scaled by land area
   - From GeoMet database (Felbermayr and Gröschl)
3. government effectiveness:
   - World Bank Index
   - captures "perceptions of the quality of public services, the quality of the civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies."
   - Sources include: institutional effectiveness from the Economist Intelligence Unit, likelihood of infrastructure disruption, state failure or political instability from S&P Global, and quality of financial and revenue management.

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Robustness

- Narrower measures of adaptation:
  - disaster preparedness ▸ dp
  - meteorological services ▸ m
- EMBI ▸ embi
- CDS ▸ cds
- Alternative exposure measures ▸ exposure
- Regulatory Quality ▸ rq
- Narrative evidence
- Validation with hand read budgets
- English and Spanish subsamples
- Drop 10% of sample
- Stricter word embedding cutoffs

▸ back

Disaster Preparedness

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

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

Table: Regression Results: Disaster Preparedness and Sovereign Rating

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Meteorological

	Meteorological Services	
sovrate	268,014,394***	786,490,187***
	(103,115,274)	(81,603,371)
gdp	0.0061	0.0010**
	(0.0040)	(0.00046)
exposure	129,812,401**	
	(64,190,146)	
government effectiveness	715,689,368***	
	(18,416,559)	
Country Fixed Effects	No	Yes
Year Fixed Effects	Yes	Yes
Observations	98	105
R-squared	0.95	0.84

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

Table: Regression Results: Meteorological Services Expenditure and Sovereign Rating

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EMBI

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

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

Table: Regression Results. EMBI spreads and adaptation services expenditure.

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CDS

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

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

Table: Regression Results. CDS spreads and adaptation services expenditure.

▸ back

Regulatory Quality

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

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Exposure

	adapt			
sovrate	67,554,921***	41,286,883***	38,411,248***	44,220,882***
	(16,647,312)	(9,241,031)	(14,524,916)	(11,551,834)
gdp	0.0022***	0.001***	0.001***	0.001***
	(0.0002)	(0.0001)	(0.0001)	(0.0001)
windspeed	143,757,032**			
	(62,519,154)			
natural		81,436,087*		
		(44,013,869)		
cyclone			37,428,812	
			(45,306,999)	
drought				27,727,914
				(43,063,322)
government	121,350,937**	21,131,829	50,668,145	42,115,495

Model

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

Law of motion for adaptation:

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

Model

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

Law of motion for adaptation:

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

Bond issued at t promises an infinite stream of coupons, which decreases at a constant rate ψ.

Resource constraint:

$$C_t = \begin{cases} y_t + q_t(b_{t+1} - (1 - \psi)b_t) - b_t - f(\lambda_t) & \text{if } D_t = 0 \\ \phi(y_t)y_t - f(\lambda_t) & \text{if } D_t = 1, \end{cases}$$

where $\phi(y_t)$ is the endowment cost of default. Regain access w.p. η. Bond price:

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

▸ recursive equilibrium

▸ back

Recursive Equilibrium

Restrict attention to Markov Perfect Equilibria.
Equilibrium defined by:

1) a set of value functions for the representative household: total value V, the value with market access V_{nd}, and the value in default V_d:

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

$$V_{nd}(y, b, \Lambda) = \max_{b', \Lambda'} u(c) + \beta \mathbb{E}[V(y', b', \Lambda')], \tag{2}$$

$$V_d(y, 0, \Lambda) = \max_{\Lambda'} u(c) + \beta \mathbb{E}[(1-\eta)V_d(y', 0, \Lambda') + \eta V(y', b', \Lambda')], \tag{3}$$

2) government policies for default D, bond issuance b, and adaptation Λ, and

3) a government debt price function q such that:

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

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Solution Algorithm

Discretize output, debt, adaptation.

Iterative algorithm:

1. Initial guesses for the unconditional debt price function and for the value functions
2. Update the value function V_{nd} by solving the maximization problem in the market access case
   - Each possible choice of debt and adaptation is associated with an additive taste shock.
   - The sovereign chooses b' conditional on having chosen a particular Λ' subject to taste shocks, and that Λ' is chosen subject to taste shocks for a fixed b'.
   - Probability of choosing a given discrete value is given by the multinomial logit formula.
3. Update the value function V by solving the discrete choice default problem.
   - Introduce extreme value shocks to the default problem.
4. Update the default value function V_d making use of the update values of V and V_{nd}.
5. Repeat (2-4) until value functions have converged.
6. Update the unconditional debt price function by imposing the default policy and the average equilibrium price function.
7. Repeat (2-6) until convergence of the unconditional debt price function.

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Calibration

Parameter		Value	Source/Target statistic
Parameters set Externally:			
Relative risk aversion	γ	2	Standard
Readmission probability	η	0.33	Richmond + Dias
Depreciation	δ	0.1	Standard
Parameters Estimated Externally:			
Risk free rate	r	0.0451	US T-Bill
Duration	ψ	0.0564	Average Maturity
Hurricane Frequency	p	0.103	NOAA
Endowment autocorr	ρ	0.95	Data
Endowment st dev	σ_ϵ	0.021	Data
Disaster st dev	σ_d	0.031	Data
Parameters Set Internally:			
Discount factor	β	0.92	Debt/GDP
Default cost	d_0	0.621	Mean Spread
Default cost	d_1	0.978	Std. dev Spread
Hurricane intensity	μ_d	0.096	Mean hurricane loss
Adaptation benefit	α	2.496	Adaptation investment/ GDP

Table: Calibrated Parameters: Caribbean.

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Calibration: Jamaica

Calibrated Parameters: Jamaica			
Moment		Value	Source/Target statistic
Relative risk aversion	γ	2	Standard
Readmission probability	λ	0.33	Richmond and Dias (2009)
Depreciation	δ	0.1	Standard
Risk free rate	r^{rf}	0.0451	US T-Bill
Duration	ψ	0.0564	Average Maturity
Hurricane Frequency	p	0.103	NOAA
Endowment autocorr	ρ	0.96	Data
Endowment st dev	σ_ϵ	0.026	Data
Discount factor	β	0.89	Debt/GDP
Output cost	κ	0.67	Mean Spread
Hurricane intensity	μ_d	0.025	Mean hurricane loss
Adaptation cost	α	2.1	Adaptation investment/ GDP

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Model Performance

Quantitative Analysis: Simulated Moments		
Moment	Model	Data
Average Spread	554	519
Debt/GDP	0.50	0.49
Default frequency	0.048	0.051
GDP loss per Cyclone	0.023	0.023
Adaptation Investment/GDP	0.0044	0.0044

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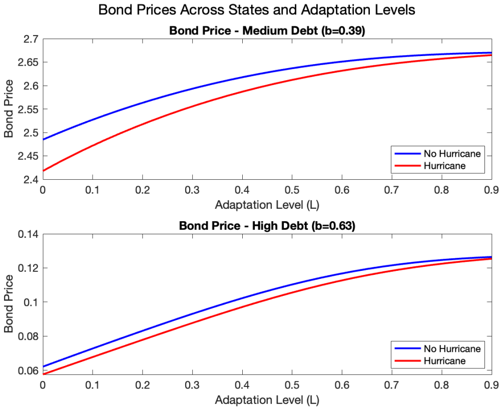
Bond Price



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