

STOCHASTIC CLIMATE DAMAGES: BUSINESS CYCLE AND POLICY RESPONSES*

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Abstract

We quantify the macroeconomic costs of climate risks using an RBC-DSGE model with heterogeneous capital, endogenous energy choice, and stochastic volatility in climate damages. Fossil energy accumulates atmospheric carbon, raising the effective depreciation rate of exposed capital — an externality firms do not internalize. Calibrated to match U.S. data, the model generates sizable and persistent contractions in output, consumption, and investment following climate-damage level and volatility shocks, and the climate state endogenously alters the propagation of standard macroeconomic shocks. Comparing mitigation — a Pigouvian tax on polluting energy — against adaptation — a tax on non-resilient capital — at equal average fiscal revenues, mitigation dominates across all welfare and macroeconomic outcomes, delivering smaller output losses, lower climate-damage costs, and lower welfare losses because it acts directly on the source of future climate damages.

Keywords: Climate risk; stochastic volatility; mitigation; adaptation; business cycles; financial frictions.

JEL Codes: E32; Q43; Q54; Q58.

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1 Introduction

Climate change poses one of the most consequential macroeconomic challenges of our time. The evidence is stark: over the past four decades, the frequency and severity of climate-related crises have increased sharply across both developed and emerging economies. Yet the macroeconomic literature has paid limited attention to two mechanisms related to CO₂ atmospheric accumulation: the increase in the likelihood of climate-related disasters, and the amplifying role that climate risks play on standard macroeconomic shocks. This paper addresses both. We quantify the real effects of climate-related shocks — both to the level and volatility of climate damages — and the amplification role of CO₂ concentration, and evaluate the relative effectiveness of mitigation and adaptation policies in reducing these costs over the business cycle.

We approach these questions from a general equilibrium perspective. We first document a sharp increase in both the frequency and aggregate costs of climate-related disasters over the past 45 years, as well as a rise in climate risk — that is, the volatility of climate damages. Motivated by this evidence, we build a dynamic stochastic general equilibrium (DSGE) real business cycle model of a closed economy with financial frictions, energy use and CO₂ accumulation as a negative externality. Firms produce using fossil and renewable energy, labor, and capital. Fossil energy use accumulates CO₂ in the atmosphere, which raises the severity of climate-related shocks that destroy exposed capital. Crucially, firms do not internalize the damage their energy choices impose on the broader economy. We extend the baseline model to allow for time-varying volatility in climate damages, so that the economy is exposed to both level shocks — realized destruction events — and volatility shocks — changes in the prevailing risk of future climate exposure.

Using this environment, we study how these shocks propagate. We calibrate the model to key aggregate, financial, energy, and climate moments of the US economy. Our quantitative analysis delivers three main findings. First, both level and volatility shocks to climate damages have meaningful real effects on the economy. Second, volatility shocks generate macroeconomic costs even in the absence of changes in CO₂ concentration, as they raise the risk of future climate losses and trigger precautionary self-insurance re-

sponses. Third, the transmission of standard macroeconomic shocks depends on the state of the climate block, with financial frictions amplifying this dependence by constraining firm-level investment when capital is directly exposed to climate destruction.

We then consider mitigation and adaptation policies. Mitigation policies aim to reduce CO₂ accumulation in the atmosphere — for instance, through a Pigouvian tax on polluting energy use or carbon pricing schemes. Adaptation policies, by contrast, aim to make the economy more resilient to climate-related damages — in our model, captured by a tax on the use of non-resilient capital. To ensure a meaningful comparison, we calibrate both policies to generate the same fiscal revenues, distributed in a lump-sum fashion to the households. Through the lens of our model, both policies reduce the economy’s exposure to climate-related shocks, but mitigation policies dominate: they achieve greater reductions in climate-damage costs and at lower welfare costs than adaptation. This ranking reflects the fact that mitigation acts directly on the source of CO₂ accumulation, addressing the externality at its root rather than limiting its consequences.

Related Literature

Our paper is at the intersection of macroeconomics and environmental economics. It contributes to the broad macro-climate literature that studies the interaction between economic activity, carbon emissions, and climate damages in general equilibrium, including both integrated assessment models and DSGE-style environments, as in [Nordhaus \(2018\)](#), [Golosov et al. \(2014\)](#), and the recent review by [Bilal and Stock \(2025\)](#). This literature has substantially improved our understanding of the macroeconomic consequences of climate change, the role of damages, and the design of climate policy. Much of this work, however, studies the social cost of carbon and optimal policy in a long-run framework, abstracting from business-cycle dynamics and short-run risk. We focus on climate damages at business-cycle horizons allowing CO₂ accumulation to raise the destruction risk of exposed capital.

Our paper also relates to contributions that emphasize uncertainty in climate damages, such as [Barnett et al. \(2020\)](#), [Brock and Hansen \(2018\)](#), [Rudik \(2020\)](#), [Lemoine \(2021\)](#), and [Lin and van Wijnbergen \(2023\)](#), which show that uncertainty about climate damages

has quantitatively important macroeconomic consequences. Complementary reduced-form evidence shows that climate-related disturbances and climate uncertainty can have sizable effects on output and other macroeconomic aggregates, as in [Ciccarelli and Marotta \(2023\)](#), [Alessandri and Mumtaz \(2023\)](#), [Donadelli et al. \(2021\)](#), [Donadelli et al. \(2022\)](#), [Sheng et al. \(2022\)](#), and [Kim et al. \(2025\)](#). We complement this literature by introducing time-varying volatility in the climate-damage process in a structural framework in which the climate externality does not merely generate an additional source of disturbance. By allowing the volatility of damages to vary over time, we study not only the effects of realized climate shocks, but also the macroeconomic consequences of changes in risk about future climate losses. Moreover, in our model, the stock of atmospheric carbon raises the effective destruction risk of non-resilient capital, so the transmission of traditional shocks, such as productivity and financial shocks, depends on the climate state of the economy. This mechanism allows the climate block to act as an endogenous amplification margin for business-cycle fluctuations.

Finally, our paper relates to the literature on mitigation and adaptation policies in dynamic macroeconomic environments. Recent surveys stress that environmental policy interacts with business-cycle conditions and that its effects depend on the specific instrument considered; see, in particular, [Annicchiarico et al. \(2022\)](#). Early contributions in RBC settings show that emissions caps, taxes, and intensity targets imply different macroeconomic responses to productivity shocks, as in [Fischer and Springborn \(2011\)](#), while [Heutel \(2012\)](#) studies the cyclical design of optimal environmental policy. [Annicchiarico and Diluiso \(2019\)](#) extend this line of research to a New Keynesian environment with nominal rigidities and monetary policy, and [Carattini et al. \(2023\)](#) show that climate policy interacts with financial frictions and transition risk. At the same time, a growing literature emphasizes adaptation and resilience-building policies as tools to limit the macroeconomic costs of climate change, as in [Carleton et al. \(2024\)](#) and [Fernández Corugedo et al. \(2023\)](#). Relative to this literature, we compare mitigation and adaptation policies within the same stochastic climate-risk environment, with both instruments calibrated to generate the same average fiscal revenues as a share of output in the steady state. This

unified framework allows us to compare their implications for welfare, output losses, and climate-damage costs following both damage shocks and volatility shocks.

The remainder of the paper goes as follows. Section 2 presents motivating empirical evidence on the time-varying costs related to climate change. Section 3 presents the baseline model in line with Golosov et al. (2014) extended to include time-varying volatility shocks. In section 4, we describe the model calibration. Section 5 provides the quantitative results, focusing on the responses of key macroeconomic variables to climate volatility shocks and the welfare implications of these second-order shocks. Section 6 studies the impact of adaptation and mitigation measures on the economic outcomes, and Section 7 concludes.

2 Climate-related risks

Several studies confirm that human action alters global weather patterns, i.e. contributes to climate change – as documented by the Intergovernmental Panel on Climate Change (IPCC (2023)). New evidence reinforces the conclusions of the previous IPCC Special Report on Global Warming of 1.5°C, showing that even relatively small increases in global warming (+0.5°C) generate statistically significant changes in extreme events at the global level and across large regions. In particular, the frequency and intensity of some weather and climate extremes have increased since preindustrial times, especially temperature-related extremes. Looking ahead, hot extremes are expected to become more frequent and more intense, while cold extremes are projected to continue declining.

Motivated by this evidence, we collect data on the costs of climate-related disaster events in the US from the National Centers for Environmental Information (NCEI).¹² These costs cover all physical damages to infrastructure, production, vehicles, public assets, electrical infrastructure, and more, caused by billion-dollar weather and climate

¹This data is publicly available at <https://www.ncei.noaa.gov/access/billions/>.

²Kim et al. (2025) reviews a different piece of evidence but points in a similar direction to ours. They review the Actuarial Climate Index, which measures severe weather developments, and which is developed by insurance professionals. They find an increase in the prevalence of weather-related disasters over time with a pattern that also shows periods of higher volatility.

events (CPI-adjusted) such as severe storms, floods, droughts, tropical cyclones, among others.³

Table 1: Billion-Dollar Disaster Statistics.

Period	Events	Avg Cost (% GDP)	Max Cost (% GDP)	Total Cost (% Total 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 (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2024).

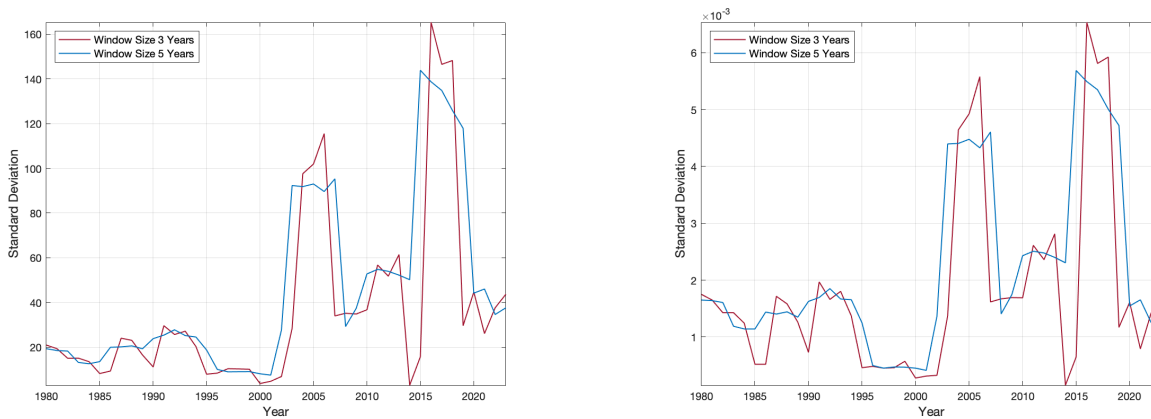
Table 1 presents the number of events, the average and maximum event cost relative to average GDP, and the ratio of cumulative disaster costs to cumulative GDP over each period, reported by decade and separately for the last part of the sample, 2020–2023. The number of events, i.e. the frequency of highly costly environmental shocks increases steadily since the 1980s. The total costs over GDP increased by a factor of 3 over the sample period. Additionally, while the average cost as a share of GDP remains stable across periods, does not, rising from 0.36% to a peak of 0.99%. This suggests that not only the frequency but also the damage costs of these events are rising, signaling growing uncertainty regarding future climate disaster events. As seen in the table, costs are sizable in the U.S. reaching a total cost of half a percentage point of GDP for the 2020-2023 period.

