Climate Change, Adaptation, and Sovereign Risk

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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'
- E.g. seawalls, reefs, early warning systems
- Adaptation can limit damages, but it is costly

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- e.g. Cyclone activity concentrated around tropics
- 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
  - Climate change increases spreads
  - Adaptation reduces spreads
  - Default risk constrains adaptation of emerging markets: Adaptation Trap

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- Data: Novel adaptation measure from government budgets
  - Adaptation increasing in exposure + ratings
- Data: Causal evidence on cyclones + sovereign risk
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- Quantitative Model: long term debt, adaptation capital
  - Counterfactual: perfect financial markets
  - Adaptation investment / GDP in Caribbean is 13% lower
  - GDP effects of hurricanes are 10% higher - increases with climate change
  - Debt relief can help

Relation to the Literature

Climate Change and Sovereign Risk

- Climate Change exacerbates fiscal vulnerabilities (Mallucci, 2022; Phan + Schwartzmann, 2023)

Contribution: Endogenous Adaptation

Climate Change and Adaptation

- Substantial welfare gains from adaptation in macro models (Hong et al, 2023; Fried, 2021)
- Access to finance matters for individual adaptation (e.g. Lane, 2024)

Contribution: Default risk affecting aggregate adaptation

Adaptation: Measurement

- Evidence of particular adaptation actions (e.g. Grover and Khan, 2024)
- Latent variable approach to macro-adaptation (e.g. Burke et al, 2024)

Contribution: Direct measure of aggregate adaptation

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

Model

disaster indicator

disaster intensity

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

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

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

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Sovereign maximizes utility:

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

adaptation investment

$$C_1 = y_1 + qB - \lambda$$

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

Model: Default

Sovereign chooses to default if $C_2(D_2 = 1) > C_2(D_2 = 0)$.

Assume simple procyclical default costs (Aguiar et al)

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

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Assume simple procyclical default costs (Aguiar et al)

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

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

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

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:

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

Climate Change, Adaptation, and the Spread

Proposition 1: The Spread is Increasing in Climate Change

$$\frac{\partial s}{\partial p} > 0$$

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

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Proposition 2: Spread decreasing in adaptation

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

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

Adaptation with Sovereign Risk

The optimal choice of adaptation trades off benefits and costs

- Counterfactual: commitment $\rightarrow$ MC $=$ MB damage reduction
- Now, additional effect through the spread

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FOC(λ):

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

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

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

Roadmap

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

Measuring Adaptation

No data on aggregate adaptation across countries

Macro literature uses a latent variable approach. Infer adaptation if:

- High hazard exposure $\rightarrow$ lower damages from a disaster of a give size
- Or, damages from a disaster of a given size are falling over time

Measuring Adaptation

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Adaptation is inferred, not observed

- Don't know what actions are taking place
- Panel variation and low power → can't compare adaptation across countries

Here: build a direct measure of adaptation expenditure utilising data from government budgets

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

Measuring Adaptation: Keyword Discovery

Which budget entries correspond to adaptation?

- Problem: 'niche language'

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

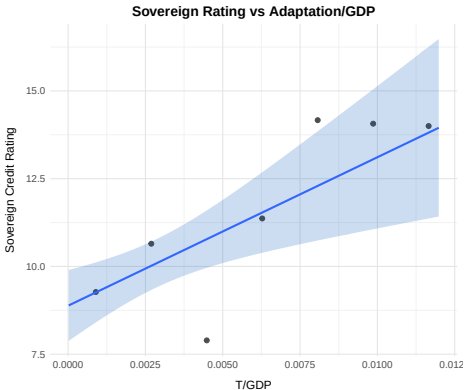
Table: Panel of 19 Latin American and Caribbean countries 2014-2025.

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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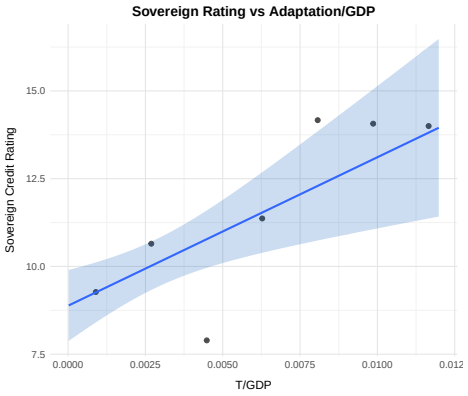

▸ data ▸ robustness

	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	

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 year t
- CDS spreads (36 countries)
- Default indicators (80 countries)

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Contribution:

- Previous empirical literature on disasters + sovereign risk uses EMDAT
- Disaster incidence data collated from news articles + insurance claims $\rightarrow$ selection bias
- Combine with adaptation data

Cyclones cause sovereign risk to increase ...

