The Real Effects of Climate Volatility Shocks

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Motivation I

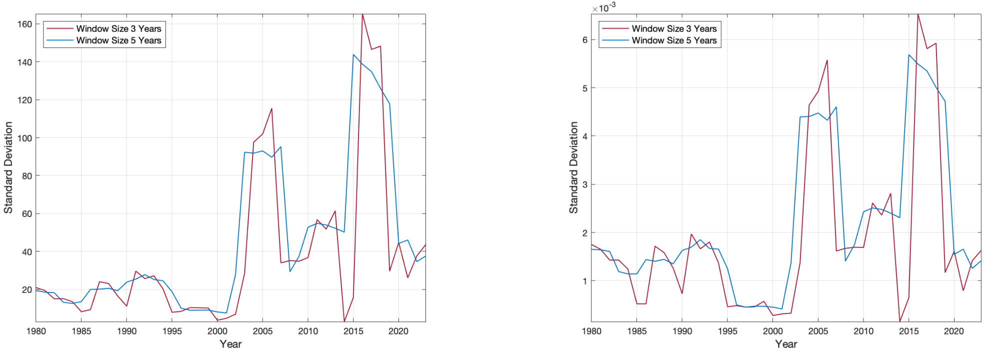
Table 1: Billion-Dollar Disaster Statistics

Period	Events	Avg Cost (% GDP)	Max Cost (% GDP)	Total Cost (% GDP)
1980-1989	33	0.05	0.48	0.17
1990-1999	57	0.04	0.36	0.21
2000-2009	67	0.05	0.99	0.31
2010-2019	131	0.03	0.69	0.42
2020-2023	88	0.02	0.45	0.51

Note: Source: NOAA National Centers for Environmental Information (2024).

- The frequency and costs of extreme events are rising, increasing uncertainty.

Motivation II



(a) CPI-Adjusted Cost.

(b) Cost over GDP.

Figure 1: Rolling window standard deviations of climate costs

- The costs of climate-related disaster events exhibit a time-varying volatility.

This paper

- Strong consensus on the impact of climate change on economic activity.
- In this paper, we quantify the real effects of the risk of climate damages.
- We do not take a stance on the source of damage volatility changes. This assumption builds on a large tradition that assumes volatility changes as exogenous to isolate its importance (Fernandez-Villaverde et al. (2011)).

The model

DSGE model with carbon cycle and climate shocks with stochastic volatility.

Extend Golosov et al. (2014): RBC with energy and climate risk.

The economy is populated by:

- Households,
- Final good producer,
- Energy firms producers: fossil and green energy.

Households

A representative household seeks to maximize:

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \frac{\left(C_t - \psi N_t^{\theta} X_t\right)^{1-\sigma} - 1}{1-\sigma}$$

where $X_t = C_t^{\eta} X_{t-1}^{1-\eta}$, subject to budget constraints,

$$C_t + I_t + B_{t+1} = r_t K_t + w_t N_t + (1 + r_{t-1}^b) B_t, \quad \forall t$$

and the law of motion of capital,

$$K_{t+1} = \left[1 - \frac{\Phi}{2}\left(\frac{I_t}{I_{t-1}} - 1\right)^2\right] I_t + (1-\delta) K_t, \quad \forall t.$$

Eq. conditions

Final good producer

$$\Pi_{0,t} \equiv \max_{K_{0,t},N_{0,t},\mathbf{E}_{0,t}} (1 - D_t)F_{0,t}(K_{0,t}, N_{0,t}, \mathbf{E}_{0,t}) - r_t K_{0,t} - w_t N_{0,t} - \sum_{i=1}^{I} p_{i,t}\mathbf{E}_{0,t}$$

Where:

- $F_{0,t}(K_{0,t}, N_{0,t}, \mathbf{E}_{0,t}) = A_{0,t}K_t^{\alpha}N_{0,t}^{(1-\alpha-\nu)}\mathbf{E_{0,t}}^{\nu}$
- $A_{0,t}$ follows an AR(1) process.
- $\mathbf{E}_{0,t} = \left(\kappa E_{g,t}^{\rho} + (1-\kappa)E_{f,t}^{\rho}\right)^{1/\rho}$
- D_t is a function of S_t: atmospheric carbon concentration

Eq. conditions

Carbon depreciation structure

$$S_t - \bar{S} = \sum_{s=0}^{t} (1 - d_s) \xi E_{f,t-s},$$

Where:

- $d_s \in [0, 1]$ for all s
- $\bar{S}$ is the pre-industrial atmospheric CO_2 concentration.