Figure 1 shows that not only are there significant costs of climate disasters but also an increasing risk associated with these events. The figure calculates the standard deviation of these costs over rolling windows of 3 and 5 years.⁴ The figure shows the time-varying nature of the dispersion of climate-related costs. Particularly, in line with the maximum

³These disaster costs do not account for losses to natural capital, environmental degradation, or mental and physical healthcare-related costs. Therefore, it should be considered conservative concerning what is truly lost.

⁴These are not measures of volatility change itself but we prefer these to the implied volatility measures as these measures depend on a model with an associated estimation strategy; instead, the rolling window volatility measure abstracts from these limitations and for the purpose of motivation, we believe this is a more agnostic strategy.

cost in terms of GDP shown in Table 1 there is a spike in the rolling-window volatility the first decade of the 2000s and other peaks around 2015-2018.



(a) CPI-Adjusted Cost.

(b) Cost over GDP.

Figure 1: Rolling window standard deviations of climate costs

Note: Cost of US Billion-Dollar Disaster Events. Moving standard deviation, windows of 3 and 5 years. The data is from NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2024).

In sum, as temperatures rise and weather patterns become more unpredictable, the macroeconomic risk stemming from climate volatility becomes more salient. Incorporating this risk into macroeconomic analysis becomes essential since it allows for a more comprehensive understanding of the associated risks and enables the formulation of more effective policy recommendations. The next section presents a micro-founded model that can be used to compute model-based climate costs and is also useful to address these questions and discuss the welfare implications of these events and the policies that may attenuate their impact.

3 The model

To study the macroeconomic consequences of climate-related shocks and the role of mitigation and adaptation policies, we develop a real business cycle model following [Goloso](#)

et al. (2014) where the production of polluting energy contributes to the accumulation of CO₂ in the atmosphere, which increases the cost associated with climate change. We extend the baseline model along three dimensions. First, instead of modeling climate damages as a direct reduction in total factor productivity, we allow carbon emissions to increase the destruction rate of physical capital that is exposed to climate risk. This choice is motivated by the data. The economic costs of climate-related disasters are predominantly recorded as losses to physical assets such as buildings, infrastructure, and productive capital, rather than as direct declines in measured productivity. Second, we consider an environment with financial frictions that limit the ability of firms to adjust their capital structure, including the adoption of resilient capital technologies. Third, we introduce stochastic volatility in the climate damage process, allowing uncertainty about the severity of capital losses to vary over time, consistent with the time-varying dispersion of disaster costs documented in Section 2.

The economy is populated by households, a representative final-good producer, energy producers operating in fossil and clean sectors, capital-goods producers differentiated by their resilience to climate damage, and entrepreneurs. We study a decentralized equilibrium in which firms take the climate state and the associated damage process as given — in particular, they do not internalize the effect of current fossil energy use on future atmospheric carbon concentrations and future climate damage. We describe each agent’s optimization problem in turn.

3.1 Households

We assume a continuum of infinitely lived households who have preferences over consumption and labor. The representative household chooses consumption, labor supply, and bond holdings to maximize expected lifetime utility:

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \frac{(c_t - \psi l_t^\theta x_t)^{1-\sigma} - 1}{1-\sigma},$$

where

$$x_t = c_t^\eta x_{t-1}^{1-\eta},$$

subject to the sequence of budget constraints,

$$c_t + b_{t+1} = w_t l_t + R_{t-1}^b b_t + \tau_t, \quad \forall t.$$

We assume preferences as in [Jaimovich and Rebelo \(2009\)](#). These preferences introduce non-separability through x_t , that allows the short-run wealth effect on labor supply to be controlled via η , nesting [Greenwood et al. \(1988\)](#) and [King et al. \(1988\)](#) as special cases. Here $\beta \in (0, 1)$ is the discount factor, c_t , l_t , and b_t denote consumption, labor supply, and holdings of the one-period risk-free bond. w_t and R_t^b are the wage and the gross interest rate on bonds; τ_t is aggregate net lump sum transfers from the productive-sector firms owned by households.⁵

3.2 Final-good producer

A representative and perfectly competitive firm produces the final good using labor, capital, and energy as production inputs. In each period, the firm solves a static problem given by:

$$\Pi_t \equiv \max_{\substack{k_{r,t}, k_{n,t}, l_{0,t} \\ e_{f,t}, e_{g,t}}} y_t - r_t^r k_{r,t} - r_t^n k_{n,t} - w_t l_{0,t} - p_t^f e_{f,t} - p_t^g e_{g,t}.$$

We assume that the technology is Cobb–Douglas,

$$y_t = a_{0,t} k_{0,t}^\alpha l_{0,t}^{1-\alpha-\nu} e_{0,t}^\nu,$$

⁵These transfers include: profits from resilient and non-resilient capital producers, which are non-zero outside steady state due to investment adjustment costs; the net transfer from the entrepreneurial sector, equal to the net worth of exiting entrepreneurs minus the seed capital provided to entering entrepreneurs; and financial intermediation profits, arising from the spread between the external financing rate and the risk-free rate.

where $a_{0,t}$ is the total factor productivity, which follows an AR(1) process. To produce a unit of energy, the firm combines fossil and green energy with a CES aggregator:

$$e_{0,t} = [\kappa e_{g,t}^\rho + (1 - \kappa)e_{f,t}^\rho]^{1/\rho},$$

where $e_{g,t}$ and $e_{f,t}$ denote green and fossil energy, κ is a share parameter, and $\rho \leq 1$ governs the elasticity of substitution between the two sources.

Similarly, a unit of capital comes from combining two types of capital, resilient and non-resilient capital with a CES technology as follows:

$$k_{0,t} = [\zeta(k_{r,t})^v + (1 - \zeta)(k_{n,t})^v]^{1/v}.$$

Here $k_{r,t}$ and $k_{n,t}$ denote resilient and non-resilient capital, respectively, ζ is the share parameter, and $v \leq 1$ governs the elasticity of substitution between the two types. The imperfect substitutability between capital varieties captures two complementary interpretations. First, the two types of capital may be deployed across heterogeneous locations, so that production in climate-exposed locations cannot simply be replaced by resilient capital elsewhere. Second, resilient and non-resilient capital may be intrinsically different in their design, so that not all capital can be produced in a way that is resistant to climate damage.

3.3 Capital-good producers

Not all capital is equally exposed to climate risk. Capital deployed in geographical areas prone to floods, tornadoes, and other climate events faces a higher destruction risk than capital in safer locations; resilient capital, by contrast, is designed to withstand such damage. As documented in Section 2, the economic costs of climate disasters fall predominantly on physical assets, motivating our focus on capital destruction as the main transmission channel of climate shocks.

We assume representative producers of each capital type $j = r, n$ who combine investment goods with the existing capital stock to produce new units of capital, selling them

to entrepreneurs at price q_t^j . The producer solves:

$$\max_{\{k_{j,t+1}, i_{j,t}\}} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \frac{\lambda_t}{\lambda_0} \{q_t^j k_{j,t+1} - q_t^j (1 - \Delta_{j,t}) k_{j,t} - i_{j,t}\}, \quad (3.1)$$

subject to

$$k_{j,t+1} = (1 - \Delta_{j,t}) k_{j,t} + \left[1 - \frac{\Phi_j}{2} \left(\frac{i_{j,t}}{i_{j,t-1}} - 1 \right)^2 \right] i_{j,t}, \quad (3.2)$$

where Φ_j captures convex investment adjustment costs in the spirit of [Christiano et al. \(2005\)](#), and can differ across types of capital.

$\Delta_{j,t}$ denotes the depreciation rate of capital type j . For resilient capital, $\Delta_{r,t} = \delta_r$ is constant. For non-resilient capital, by contrast, the depreciation rate is endogenous and increasing in the stock of atmospheric carbon, denoted by s_t . Specifically, following [Goloso et al. \(2014\)](#), we assume an exponential form:

$$\Delta_{n,t} = \hat{\delta}_n \exp(\delta_{n,t}(s_t - \bar{s})).$$

This specification captures the impact of climate-related disasters on physical capital. $\hat{\delta}_n$ is the baseline depreciation and \bar{s} is the pre-industrial level of atmospheric carbon. As CO2 accumulates, non-resilient capital faces a higher effective depreciation rate. The exponential form provides a parsimonious reduced-form approximation to the composition of two mappings: a concave mapping from atmospheric carbon concentration to temperature, and a convex mapping from temperature to economic damages, following the discussion in [Goloso et al. \(2014\)](#).