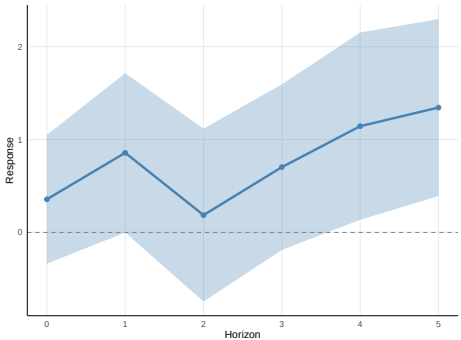

Figure: LP irf. Hurricane shock, CDS outcome.

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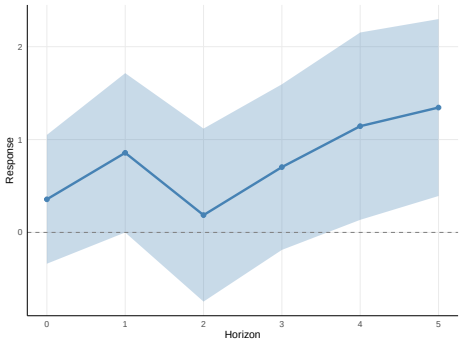

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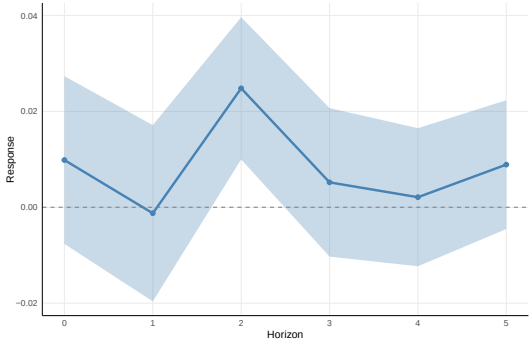

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... mostly for low adaptation economies

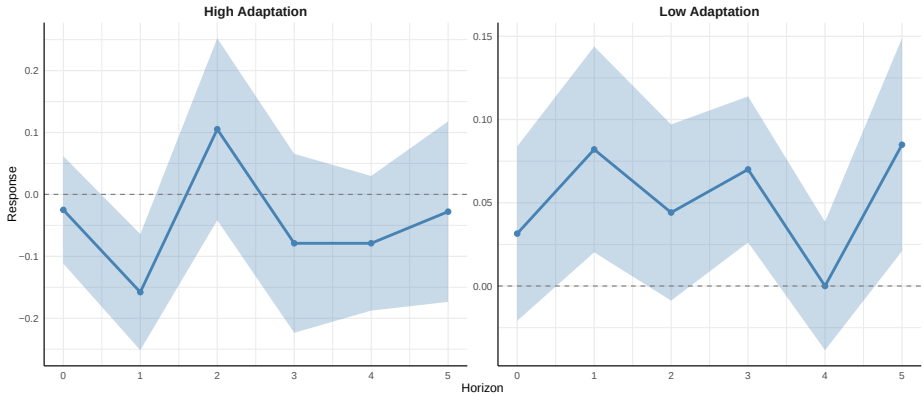

Figure: LP irfs. Hurricane shock, default indicator outcome. High adaptation: above median adaptation/GDP.

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?
- Could debt relief help?

Extend the two period model: infinite horizon ▸ details ▸ algorithm

- Long term debt
- Adaptation investment cumulates into capital
- Quadratic default costs
- Estimated to match moments ▸ details

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:

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

where $\phi(y_t)$ is the endowment cost of default. 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

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

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

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
Untargeted		
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	Commitment 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

Policy Counterfactual: Interest Free Loan

"Liquidity is not enough: these crises have systemic roots. Only investment will change their course... lending should prioritize building climate resilience in climate vulnerable countries."