Carbon depreciation structure: $(1 - d_s) = \varphi_0 (1 - \varphi)^s$

- Then, S_t:

$$S_t - \bar{S} = \varphi_0 \xi E_{f,t} + (1 - \varphi)(S_{t-1} - \bar{S})$$

Damage function

Following Golosov et al. (2014), that approximates Nordhaus formulation of damage costs,

$$(1 - D_t(S_t)) = e^{-\gamma_t(S_t - \bar{S})}$$

- Suggestive evidence: damage costs are volatile and their volatility also varies over time.
  - γ_t and σ_t follow AR(1) processes:

$$\log(\gamma_t) = (1 - \rho_\gamma)\log(\bar{\gamma}) + \rho_\gamma \log(\gamma_{t-1}) + \exp{(\sigma_t^\gamma)}\epsilon_t^\gamma$$

$$\sigma_t^\gamma = (1 - \rho_\sigma)\bar{\sigma}^\gamma + \rho_\sigma \sigma_{t-1}^\gamma + \sigma_t^\sigma \epsilon_t^\sigma$$

Energy firms

- Two primary sectors:
  - Fossil
  - Green

- Each period, they hire labor to produce:

$$E_{i,t} = A_{i,t} N_{i,t} \quad \text{for i = f, g}$$

Where:

- $A_{i,t}$ is the exogenous productivity for each sector $i = f, g$;

- each $A_{i,t}$ follows independent AR(1) process.

Eq. conditions

Calibration

- Quarterly model - US economy: in the literature this has some limitations (some important factors are global).

- Data from 1980Q1 to 2023Q3.

- We calibrate the model to match the business cycle of the US economy together with the energy consumption and the evolution of the stock of carbon in the atmosphere.

- Use the production function to recover the Solow Residual,

$$SR_t = (1 - D_t)A_{0,t} = Y_t - K_t^{\alpha} N_{0,t}^{(1-\alpha-\nu)} \mathbf{E_{0,t}}^{\nu}. \tag{1}$$

  Prior: information about damage cost and the CO2 accumulation and the measurement of SR in the data can help us identify the different components.

Calibration

Table 2: Parametrization based on existing literature

Parameter	Value	Target/source
β	$0.985^{1/4}$	Nakov-Thomas (2023)
σ	2	Standard
ψ	1	Target avg. labor $= 1$
δ	0.0073	Target stock of capital
α	0.3	Standard
ν	0.057	EIA(2023)
ρ	0.65	Nakov-Thomas (2023)
κ	0.2571	Nakov-Thomas (2023)
$\bar{\gamma}$	0.000024	Golosov et al (2014)
$\bar{s}$	581	Golosov et al (2014)
ξ	0.879	Nakov-Thomas (2023)
$\bar{A}_0$	9.94	Target Solow residual

Calibration

Table 3: Calibrated coefficients

Parameter	Description	Value
ρ_{A_0}	Persistence of the TFP shock	0.94
σ_{A_0}	Volatility of the TFP shock	0.0022
ρ_γ	Persistence of the Damage elasticity	0.897
$\bar{\sigma}_\gamma$	Avg. volatility of the Damage elasticity	0.4
ρ_{σ_γ}	Persistence of volatility shocks	0.97
σ_{σ_γ}	Std dev of the volatility shock	0.42
$\bar{A}_f$	Avg. productivity of fossil energy production	45
ρ_{A_f}	Persistence of fossil energy productivity	0.91
σ_{A_f}	Volatility of fossil energy productivity	0.0075
$\bar{A}_g$	Avg. productivity of green energy production	169
ρ_{A_g}	Persistence of green energy productivity	0.97
σ_{A_g}	Volatility of green energy productivity	0.0121
ϕ	Carbon depreciation structure	0.0464
ϕ_0	Carbon depreciation structure	0.2963
Φ	Investment adjustment cost	3.5
θ	Inverse Frisch Elasticity	1.2
η	Preference parameter	0.0055