3.4 The stock of atmospheric carbon

The climate state variable is the stock of atmospheric carbon, s_t .⁶ Fossil energy use increases the atmospheric stock gradually over time. Specifically, the climate state evolves

⁶A standard assumption in the climate-macro literature is to measure the atmospheric carbon stock in gigatons of carbon content (GtC).

in line with the following expression:

$$s_t - \bar{s} = \sum_{j=0}^{\infty} (1 - d_j) \xi e_{f,t-j},$$

where $d_j \in [0, 1]$ for all j , ξ serves as a parameter that converts the energy intensity e_f into gigatons of carbon (GtC).⁷

Following [Nakov and Thomas \(2023\)](#), the carbon depreciation structure is defined as: $(1 - d_j) = \phi_0(1 - \phi)^j$, ensuring a well-defined steady state.⁸ Under this structure, the carbon stock can be written recursively. For period 1, the stock of CO₂ in the atmosphere is:

$$\begin{aligned} \text{t=1} \quad s_1 - \bar{s} &= (1 - d_0)\xi e_{f,1} + (1 - d_1)\xi e_{f,0} \\ &= \phi_0\xi e_{f,1} + \phi_0(1 - \phi)\xi e_{f,0}. \end{aligned}$$

We can use these expressions in the stock of CO₂ in the atmosphere in period 2 as follows:

$$\begin{aligned} \text{t=2} \quad s_2 - \bar{s} &= (1 - d_0)\xi e_{f,2} + (1 - d_1)\xi e_{f,1} + (1 - d_2)\xi e_{f,0} \\ &= \phi_0\xi e_{f,2} + \phi_0(1 - \phi)\xi e_{f,1} + \phi_0(1 - \phi)^2\xi e_{f,0} \\ &= \phi_0\xi e_{f,2} + (1 - \phi)[\phi_0\xi e_{f,1} + \phi_0(1 - \phi)\xi e_{f,0}] \\ &= \phi_0\xi e_{f,2} + (1 - \phi)(s_1 - \bar{s}). \end{aligned}$$

More generally, for any period t the stock of CO₂ in the atmosphere evolves according to

$$s_t - \bar{s} = \phi_0\xi e_{f,t} + (1 - \phi)(s_{t-1} - \bar{s}).$$

⁷We adhere to the methodology outlined in [Nakov and Thomas \(2023\)](#), where energy is measured in gigatons of oil equivalent ($Gtoe$) for calibration purposes. Consequently, a conversion is necessary to express fossil energy consumption in terms of gigatons of carbon content (GtC).

⁸This specification is a special case of [Golosov et al. \(2014\)](#), where no carbon emission stays forever in the atmosphere, preventing s from growing unboundedly.

The parameter $\phi_0 \in (0, 1)$ is the fraction of current-period emissions that remains in the atmosphere within the period, while $1 - \phi_0$ is absorbed by the biosphere and the upper ocean. The parameter ϕ captures the decay rate of the atmospheric carbon stock.

We depart from the existing literature by introducing time-varying volatility. In order to study the changing risks surrounding damage costs we assume that the $\delta_{n,t}$, which measures the sensitivity of climate damages to the atmospheric carbon stock, follows an AR(1) process in logs:

$$\log \delta_{n,t} = (1 - \rho_\delta) \log \bar{\delta}_n + \rho_\delta \log \delta_{n,t-1} + \sigma_t^\delta \varepsilon_t^\delta, \quad \varepsilon_t^\delta \sim \mathcal{N}(0, 1).$$

Moreover, we allow the volatility of this process to vary over time. Specifically,

$$\log \sigma_t^\delta = (1 - \rho_\sigma) \log \bar{\sigma}^\delta + \rho_\sigma \log \sigma_{t-1}^\delta + \sigma_\sigma \varepsilon_t^\sigma, \quad \varepsilon_t^\sigma \sim \mathcal{N}(0, 1).$$

Thus, shocks to σ_t^δ capture time-varying uncertainty about future climate damages, even holding fixed the current level of the damage process itself.

3.5 Entrepreneurs

A representative entrepreneur purchases both types of capital from capital producers and rents them to the final-good producer at the equilibrium rental rates. These positions are financed with a combination of net worth, n_t , and external debt, d_t . The entrepreneur's balance sheet is

$$q_t^r k_{r,t+1} + q_t^n k_{n,t+1} = d_t + n_t.$$

The gross returns on resilient and non-resilient capital are defined by

$$R_t^r = \frac{r_t^r + (1 - \delta_r) q_t^r}{q_{t-1}^r}, \quad R_t^n = \frac{r_t^n + (1 - \Delta_{n,t}) q_t^n}{q_{t-1}^n}.$$

External finance carries a leverage-dependent premium. We model financial frictions in the spirit of [Bernanke et al. \(1999\)](#), using the reduced-form implementation in [Gilchrist \(2003\)](#). The funding rate faced by the entrepreneur is

$$R_t^d = \chi\left(\frac{d_t}{n_t}, \xi_t^{\text{fin}}\right) R_t^b,$$

where the spread over the risk-free rate is determined by

$$\chi\left(\frac{d_t}{n_t}, \xi_t^{\text{fin}}\right) = \bar{\chi} + \left(\frac{d_t}{n_t}\right)^{\chi_e} - \bar{d}n^{\chi_e} + \xi_t^{\text{fin}}.$$

This specification implies that the external finance premium is increasing in leverage and is also subject to an exogenous financial shock ξ_t^{fin} .

Optimal portfolio choice implies two no-arbitrage conditions,

$$0 = \mathbb{E}_t \left[\beta \frac{\lambda_{t+1}}{\lambda_t} (R_{t+1}^r - R_t^d) \right], \quad 0 = \mathbb{E}_t \left[\beta \frac{\lambda_{t+1}}{\lambda_t} (R_{t+1}^n - R_t^d) \right].$$

Entrepreneurial net worth evolves according to

$$n_t = \omega (R_t^r q_{t-1}^r k_{r,t} + R_t^n q_{t-1}^n k_{n,t} - R_{t-1}^d d_{t-1}) + (1 - \omega) \bar{W}.$$

The parameter ω governs the survival rate of entrepreneurs, while $(1 - \omega) \bar{W}$ captures transfers from entering entrepreneurs.

3.6 Energy producers

Following [Nakov and Thomas \(2023\)](#), the energy sector is divided into fossil and green energy producers. In each period, firms in sector $i \in \{f, g\}$ hire labor to produce energy according to

$$e_{i,t} = a_{i,t} l_{i,t}.$$

Here $a_{f,t}$ and $a_{g,t}$ denote sector-specific productivity in fossil and green energy production, respectively, and they follow an AR(1) process. Under perfect competition, prices satisfy

$$p_t^f = \frac{w_t}{a_{f,t}}, \quad p_t^g = \frac{w_t}{a_{g,t}}.$$

3.7 Definitions

Given the previous assumptions, climate-related destruction of capital relative to output is defined as

$$\frac{\text{cost}_t}{y_t} = \frac{q_t^n (\Delta_{n,t} - \hat{\delta}_n) k_{n,t}}{y_t}.$$

This object measures the portion of output lost due to climate-induced depreciation in excess of the baseline depreciation rate $\hat{\delta}_n$. It therefore isolates the endogenous component of capital destruction attributable to the climate state.

For completeness, we assume the government runs a balance budget and use the lump sum taxes to finance a given level of unproductive government spending. We present the complete set of equilibrium conditions in the appendix.

4 Solution and calibration

As our model includes a stochastic volatility shocks, we solve the model numerically using a third-order perturbation method with pruning, following [Andreasen et al. \(2018\)](#) and [Fernández-Villaverde et al. \(2011\)](#). Our quantitative strategy combines external parameterization with calibration through a moment-matching procedure. We target the U.S. economy at quarterly frequency over the period 1980Q1–2023Q3. We match moments for real macroeconomic variables, damage costs, energy use, and atmospheric CO2 concentration.

Table 2 reports the parameters calibrated directly from the literature or pinned down by standard steady-state targets. We set the discount factor to $\beta = 0.9975$, consistent with an annual real interest rate of 1%. The coefficient of relative risk aversion is set to $\sigma = 2$, a standard value in the macroeconomic literature. The labor disutility parameter is fixed at $\psi = 0.4740$ to normalize steady-state labor supply to one. We set the depreciation rate of resilient capital to $\delta_r = 0.025$, the capital share to $\alpha = 0.3$, and the energy share to $\nu = 0.057$; ν , is chosen to match the share of energy expenditures in U.S. GDP reported by the U.S. Energy Information Administration (2023).

Following Nakov and Thomas (2023), we set the parameter governing substitution between green and fossil energy to $\rho = 0.65$, based on the empirical evidence in Papageorgiou et al. (2017). We also adopt from Nakov and Thomas (2023) the weight of renewable energy, $\kappa = 0.2571$, and the conversion factor from Gtoe to GtC, $\xi = 0.879$. As in Golosov et al. (2014), we set the pre-industrial atmospheric CO2 stock to $\bar{s} = 581$. In addition, we set $\bar{a}_0 = 9.87$ to match the average Solow residual in the data. The steady-state government expenditure share is fixed at $\bar{g} = 0.21$, in line with standard values and U.S. data. Finally, for non-resilient capital, we normalize $\bar{\delta}_n = 1$ and set $\hat{\delta}_n = 0.025$.

For the financial intermediation block, we set the gross steady-state credit spread to $\bar{\chi} = 1.0164$, which targets the average Moody's Seasoned Aaa Corporate Bond Yield. The elasticity of the spread with respect to leverage is set to $\chi_e = 0.04$, following Dedola and Lombardo (2012), and the steady-state debt-to-net-worth ratio is fixed at $\bar{d}n = 1/3$. Finally, entrepreneurs survive into the next period with probability $\omega = 0.95$, following Gertler and Kiyotaki (2015).

Table 2: Parameterization based on the existing literature

Parameter	Value	Target/source
β	0.9975	U.S. 1% annual discount rate
σ	2	Standard
ψ	0.4740	Normalize $l = 1$
α	0.3	Standard
ν	0.057	EIA (2023)
ρ	0.65	Papageorgiou et al. (2017)
κ	0.2571	Nakov and Thomas (2023)
\bar{s}	581	Golosov et al. (2014)
ξ	0.879	Nakov and Thomas (2023)
\bar{a}_0	9.87	Target average Solow residual
\bar{g}	0.21	Standard / U.S. data
δ_r	0.025	Standard
$\bar{\delta}_n$	1	Normalization
$\hat{\delta}_n$	0.025	Standard
$\bar{\chi}$	1.0164	Moody's Aaa corporate yield
χ_e	0.04	Dedola et al. (2012)
\overline{dn}	1/3	Standard
ω	0.95	Gertler and Kiyotaki (2015)

Note: This table reports parameters taken from the literature and calibrated to match averages to steady-state values.

Table 3 reports the remaining parameters. We fix these coefficients to target the empirical moments reported in Table 4. In total, we calibrate 22 parameters using 25 moments.

Table 4 reports the set of empirical moments targeted in the calibration. The first block presents the sample means of atmospheric CO2 concentration (s), the mean disaster cost-to-output ratio (cost/y), and the mean corporate lending rate (R_d). The second block reports the volatility of the main macroeconomic, environmental, and financial variables: output (y), investment (i), total energy use (e_0), fossil energy (e_f), green energy (e_g), atmospheric CO2 concentration (s), labor (l), and the corporate lending rate (R_d). The third block reports the contemporaneous cross-correlations across selected variables, while the final block presents their first-order autocorrelations.⁹

⁹The cost series corresponds to climate- and weather-related disasters with damages exceeding one billion dollars. Event-level damages, measured in billions of dollars, are allocated across quarters, and the cost-to-output ratio is defined as total quarterly damages divided by quarterly GDP, also measured in billions of dollars.

