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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  - Adaptation increasing in exposure + ratings
- Data: Causal evidence on cyclones + sovereign risk
  - Hurricane causes CDS spreads $\uparrow$ 1% 6 months out

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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

$$y_t = y_{t-1}^{\rho}(1 - \overbrace{x_t}^{\text{disaster indicator}} \; \overbrace{\boxed{d_t}}^{\text{disaster intensity}} (1 - \lambda_{t-1}))\epsilon_t$$

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

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:

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

$$C_1 = y_1 + qB - \underbrace{\boxed{f(\lambda)}}_{\text{adaptation cost}} \qquad C_2 = \begin{cases} y_2 - B & \text{if } D_2 = 0 \\ \phi(y_2)y_2 & \text{if } D_2 = 1, \end{cases}$$

Model: Default

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

- i.e. default if disaster adjusted endowment below an endogenous default threshold ▸ Details

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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):

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

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

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

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 $\rightarrow$ 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
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

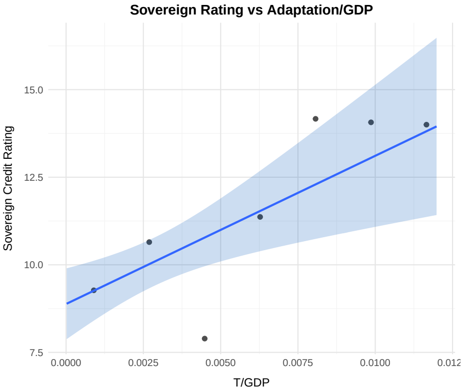
Table: Panel of 19 Latin American and Caribbean countries 2014-2025.

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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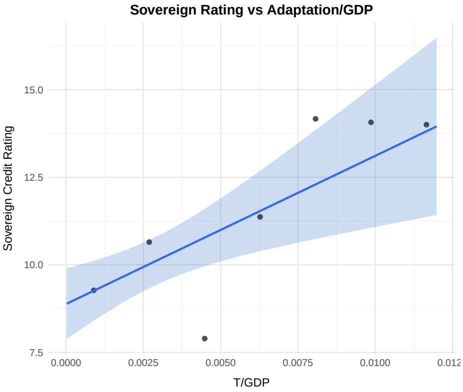

	adapt	
sovrate	67,554,921***	30,964,525***
	(16,647,312)	(9,241,031)
gdp	0.0022***	0.0069***
	(0.0002)	(0.0018)
exposure	143,757,032**	
	(62,519,154)	
government effectiveness	121,350,937**	
	(48,299,257)	
Country Fixed Effects	No	Yes
Year Fixed Effects	Yes	Yes
Observations	98	105
R-squared	0.95	0.84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

▸ data ▸ robustness

Simple Model and Empirical Evidence: Summary

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

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	5.02%	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

Policy Counterfactuals

1. Interest Free Loan
   - Motivated by IMF Resilience and Sustainability Trust
   - 10% of pre-loan output with a 3 year grace period: 5% increase in Λ/GDP
2. Adaptation Bond
   - Sustainability linked bonds:lower coupon payment if reach environmental target
   - Consider an *adaptation* linked bond
   - 2.5% coupon reduction if adaptation capital 5% larger
   - 13% increase in Λ/GDP
3. Debt for Adaptation swap

Conclusion

Sovereign Risk restricts adaptation and increases the costs of disasters

- Data: robust negative correlation between sovereign risk and adaptation
- Theory: Adaptation causes spreads to fall, but sovereign risk restricts adaptation
- Quantitative: In Caribbean, hurricanes have a 10% larger effect through restricted adaptation than they would have under commitment

Questions and comments very welcome!

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Details

Assume:

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

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

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

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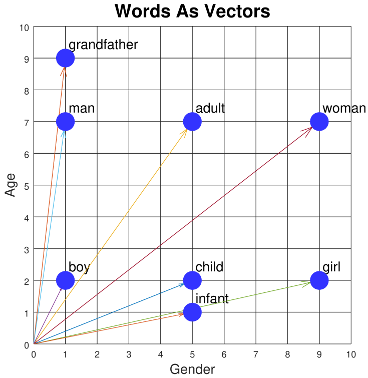
Initial Keywords

- 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

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

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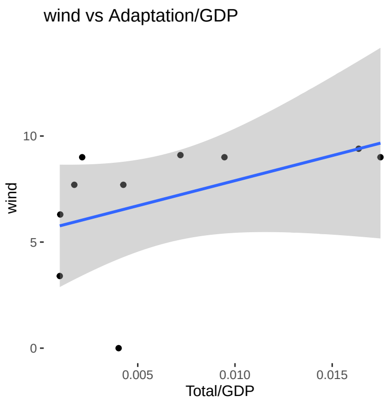
Exposure



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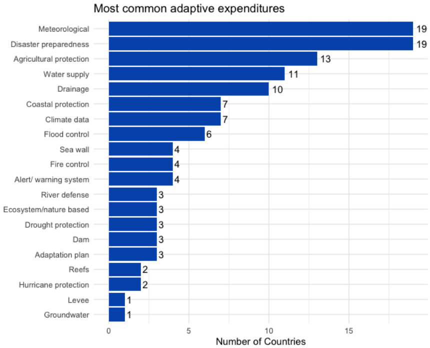
Adaptation Measure: Disaggregated

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

▸ back

Expenditure Comparisons

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

Table: Source: ELAC

▸ back

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

▸ back

Model

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

Law of motion for adaptation:

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

Model

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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:

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

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

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

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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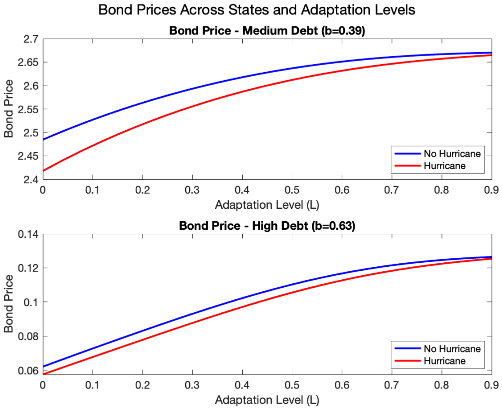
Bond Price



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