Calibration

Table 4: Targeted Moments

Moment	Data	Model
$\mathbb{E}(S)$	6.6	6.4
$\mathbb{E}(cost/Y)$	0.003	0.002
$\mathbb{E}(SR)$	2.3	2.3
$\sigma(Y)$	4.8	4.8
$\sigma(I)$	11.0	7.2
$\sigma(S)$	0.5	0.1
$\sigma(SR)$	2.0	1.6
$\sigma(N)$	5.2	4.9
$\sigma(E_0)$	5.6	5.5
$\sigma(E_f)$	6.6	6.6
$\sigma(E_g)$	12.4	12.4
$\sigma(cost/Y)$	0.6	1.5
$\rho(Y, N)$	86.9	95.0
$\rho(Y, SR)$	72.9	82.6
$\rho(Y, E_0)$	88.2	88.1
$\rho(SR, E_0)$	52.5	56.3
$\rho(SR, E_{0,-1})$	53.4	51.8
$\rho(E_0, N)$	83.0	92.2
$\rho(Y, Y_{-1})$	0.97	0.97
$\rho(E_f, E_{f,-1})$	0.93	0.92
$\rho(E_g, E_{g,-1})$	0.97	0.96

Note: Standard deviations and correlations in percent.

Generalized Impulse Responses

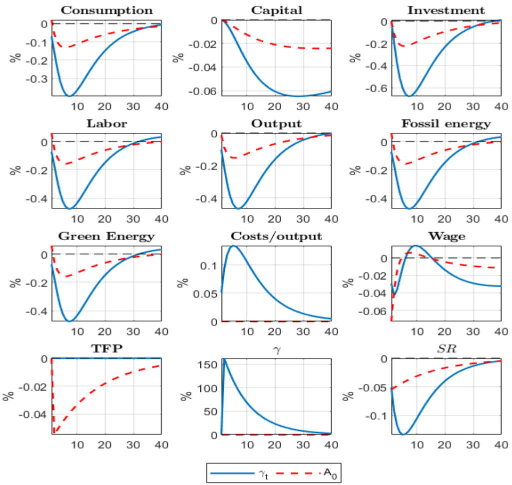


Figure 2: GIRFs to a one standard deviation shock to climate damage and TFP.

Note: Impulse response functions are presented in percent deviation from the steady state.

Generalized Impulse Responses

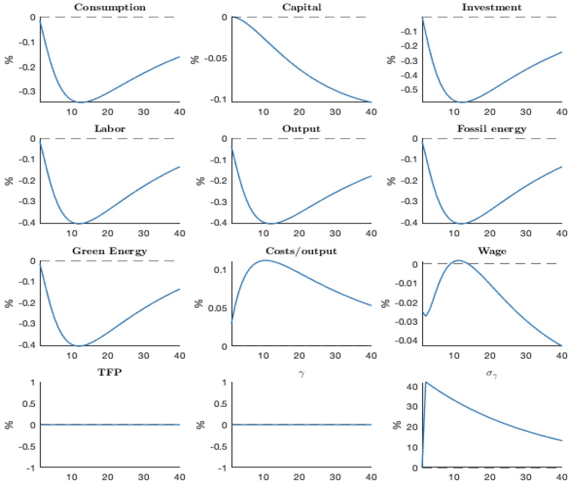


Figure 3: GIRFs to a one standard deviation shock to the volatility of climate damage.

Note: Impulse response functions are presented in percent deviation from the steady state.

Quantitative Analysis

- Comparing a 1 s.d. damage-cost shock (γ_t) to a TFP shock calibrated to match the same on-impact fall in the Solow residual.
- The damage shock yields larger, more persistent cycles and a hump-shaped Solow residual.
- A volatility ("risk") shock yields supply-side recession dynamics of similar magnitude but greater persistence than a level shock.