Table 3: Calibrated coefficients

Parameter	Description	Value
ρ_{a_0}	Persistence of the TFP shock	0.8025
σ_{a_0}	Volatility of the TFP shock	0.0058
ρ_δ	Persistence of the damage elasticity	0.4479
$\bar{\sigma}^\delta$	Average volatility of the damage elasticity	0.6989
ρ_σ	Persistence of volatility shocks	0.96
σ_σ	Standard deviation of the volatility shock	0.5008
\bar{a}_f	Average productivity of fossil energy production	15.6621
ρ_{a_f}	Persistence of fossil energy productivity	0.8148
σ_{a_f}	Volatility of fossil energy productivity	0.0035
\bar{a}_g	Average productivity of green energy production	84.0836
ρ_{a_g}	Persistence of green energy productivity	0.98
σ_{a_g}	Volatility of green energy productivity	0.0117
ρ_f	Persistence of the financial shock	0.7073
σ_f	Volatility of the financial shock	0.0016
ϕ	Damage cost parameter	0.027
ϕ_0	Damage cost parameter	0.15
Φ_r	Investment adjustment cost, resilient capital	6.9102
Φ_n	Investment adjustment cost, non-resilient capital	0.0726
ζ	Share of resilient capital	0.2301
ν	Elasticity of substitution between capital types	0.2827
η	Preference parameter	0.0512
θ	Inverse Frisch elasticity	1.1899

Note: Parameters are calibrated to match the empirical moments reported in Table 4. The model is solved using third-order perturbation method in logs.

Table 4: Targeted moments

Moment	Data	Model	Moment	Data	Model
Means					
$\mathbb{E}(s)$	6.57	6.36	$\mathbb{E}(\text{cost}/y)$	0.003	0.018
$\mathbb{E}(R_d)$	1.016	1.019			
Standard deviations (%)					
$\sigma(y)$	4.84	4.08	$\sigma(i)$	10.96	8.83
$\sigma(e_0)$	5.70	5.81	$\sigma(e_f)$	6.61	7.52
$\sigma(e_g)$	12.44	12.22	$\sigma(s)$	0.47	0.001
$\sigma(R_d)$	0.60	0.63	$\sigma(l)$	5.23	4.86
Contemporaneous correlations (%)					
$\rho(y, i)$	63.37	63.01	$\rho(i, e_0)$	54.38	71.24
$\rho(y, e_0)$	88.56	77.79	$\rho(i, e_f)$	54.08	54.44
$\rho(y, \text{cost}/y)$	-4.03	-25.27	$\rho(e_0, \text{cost}/y)$	-4.83	-10.68
$\rho(y, l)$	86.95	87.52	$\rho(e_0, l)$	82.99	84.75
First-order autocorrelations					
$\rho(y_t, y_{t-1})$	0.97	0.87	$\rho(i_t, i_{t-1})$	0.94	0.90
$\rho(e_{0,t}, e_{0,t-1})$	0.91	0.92	$\rho(e_{f,t}, e_{f,t-1})$	0.93	0.94
$\rho(e_{g,t}, e_{g,t-1})$	0.97	0.96	$\rho(s_t, s_{t-1})$	0.98	0.995

Note: $\mathbb{E}(x)$ denotes the sample mean, $\sigma(x)$ the standard deviation, and $\rho(x, y)$ the contemporaneous correlation between x and y . Autocorrelations are reported as first-order correlations between a variable and its lag. Standard deviations and contemporaneous correlations are reported in percent whenever applicable.

Table 5: Untargeted moments

Moment	Data	Model
Means		
$\mathbb{E}(c/y)$	0.66	0.61
$\mathbb{E}(i/y)$	0.18	0.18
Standard deviations (%)		
$\sigma(c/y)$	2.25	1.24
$\sigma(i/y)$	1.50	1.24

Note: $\mathbb{E}(x)$ denotes the sample mean and $\sigma(x)$ the standard deviation. Standard deviations are in percent.

Overall, the model matches the main patterns in the data well. Table 5 reports untargeted moments for the consumption-to-output and investment-to-output ratios; the model matches their mean values closely and approximates their volatility reasonably well.

The model captures the relative volatilities and comovement of macroeconomic and energy variables accurately. It slightly understates the volatility of investment, but it noticeably understates the volatility of atmospheric CO2 concentration. The fit is also less precise for the disaster-cost moments, especially for the mean cost-to-output ratio, which the model overstates relative to the data. This discrepancy reflects the difficulty of matching moments driven by rare and uneven climate-disaster realizations within a framework that is calibrated jointly to broader macroeconomic, financial, and energy moments, although the model still captures the broad cyclical behavior of disaster costs.

5 Quantitative analysis

We now study the dynamic effects of traditional macroeconomic shocks — a TFP shock and a financial shock — and assess how these shocks transmit to macroeconomic variables while also tracing their effects on CO2 and climate damage through the model’s propagation mechanism. We then study the impact of shocks to the climate-damage process: a shock to the level of climate damages and a shock to its volatility. Comparing the responses across all four shocks allows us to evaluate the relative quantitative importance of climate shocks as drivers of aggregate fluctuations relative to conventional macroeconomic shocks.

We compute Generalized Impulse Response Functions (GIRFs) following [Andreasen et al. \(2018\)](#). In the case of the volatility disturbance, we isolate the effect of a one-standard-deviation shock to σ_t^δ , keeping the contemporaneous innovation to the level of the damage process fixed at zero. As such, we interpret this shock as a temporary increase in climate-related risk.

5.1 Traditional macroeconomic shocks

Figure 2 reports the GIRFs to a one-standard-deviation TFP shock. The dark-blue lines are for the baseline calibration. The responses are standard for a persistently positive supply shock: output, consumption, and investment increase on impact, with investment displaying the largest response. The model displays consumption smoothing, as the shock is transitory. The TFP shock increases the marginal product of all production factors, raising both fossil and green energy demand. At the same time, the cost-to-output ratio declines, reflecting that stronger current production lowers the relative importance of climate-related depreciation losses. The responses of resilient and non-resilient capital are likewise positive; the difference in adjustment speed reflects the higher adjustment costs of resilient capital. Notably, the effective climate damage increases only gradually and by a small amount as a consequence of higher fossil energy production. Thus, a TFP shock operates primarily through higher production efficiency, with negligible implications for climate-related capital destruction.

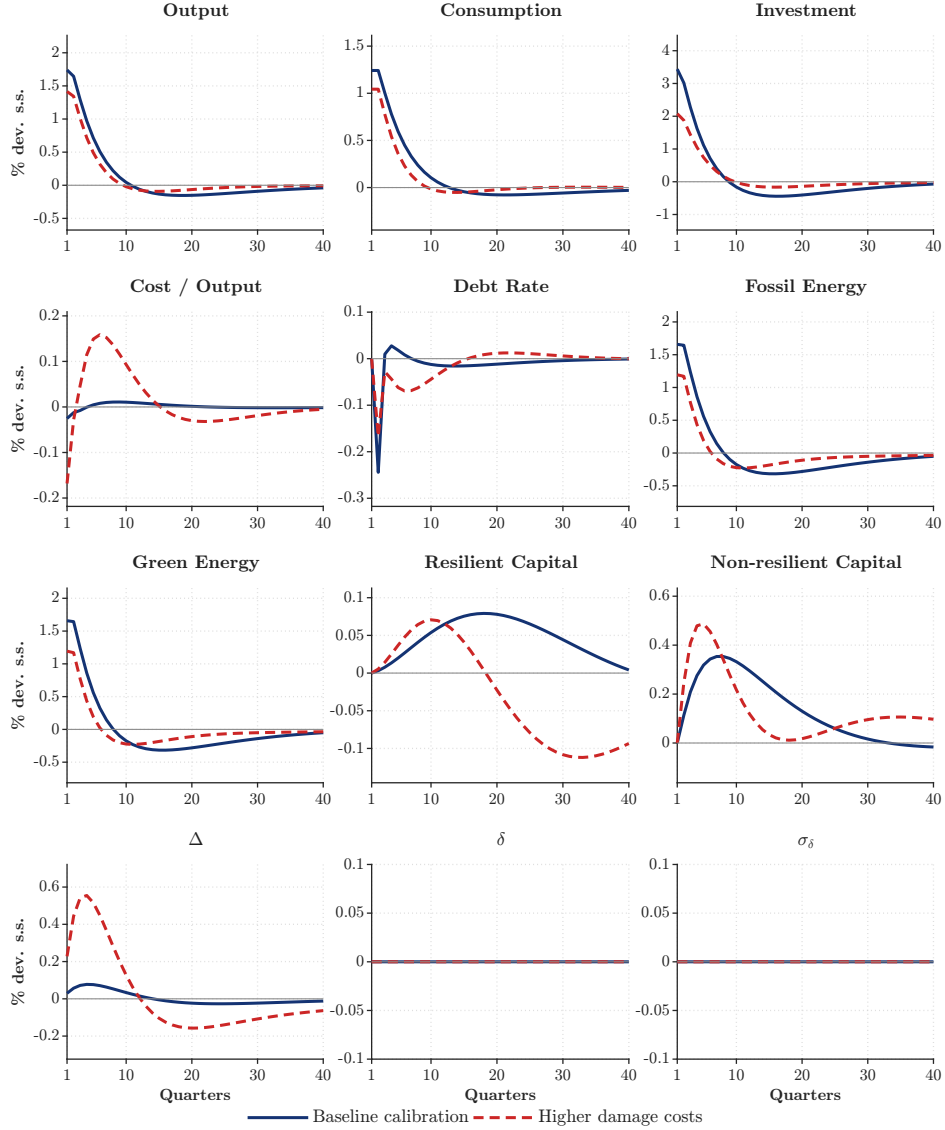


Figure 2: GIRFs to a one-standard-deviation TFP shock. Higher average s

Note: Impulse response functions are reported as percent deviations from steady state.

The red-dashed lines present the responses to the same shock but recalibrating the model to produce a larger average stock of CO2. Specifically, we augment the parameter ϕ_0 — the fraction of current-period emissions that remains in the atmosphere within the period — from its baseline value to 0.27, which raises the average damage cost to 0.1755.¹⁰

¹⁰This recalibration is equivalent to increasing $\bar{\delta}_n$, the average damage elasticity, to 10, holding ϕ_0 fixed at its baseline value.