- Bridgetown Initiative

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IMF Resilience and Sustainability Trust:

- New lending facility established 2022
- Earmarked to provide long term funding to increase capacity to address 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	Commitment	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'

- Use of proceeds bonds potentially pose a problem for governments: fungibility requirements
- Instead, outcome linked bonds
- E.g. Chile: bond linked to greenhouse gas reduction

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- Instead, outcome linked bonds
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Here consider an 'Adaptation Bond'

- 2.5% 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

Simulated Moments: Caribbean			
Moment	Baseline	Commitment	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%	4.71%

Conclusion

Sovereign Risk restricts adaptation and increases the costs of disasters

- Theory: Framework integrating sovereign risk, climate risk, and adaptation
  - Adaptation causes spreads to fall
  - Sovereign risk restricts adaptation
- 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 than they would have under commitment
  - This wedge grows with climate change
  - Debt relief can help: adaptation bond, interest free loan

Details

Assume:

- $T = 2$
- $\Lambda_1 = 0$, $y_1 = 1$
- log utility
- Simple pro-cyclical default costs: $\phi(y_t) = \left(1 - \overline{l} e^{\psi g}\right)$

Default if $C_2(D = 1) > C_2(D = 0)$, i.e. if:

$$\underbrace{g + \frac{1}{1+\psi} \ln(1 - x_t d_t (1 - \lambda_t))}_{\tilde{g}} < \underbrace{\frac{1}{1+\psi} \ln\left(\frac{B}{\overline{l} y_1^{\rho}}\right)}_{\bar{g}(B)}$$

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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

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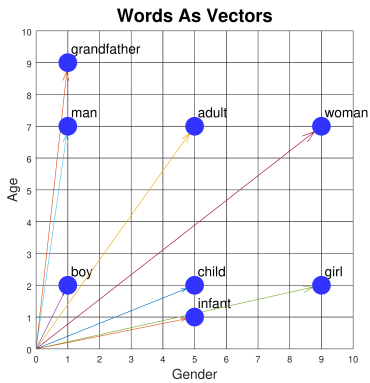
Word Embeddings

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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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

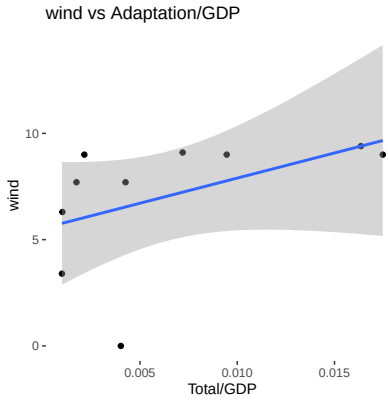
- Latin America: 18 sovereigns. Caribbean: 13 sovereigns
- Lose 2 due to language
  - Haiti, Brazil
- Lose 3 due to lack of rating
  - Saint Lucia, Antigua + Barbuda, Dominica
- Lose 7 due to lack of machine readability
  - Trinidad and Tobago, Cuba, Bolivia, El Salvador, Nicaragua, Paraguay, Venezuela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

Final sample: Unbalanced panel of 19 economies 2014-2025

- 163 country-year observations

▸ back

Exposure



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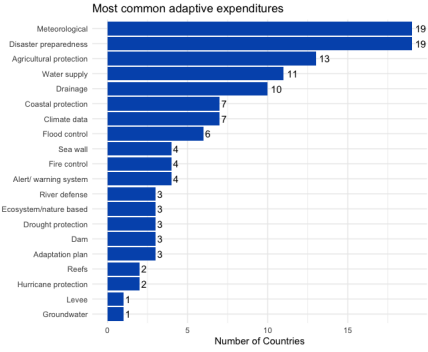
Adaptation Measure: Disaggregated

How are governments adapting?



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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:
   - climate vulnerability index from INFORM RISK
   - Constructed by the EU commission
3. regulatory quality:
   - World Bank Index

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Robustness

- Narrower measures of adaptation: disaster preparedness, meteorological services
- Validation with hand read budgets
- English and Spanish subsamples
- Drop 10% of sample
- Stricter word embedding cutoffs
- Instrument for ratings with a global factor

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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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Calibration Strategy

1. External parameters: η, γ, δ

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

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
   - κ: mean spread

▸ Jamaica ▸ model performance ▸ bond price

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: 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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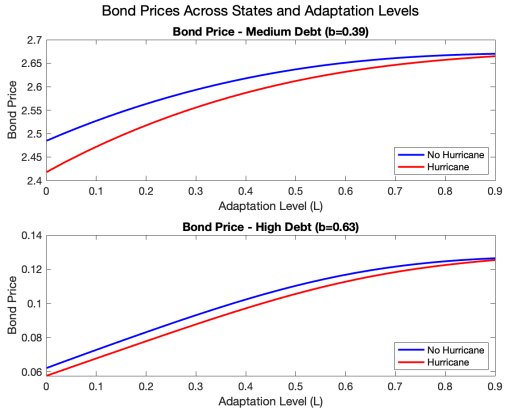
Bond Price



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