Welfare Comparison

$$E_0 \sum_{t=0}^{\infty} \beta^t U\left(C_t^w, N_t^w\right) = E_0 \sum_{t=0}^{\infty} \beta^t U\left((1-\lambda) C_t^{w/o}, N_t^{w/o}\right)$$

where:

- Superscript w: benchmark economy with climate volatility risk.
- Superscript w/o: economy (1) without climate costs and (2) climate costs without risks.
- λ: Permanent consumption loss.

- Households require a permanent consumption increase of:
  - $\boldsymbol{\lambda = 0.11\%}$: to remain in the economy with climate externality.
  - $\boldsymbol{\lambda = 0.09\%}$: to remain in the economy with climate volatility risk.

$\Rightarrow$ More than four times the costs of business cycle documented by Lucas (1987).

Variance Decomposition

Table 5: Variance decomposition

Variable	ϵ_t^{σ}	ϵ_t^{γ}	$\epsilon_t^{a_0}$	$\epsilon_t^{a_f}$	$\epsilon_t^{a_g}$
C	53%	76%	24%	0%	0%
K	67%	67%	33%	0%	0%
I	51%	80%	20%	0%	0%
N	50%	79%	21%	0%	0%
Y	52%	78%	22%	0%	0%
E_0	40%	63%	17%	7%	13%
E_f	28%	44%	9%	23%	21%
E_g	8%	12%	3%	3%	82%

Conclusions

- There is suggestive evidence that damage costs related to climate change exhibit time-varying volatility.
- We quantify the real effects of volatility shocks on the cost of climate change.
  - Our findings indicate that a climate volatility shock negatively impacts real macroeconomic variables.
  - We determine that the welfare costs of climate risks are more than four times the costs of business cycles documented by Lucas (1987).

Thank you!

Set of equilibrium equations - Households

$$\lambda_t = \left(C_t - \psi N_t^{\theta} X_t\right)^{-\sigma} + \mu_t \eta C_t^{\eta-1} X_{t-1}^{1-\eta} \tag{2}$$

$$\mu_t = \beta \mathbb{E}_t[\mu_{t+1} C_{t+1}^{\eta}(1+\eta) X_t^{-\eta}] - \psi N_t^{\theta} \left(C_t - \psi N_t^{\theta} X_t\right)^{-\sigma} \tag{3}$$

$$\lambda_t w_t = \psi \theta N_t^{\theta-1} X_t \left(C_t - \psi N_t^{\theta} X_t\right)^{-\sigma} \tag{4}$$

$$\lambda_t = \beta \mathbb{E}_t[\lambda_{t+1}(1 + (r_{t+1}^b))] \tag{5}$$

$$\lambda_t q_t = \beta \mathbb{E}_t[\lambda_{t+1}\left(r_{t+1} + q_{t+1}(1-\delta)\right)] \tag{6}$$

$$\begin{aligned} 1 &= q_t \left[1 - \frac{\Phi}{2}\left(\frac{I_t}{I_{l-1}} - 1\right)^2 - \Phi\left(\frac{I_t}{I_{t-1}} - 1\right)\frac{I_t}{I_{t-1}}\right] \\ &+ \beta \mathbb{E}_t\left[\frac{\lambda_{t+1}}{\lambda_t} q_{t+1} \Phi \left(\frac{I_{t+1}}{I_t} - 1\right)\left(\frac{I_{t+1}}{I_t}\right)^2\right] \end{aligned} \tag{7}$$

$$X_t = C_t^{\eta} X_{t-1}^{1-\eta} \tag{8}$$

$$K_{t+1} = \left[1 - \frac{\Phi}{2}\left(\frac{I_t}{I_{t-1}} - 1\right)^2\right] I_t + (1-\delta) K_t \tag{9}$$