As shown in the figures, an explicit modeling of the damage of climate change ($\bar{\delta}_n$) is relevant for the regular business cycle shocks. The exposure to climate risks dampen the expansion of the economy in the event of a positive TFP shock. The reason is that the expansion trigger an increase of CO2 in the atmosphere due to the endogenous response of production and a higher demand of polluting energy, which reduces the marginal return of production factors. The higher the average cost (due to average larger CO2 in the atmosphere) the lower the response of the economy and the stronger the reaction of damage costs.

Figure 3 reports the effects of a one-standard-deviation financial shock, interpreted as an increase in the external finance premium. As before, the dark-blue line is the response under the baseline calibration whereas the dashed-red line is the one under the alternative calibration with large average CO2 in the atmosphere. As expected, the shock raises the debt rate on impact and generates a short-run contraction in output, consumption, investment, and energy use. The cost-to-output ratio increases only temporarily, mostly because lower output and tighter financing conditions amplify the short-run burden of capital losses.

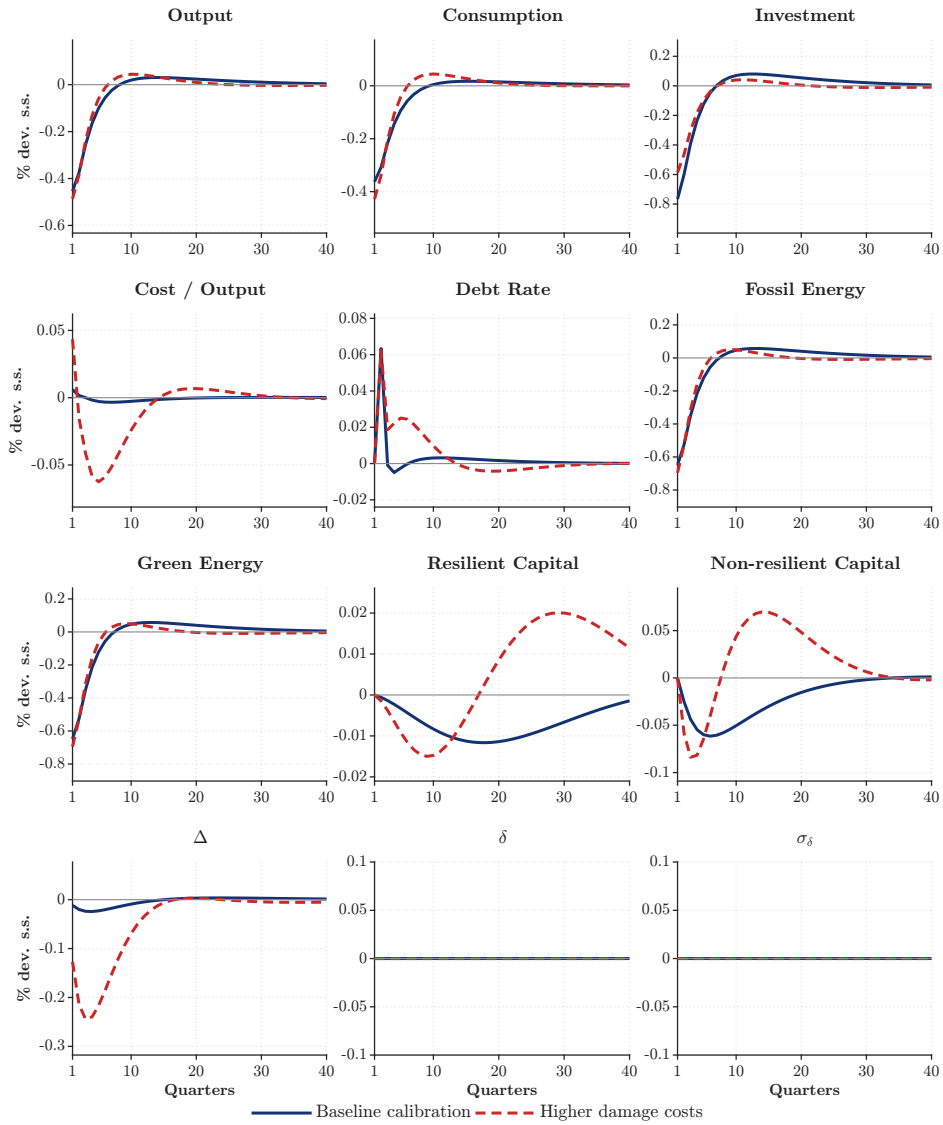


Figure 3: GIRFs to a one-standard-deviation financial shock. Higher average s.

Note: Impulse response functions are reported as percent deviations from steady state.

5.2 Climate damage related shocks

We now focus on the impact of a damage shock. Figure 4 reports the GIRFs to a one-standard-deviation shock to the level of climate damages, $\delta_{n,t}$ keeping the risk associated to the shock constant at the steady state.

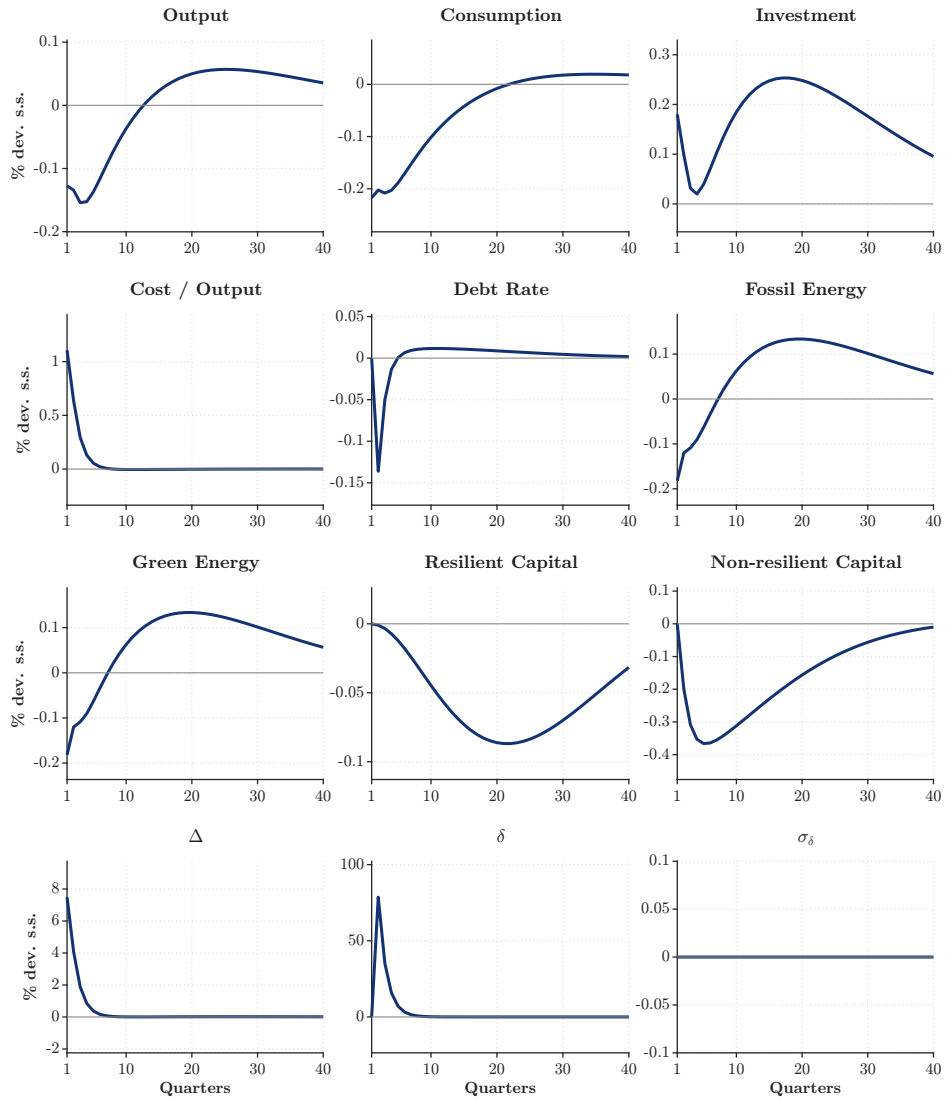


Figure 4: GIRFs to a one-standard-deviation shock to climate damages.

Note: Impulse response functions are reported as percent deviations from steady state.

This shock is contractionary on impact, reducing output and consumption. The worsening of the damage process raises effective depreciation for non-resilient capital, leading to a pronounced decline in the stock of exposed capital. This persistently higher depreciation requires a mild increase in investment in the short run, reflecting rebuilding needs in response to higher depreciation. The debt rate falls on impact, consistent with weaker borrowing demand as firms cut back on the accumulation of exposed capital, although

the shock also affects output through financial conditions. Energy use declines initially with lower activity and then gradually recovers.

Overall, the figure shows that a climate-damage shock differs fundamentally from a standard macroeconomic shock: rather than operating through production efficiency or tighter financing alone, it works through capital destruction and changes in the composition of capital.

This mechanism is even more transparent in Figure 5, which shows the effects of a one-standard-deviation shock to the volatility of climate damages. Relative to the level shock, the volatility shock has larger and more persistent real effects. Output and consumption fall sharply on impact and recover only gradually, highlighting that climate risk matters not only through realized damages but also through changes in uncertainty about future damages. Investment also displays a distinctive pattern, similar to the response to a volatility shock in [Fernández-Villaverde et al. \(2011\)](#): it declines initially because of the risk associated with future returns of capital, but later turns positive as the investment in resilient capital accelerates and the economy gradually rebuilds its capital stock.

As shown in the figure, the composition of capital adjusts substantially, with resilient capital rising over time while non-resilient capital contracts strongly and persistently. Hence, higher climate risk induces endogenous adaptation through reallocation away from the type of capital that is more exposed to this risk. The effective depreciation term also rises on impact, even though there is no contemporaneous shock to the level of climate damages. This is a higher-order risk effect captured by the third-order solution: a volatility shock increases uncertainty about future damage realizations and, through the nonlinear depreciation mapping, raises the conditional mean of effective depreciation.

Comparing Figures 5 and 3 helps clarify the specific role of climate risk in the model. Both shocks are contractionary, but the climate-volatility shock generates a much more persistent response and, crucially, triggers a marked reallocation away from non-resilient capital together with a sustained rise in endogenous climate damage. By contrast, the financial shock mainly works through tighter borrowing conditions and a temporary decline in activity. This comparison underscores that climate risk and financial frictions are complementary amplification mechanisms, but not equivalent sources of fluctuations.

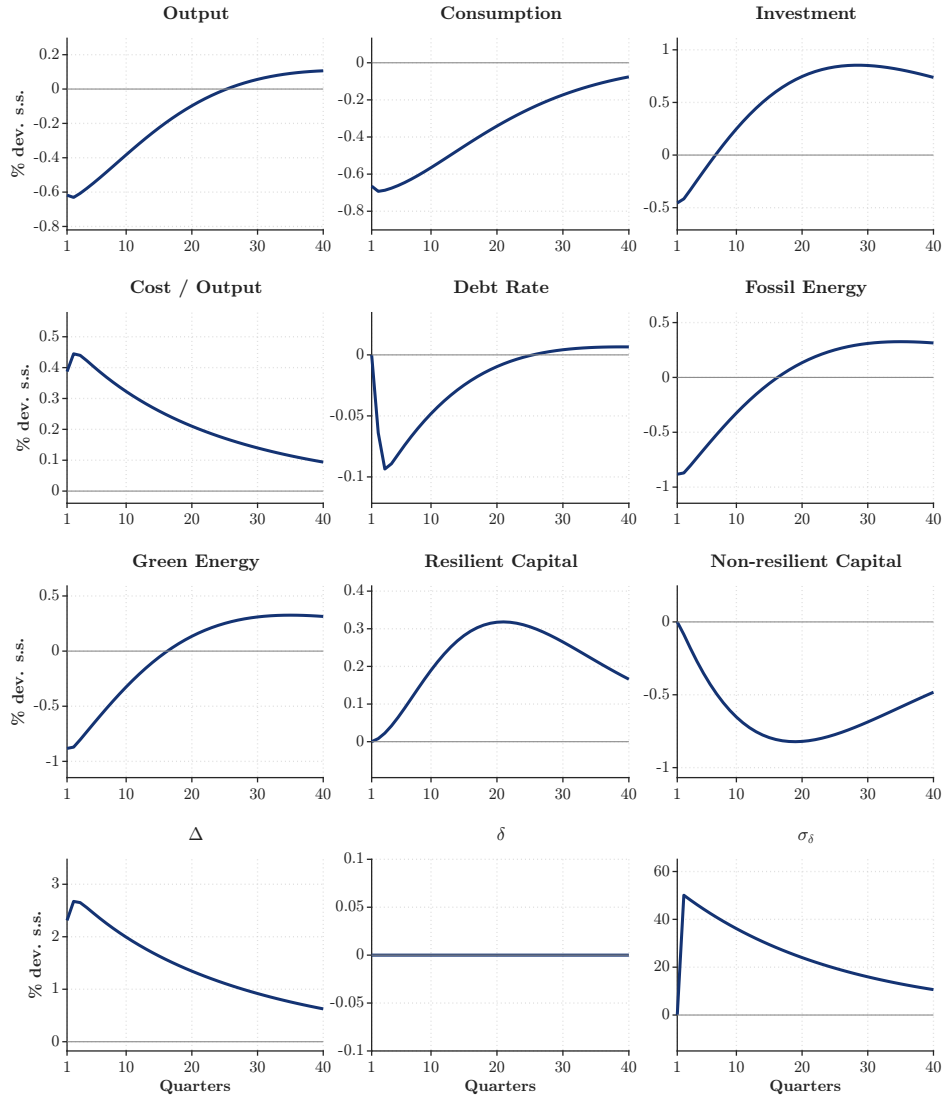


Figure 5: GIRFs to a one-standard-deviation shock to the volatility of climate damages.

Note: Impulse response functions are reported as percent deviations from steady state.

Taken together, the GIRFs deliver two main messages that speak directly to the quantitative role of climate shocks relative to conventional macroeconomic shocks. First, shocks to climate damages generate macroeconomic effects that are distinct from those of TFP and financial shocks because they operate through capital destruction and the endogenous reallocation of capital. Second, uncertainty about future climate damages is itself an important driver of aggregate fluctuations. Among the climate shocks considered, the volatility shock produces the strongest and most persistent contraction, as well as the largest shift away from non-resilient capital. More broadly, the comparison across all four shocks shows that climate shocks are not merely secondary propagation channels, but can act as quantitatively important sources of business-cycle dynamics alongside standard macroeconomic shocks.

The Appendix reports complementary impulse responses that implement sensitivity exercises regarding the degree of financial frictions and the composition of the capital stock, supporting the quantitative analysis presented above. The results reveal that tighter financial frictions amplify the contractionary effects of climate damage shocks, reflecting the greater difficulty of reallocating resources when credit conditions are more constrained. Conversely, a higher steady-state share of resilient capital attenuates the macroeconomic impact of climate-damage-related shocks, since a larger share of the capital stock is not exposed to the destruction caused by such shocks.

Having established that climate shocks generate quantitatively important macroeconomic fluctuations, the following section uses this environment to analyze how mitigation and adaptation policies affect the real allocations and welfare of the economy.

6 Mitigation and adaptation to climate risks

Our model produces plausible quantitative dynamics for key macroeconomic variables. We use the model to analyze the role of policies that induce mitigation or adaptation behavior by firms. We measure which type of policy is more relevant in terms of welfare, output costs, and cost-to-output ratios. The mitigation policy is a Pigouvian tax on polluting energy; the adaptation policy is a tax on non-resilient capital. Both policies generate

equal fiscal revenues over output in steady state, redistributed to households as lump-sum transfers.¹¹

Figure 6 reports the GIRFs to a one-standard-deviation shock to the level of climate damages under both policy regimes. Under mitigation, the Pigouvian tax on fossil energy directly reduces the polluting input responsible for the build-up of atmospheric carbon, limiting the transmission of the damage shock through the depreciation channel. As a consequence, the contraction in output and consumption is somewhat more contained under mitigation, and the increase in the cost-to-output ratio is smaller.

¹¹To ensure a fair comparison, we calibrate the adaptation tax rate so that the steady state of fiscal revenues relative to output exactly matches the corresponding ratio under the mitigation tax. The resulting revenue-to-output ratio is 0.22% of GDP under both policies.

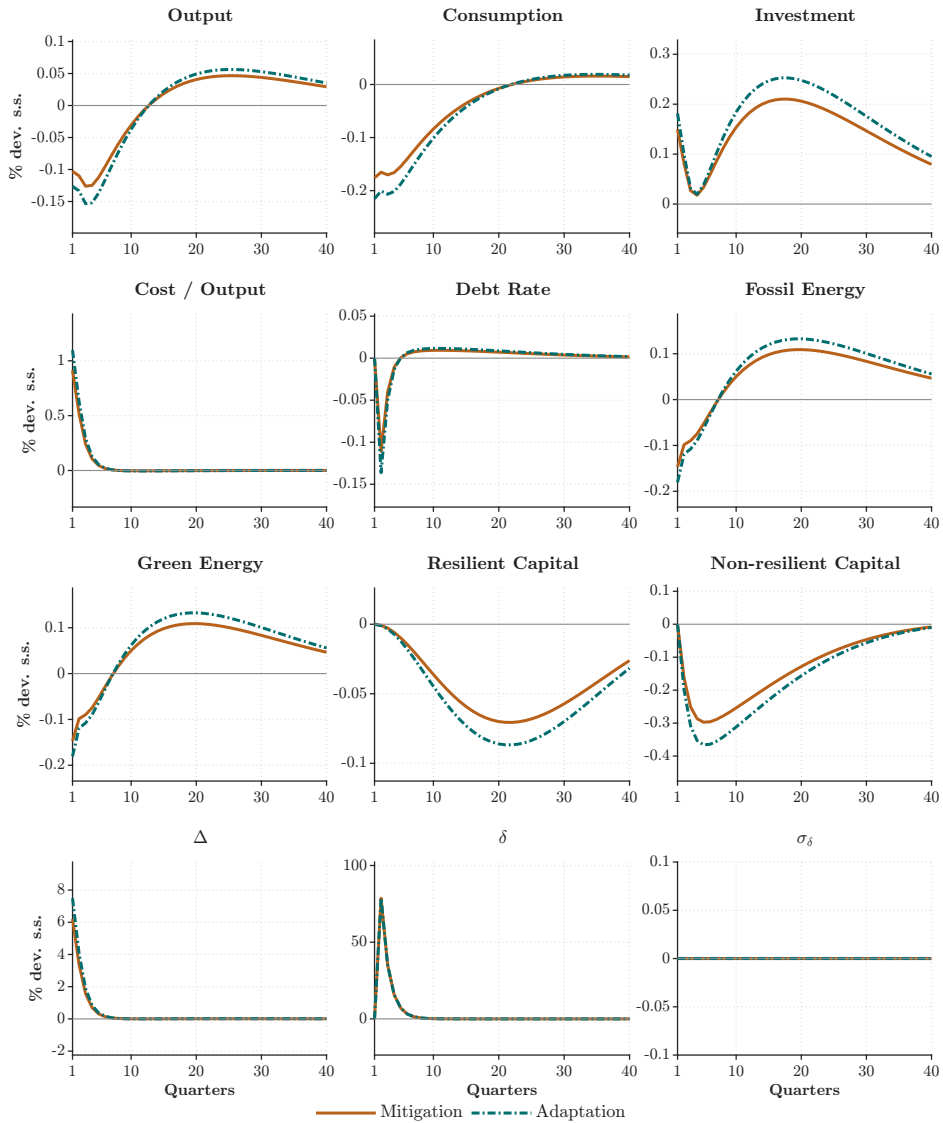


Figure 6: Generalized impulse responses to a one-standard-deviation shock to climate damages under mitigation and adaptation policies. Responses are reported as percent deviations from steady state.

Figure 7 shows the responses to a one-standard-deviation shock to the volatility of climate damages. As stated above, this shock does not immediately alter the level of damages but raises uncertainty about future capital losses, triggering precautionary contractions in output, consumption, and non-resilient capital. Relative to the damage-level shock, the divergence between policies is somewhat more visible.

The evidence so far suggests that, although both policies generate qualitatively similar dynamics, mitigation makes the economy more resilient to climate-related damages. The

adaptation tax does encourage a shift toward resilient capital, but it does not reduce the underlying flow of climate damages. As a result, the stronger contraction under adaptation lowers overall investment during the first quarters, so resilient investment increases less than under mitigation. By contrast, mitigation reduces the use of the polluting input at the source and helps sustain aggregate activity, allowing resilient investment to rise more strongly.