Back

Set of equilibrium equations - Final good firm

$$r_t = e^{-\gamma_t(S_t - \bar{S})} A_{0,t} \alpha K_t^{\alpha-1} N_{0,t}^{1-\alpha-\nu} \mathbf{E_{0,t}}^{\nu} \tag{10}$$

$$w_t = e^{-\gamma_t(S_t - \bar{S})} A_{0,t} K_t^{\alpha} (1-\alpha-\nu) N_{0,t}^{-\alpha-\nu} \mathbf{E_{0,t}}^{\nu} \tag{11}$$

$$p_{f,t} = e^{-\gamma_t(S_t - \bar{S})} A_{0,t} K_t^{\alpha} N_{0,t}^{1-\alpha-\nu} \nu \mathbf{E_{0,t}}^{\nu-\rho} (1-\kappa) E_{f,t}^{\rho-1} \tag{12}$$

$$p_{g,t} = e^{-\gamma_t(S_t - \bar{S})} A_{0,t} K_t^{\alpha} N_{0,t}^{1-\alpha-\nu} \nu \mathbf{E_{0,t}}^{\nu-\rho} \kappa E_{g,t}^{\rho-1} \tag{13}$$

$$Y_t = e^{-\gamma_t(S_t - \bar{S})} A_{0,t} K_t^{\alpha} N_{0,t}^{(1-\alpha-\nu)} \mathbf{E_{0,t}}^{\nu} \tag{14}$$

$$\mathbf{E}_{0,t} = (\kappa (E_{g,t})^{\rho} + (1-\kappa)(E_{f,t})^{\rho})^{1/\rho} \tag{15}$$

Back

Set of equilibrium equations - Energy firms

- Green energy producer

$$p_{g,t} = \frac{w_t}{A_{g,t}} \tag{16}$$

$$E_{g,t} = A_{g,t} N_{g,t} \tag{17}$$

- Fossil energy producer

$$p_{f,t} = \frac{w_t}{A_{f,t}} \tag{18}$$

$$E_{f,t} = A_{f,t} N_{f,t} \tag{19}$$

Back

Set of equilibrium equations - Market clearing conditions and Definitions

$$Y_t = C_t + X_t + \bar{G} \tag{20}$$

$$N_t = N_{0,t} + N_{f,t} + N_{g,t} \tag{21}$$

$$S_t - \bar{S} = \phi_0 \xi E_{f,t} + (1-\phi)(S_{t-1} - \bar{S}) \tag{22}$$

$$D_t(S_t) = 1 - e^{-\gamma_t (S_t - \bar{S})} \tag{23}$$

$$(cost/Y)_t = \frac{D_t(S_t) A_{0,t} K_t^{\alpha} N_{0,t}^{(1-\alpha-\nu)} \mathbf{E_{0,t}}^{\nu}}{Y_t} \tag{24}$$

$$SR_t = e^{-\gamma_t (S_t - \bar{S})} A_{0,t} \tag{25}$$

Set of equilibrium equations - Exogenous process

$$\log(A_{0,t}) = (1-\rho_{a_0})\log(\bar{A}_0) + \rho_{a_0}\log A_{0,t-1} + \sigma^{A}\epsilon_t^{a_0}, \quad \epsilon_t^{a_0} \sim N(0,1) \tag{26}$$

$$\log(A_{f,t}) = (1-\rho_{a_f})\log(\bar{A}_f) + \rho_{a_f}\log A_{f,t-1} + \sigma^{A_f}\epsilon_t^{a_f}, \quad \epsilon_t^{a_f} \sim N(0,1) \tag{27}$$

$$\log(A_{g,t}) = (1-\rho_{a_g})\log(\bar{A}_g) + \rho_{a_g}\log A_{g,t-1} + \sigma^{A_g}\epsilon_t^{a_g}, \quad \epsilon_t^{a_g} \sim N(0,1) \tag{28}$$

$$\log(\gamma_t) = (1-\rho_{\gamma})\log(\bar{\gamma}) + \rho_{\gamma}\log(\gamma_{t-1}) + \sigma_t^{\gamma}\epsilon_t^{\gamma}, \quad \epsilon_t^{\gamma} \sim N(0,1) \tag{29}$$

$$\log(\sigma_t) = (1-\rho_{\sigma})\log(\bar{\sigma}) + \rho_{\sigma}\log(\sigma_{t-1}) + \sigma^{\sigma}\epsilon_t^{\sigma}, \quad \epsilon_t^{\sigma} \sim N(0,1) \tag{30}$$