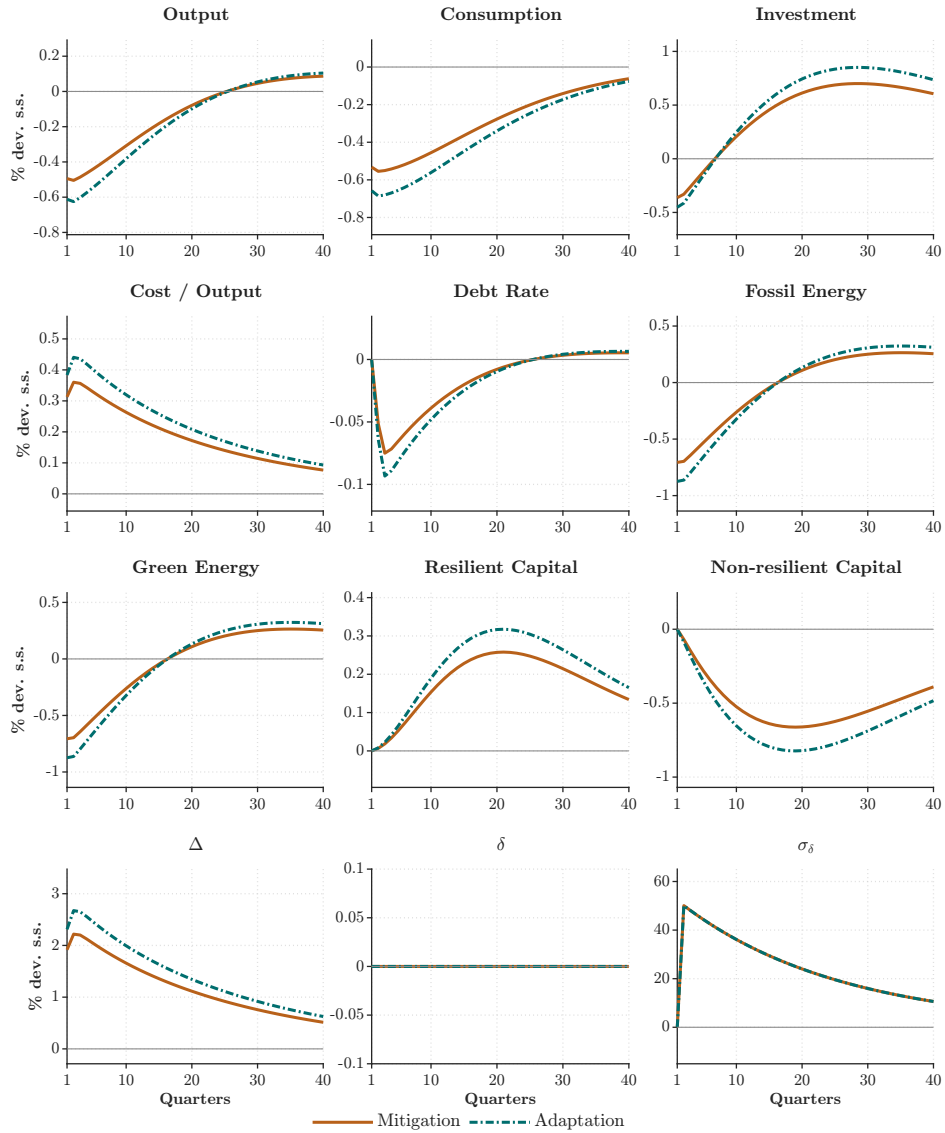


Figure 7: Generalized impulse responses to a one-standard-deviation shock to the volatility of climate damages under mitigation and adaptation policies. Responses are reported as percent deviations from steady state.

Table 6: Mitigation versus adaptation policies under damage and volatility shocks

	Mitigation	Adaptation
Damage shock		
Rev./Y (%)	0.22	0.22
Impact welfare loss (utils)	0.000122	0.000151
Disc. welfare loss (utils)	0.002311	0.002837
Peak output loss (%)	0.1261	0.1533
Cum. cost/Y (p.p.)	1.8254	2.1912
Volatility shock		
Rev./Y (%)	0.22	0.22
Impact welfare loss (utils)	0.000144	0.000177
Disc. welfare loss (utils)	0.005139	0.006354
Peak output loss (%)	0.5048	0.6252
Cum. cost/Y (p.p.)	5.2356	6.3694

Note: Rev./Y is the steady-state value of fiscal revenues relative to output. Impact welfare is the contemporaneous decline in period utility on impact. Disc. welfare is the discounted sum of period-utility losses over 20 quarters. Peak output loss is the maximum decline in output relative to the no-shock baseline. Cum. cost/Y is the 20-quarter cumulative increase in the cost-to-output ratio.

Table 6 summarizes the welfare and output-cost metrics for both policies across both shocks. Mitigation dominates adaptation uniformly across all metrics. Under the damage shock, the impact welfare loss under mitigation is 0.000122 utils against 0.000151 utils under adaptation, and the discounted sum of welfare losses over 20 quarters is 0.0023 under mitigation compared with 0.0028 under adaptation. Peak output losses and cumulative cost-to-output losses follow the same ordering, with the adaptation regime generating larger macroeconomic disruptions in every dimension. The same ranking holds under the volatility shock, where all losses are substantially amplified relative to the damage shock: peak output losses are roughly four times larger and cumulative cost-to-output losses approximately three times larger for both regimes, underscoring the quantitative importance of the second-moment channel documented in Section 5. The relative advantage of mitigation over adaptation is stable across both shocks and all metrics, with the discounted welfare loss under adaptation exceeding that under mitigation by roughly 23 percent regardless of the shock considered.

The intuition for the dominance of mitigation is straightforward. The Pigouvian tax addresses the source of climate damages by curbing the use of the polluting input, thereby limiting future accumulation of atmospheric carbon and reducing the economy's exposure to capital destruction. The adaptation tax, while redirecting investment toward the resilient variety of capital, does not reduce the underlying damage flow itself and therefore requires a larger reallocation of productive resources to contain climate losses.

7 Concluding remarks

This paper documents that the frequency and severity of climate-related shocks have increased in the US over the past four decades. We develop a real business cycle model to study how CO₂ accumulation in the atmosphere shapes the transmission of climate shocks and standard macroeconomic shocks. We calibrate the model to match the most salient features of the U.S. economy and show that the model can produce quantitatively plausible dynamics.

We show that the climate block of the model acts as an endogenous as an asymmetric propagation margin for traditional macroeconomic shocks. Particularly, the exposure to climate risks dampens the expansion of the economy after a positively supply shock. Moreover, the climate block generates sizable effects on macroeconomic outcomes through both level and volatility shocks to climate damages.

In this context, we evaluate two policy responses. Mitigation policies, modeled as a tax on polluting energy use, reduce CO₂ emissions directly and thereby attenuate the source of climate risk; and adaptation policies, modeled as a tax on non-resilient capital, induce firms to shift toward climate-resilient investment. When computing the dynamics of the economy after climate shocks, we find that mitigation policies are more effective, implying lower output costs and lower welfare costs, reflecting their direct impact on the accumulation of atmospheric CO₂.

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Appendix

A.1 Equilibrium conditions

This appendix reports the full set of equilibrium conditions implied by the optimization problems of households, capital producers, entrepreneurs, and firms, together with market-clearing conditions, auxiliary definitions, and the laws of motion for the exogenous processes.

A.1.1 Households

$$\lambda_t = (c_t - \psi l_t^\theta x_t)^{-\sigma} + \mu_t \eta c_t^{\eta-1} x_{t-1}^{1-\eta}, \quad (\text{A.1})$$

$$(c_t - \psi l_t^\theta x_t)^{-\sigma} \psi l_t^\theta + \mu_t = \beta \mathbb{E}_t [\mu_{t+1} c_{t+1}^\eta (1 - \eta) x_t^{-\eta}], \quad (\text{A.2})$$

$$(c_t - \psi l_t^\theta x_t)^{-\sigma} \psi \theta l_t^{\theta-1} x_t = \lambda_t w_t, \quad (\text{A.3})$$

$$\lambda_t = \beta R_t^b \mathbb{E}_t [\lambda_{t+1}], \quad (\text{A.4})$$

$$x_t = c_t^\eta x_{t-1}^{1-\eta}. \quad (\text{A.5})$$

A.1.2 Resilient capital producers

$$1 = q_t^r \left[1 - \frac{\Phi_r}{2} \left(\frac{i_{r,t}}{i_{r,t-1}} - 1 \right)^2 - \Phi_r \left(\frac{i_{r,t}}{i_{r,t-1}} - 1 \right) \frac{i_{r,t}}{i_{r,t-1}} \right] + \beta \mathbb{E}_t \left[\frac{\lambda_{t+1}}{\lambda_t} q_{t+1}^r \Phi_r \left(\frac{i_{r,t+1}}{i_{r,t}} - 1 \right) \left(\frac{i_{r,t+1}}{i_{r,t}} \right)^2 \right], \quad (\text{A.6})$$

$$k_{r,t+1} = (1 - \delta_r) k_{r,t} + \left[1 - \frac{\Phi_r}{2} \left(\frac{i_{r,t}}{i_{r,t-1}} - 1 \right)^2 \right] i_{r,t}. \quad (\text{A.7})$$

A.1.3 Non-resilient capital producers

$$1 = q_t^n \left[1 - \frac{\Phi_n}{2} \left(\frac{i_{n,t}}{i_{n,t-1}} - 1 \right)^2 - \Phi_n \left(\frac{i_{n,t}}{i_{n,t-1}} - 1 \right) \frac{i_{n,t}}{i_{n,t-1}} \right] + \beta \mathbb{E}_t \left[\frac{\lambda_{t+1}}{\lambda_t} q_{t+1}^n \Phi_n \left(\frac{i_{n,t+1}}{i_{n,t}} - 1 \right) \left(\frac{i_{n,t+1}}{i_{n,t}} \right)^2 \right], \quad (\text{A.8})$$

$$k_{n,t+1} = (1 - \Delta_{n,t})k_{n,t} + \left[1 - \frac{\Phi_n}{2} \left(\frac{i_{n,t}}{i_{n,t-1}} - 1 \right)^2 \right] i_{n,t}, \quad (\text{A.9})$$

$$\Delta_{n,t} = \hat{\delta}_n \exp(\delta_{n,t}(s_t - \bar{s})). \quad (\text{A.10})$$

A.1.4 Entrepreneurs

$$R_t^r = \frac{r_t^r + (1 - \delta_r)q_t^r}{q_{t-1}^r}, \quad (\text{A.11})$$

$$R_t^n = \frac{r_t^n + (1 - \Delta_{n,t})q_t^n}{q_{t-1}^n}, \quad (\text{A.12})$$

$$0 = \mathbb{E}_t \left[\beta \frac{\lambda_{t+1}}{\lambda_t} (R_{t+1}^r - R_t^d) \right], \quad (\text{A.13})$$

$$0 = \mathbb{E}_t \left[\beta \frac{\lambda_{t+1}}{\lambda_t} (R_{t+1}^n - R_t^d) \right], \quad (\text{A.14})$$

$$R_t^d = \chi_t R_t^b, \quad (\text{A.15})$$

$$\chi_t = \bar{\chi} + \left(\frac{d_t}{n_t} \right)^{\chi_e} - \bar{d}n^{\chi_e} + \xi_t^{\text{fin}}, \quad (\text{A.16})$$

$$q_t^r k_{r,t+1} + q_t^n k_{n,t+1} = d_t + n_t, \quad (\text{A.17})$$

$$n_t = \omega (R_t^r q_{t-1}^r k_{r,t} + R_t^n q_{t-1}^n k_{n,t} - R_{t-1}^d d_{t-1}) + (1 - \omega)\bar{W}. \quad (\text{A.18})$$

A.1.5 Final-good producers

$$y_t = a_{0,t} k_{0,t}^\alpha l_{0,t}^{1-\alpha-\nu} e_{0,t}^\nu, \quad (\text{A.19})$$

$$e_{0,t} = [\kappa e_{g,t}^\rho + (1 - \kappa) e_{f,t}^\rho]^{1/\rho}, \quad (\text{A.20})$$

$$k_{0,t} = [\zeta (k_{r,t})^\nu + (1 - \zeta) (k_{n,t})^\nu]^{1/\nu}, \quad (\text{A.21})$$

$$w_t = a_{0,t} (1 - \alpha - \nu) k_{0,t}^\alpha l_{0,t}^{-\alpha-\nu} e_{0,t}^\nu, \quad (\text{A.22})$$

$$r_t^r = a_{0,t} \alpha k_{0,t}^{\alpha-\nu} \zeta (k_{r,t})^{\nu-1} l_{0,t}^{1-\alpha-\nu} e_{0,t}^\nu, \quad (\text{A.23})$$

$$r_t^n = a_{0,t} \alpha k_{0,t}^{\alpha-\nu} (1 - \zeta) (k_{n,t})^{\nu-1} l_{0,t}^{1-\alpha-\nu} e_{0,t}^\nu, \quad (\text{A.24})$$

$$p_t^f = a_{0,t} \nu k_{0,t}^\alpha l_{0,t}^{1-\alpha-\nu} e_{0,t}^{\nu-\rho} (1 - \kappa) e_{f,t}^{\rho-1}, \quad (\text{A.25})$$

$$p_t^g = a_{0,t} \nu k_{0,t}^\alpha l_{0,t}^{1-\alpha-\nu} e_{0,t}^{\nu-\rho} \kappa e_{g,t}^{\rho-1}. \quad (\text{A.26})$$

A.1.6 Energy producers

$$p_t^f = \frac{w_t}{a_{f,t}}, \quad (\text{A.27})$$

$$e_{f,t} = a_{f,t} l_{f,t}, \quad (\text{A.28})$$

$$p_t^g = \frac{w_t}{a_{g,t}}, \quad (\text{A.29})$$

$$e_{g,t} = a_{g,t} l_{g,t}. \quad (\text{A.30})$$

A.1.7 Market clearing

$$(1 - \bar{g}) y_t = c_t + i_{r,t} + i_{n,t}, \quad (\text{A.31})$$

$$l_t = l_{0,t} + l_{f,t} + l_{g,t}. \quad (\text{A.32})$$

A.1.8 Definitions

$$s_t - \bar{s} = \phi_0 \xi e_{f,t} + (1 - \phi) (s_{t-1} - \bar{s}), \quad (\text{A.33})$$

$$\frac{\text{cost}_t}{y_t} = \frac{q_t^n (\Delta_{n,t} - \hat{\delta}_n) k_{n,t}}{y_t}. \quad (\text{A.34})$$

A.1.9 Exogenous processes

$$\log a_{0,t} = (1 - \rho_{a_0}) \log \bar{a}_0 + \rho_{a_0} \log a_{0,t-1} + \sigma_{a_0} \varepsilon_t^{a_0}, \quad \varepsilon_t^{a_0} \sim \mathcal{N}(0, 1), \quad (\text{A.35})$$

$$\log a_{f,t} = (1 - \rho_{a_f}) \log \bar{a}_f + \rho_{a_f} \log a_{f,t-1} + \sigma_{a_f} \varepsilon_t^{a_f}, \quad \varepsilon_t^{a_f} \sim \mathcal{N}(0, 1), \quad (\text{A.36})$$

$$\log a_{g,t} = (1 - \rho_{a_g}) \log \bar{a}_g + \rho_{a_g} \log a_{g,t-1} + \sigma_{a_g} \varepsilon_t^{a_g}, \quad \varepsilon_t^{a_g} \sim \mathcal{N}(0, 1), \quad (\text{A.37})$$

$$\log \delta_{n,t} = (1 - \rho_\delta) \log \bar{\delta}_n + \rho_\delta \log \delta_{n,t-1} + \sigma_t^\delta \varepsilon_t^\delta, \quad \varepsilon_t^\delta \sim \mathcal{N}(0, 1), \quad (\text{A.38})$$

$$\log \sigma_t^\delta = (1 - \rho_\sigma) \log \bar{\sigma}^\delta + \rho_\sigma \log \sigma_{t-1}^\delta + \sigma_\sigma \varepsilon_t^\sigma, \quad \varepsilon_t^\sigma \sim \mathcal{N}(0, 1), \quad (\text{A.39})$$

$$\xi_t^{\text{fin}} = \rho_f \xi_{t-1}^{\text{fin}} + \sigma_f \varepsilon_t^{\text{fin}}, \quad \varepsilon_t^{\text{fin}} \sim \mathcal{N}(0, 1). \quad (\text{A.40})$$

A.2 Steady state

$$\xi^{\text{fin}} = 0 \quad (\text{A.41})$$

$$a_0 = \bar{a}_0 \quad (\text{A.42})$$

$$a_f = \bar{a}_f \quad (\text{A.43})$$

$$a_g = \bar{a}_g \quad (\text{A.44})$$

$$\sigma^\delta = \bar{\sigma}^\delta \quad (\text{A.45})$$

$$\delta_n = \bar{\delta}_n \quad (\text{A.46})$$

$$q^r = 1 \quad (\text{A.47})$$

$$q^n = 1 \quad (\text{A.48})$$

$$R^b = \frac{1}{\beta} \quad (\text{A.49})$$

$$\chi = \bar{\chi} \quad (\text{A.50})$$

$$R^d = \chi R^b \quad (\text{A.51})$$

$$R^r = R^d \quad (\text{A.52})$$

$$R^n = R^d \quad (\text{A.53})$$

$$r^r = R^r - 1 + \delta_r \quad (\text{A.54})$$

$$l = 1 \quad (\text{A.55})$$

$$\varrho = \left(\frac{\kappa a_g}{(1-\kappa)a_f} \right)^{\frac{1}{\rho-1}} \left(\frac{a_g}{a_f} \right) \quad (\text{A.56})$$

$$0 = \nu \kappa a_g^\rho l_g^{\rho-1} (l - \varrho l_g - l_g) - (1 - \alpha - \nu) [\kappa (a_g l_g)^\rho + (1 - \kappa) (a_f \varrho l_g)^\rho] \quad (\text{A.57})$$

$$l_f = \varrho l_g \quad (\text{A.58})$$

$$l_0 = l - l_f - l_g \quad (\text{A.59})$$

$$e_f = a_f l_f \quad (\text{A.60})$$

$$e_g = a_g l_g \quad (\text{A.61})$$

$$e_0 = [\kappa e_g^\rho + (1 - \kappa) e_f^\rho]^{1/\rho} \quad (\text{A.62})$$

$$s = \bar{s} + \frac{\phi_0 \xi}{\phi} e_f \quad (\text{A.63})$$

$$\Delta_n = \hat{\delta}_n \exp(\delta_n (s - \bar{s})) \quad (\text{A.64})$$

$$r^n = R^n - 1 + \Delta_n \quad (\text{A.65})$$

$$\varpi = \left[\left(\frac{r^r}{r^n} \right) \left(\frac{1 - \zeta}{\zeta} \right) \right]^{\frac{1}{v-1}} \quad (\text{A.66})$$

$$k_n = \left[\frac{a_0 \alpha (\zeta \varpi^v + 1 - \zeta)^{\frac{\alpha-v}{v}} (1 - \zeta) l_0^{1-\alpha-\nu} e_0^\nu}{r^n} \right]^{\frac{1}{1-\alpha}} \quad (\text{A.67})$$

$$k_r = \varpi k_n \quad (\text{A.68})$$

$$k_0 = [\zeta k_r^v + (1 - \zeta) k_n^v]^{1/v} \quad (\text{A.69})$$

$$y = a_0 k_0^\alpha l_0^{1-\alpha-\nu} e_0^\nu \quad (\text{A.70})$$

$$i_r = \delta_r k_r \quad (\text{A.71})$$

$$i_n = \Delta_n k_n \quad (\text{A.72})$$

$$n = \frac{q^r k_r + q^n k_n}{1 + \overline{dn}} \quad (\text{A.73})$$

$$d = \overline{dn} n \quad (\text{A.74})$$

$$\bar{W} = \frac{n - \omega (R^r q^r k_r + R^n q^n k_n - R^d d)}{1 - \omega} \quad (\text{A.75})$$

$$c = y - i_r - i_n - \bar{g}y \quad (\text{A.76})$$

$$x = c \quad (\text{A.77})$$

$$w = a_0 (1 - \alpha - \nu) k_0^\alpha l_0^{1-\alpha-\nu} e_0^\nu \quad (\text{A.78})$$

$$p^f = a_0 \nu k_0^\alpha l_0^{1-\alpha-\nu} e_0^{\nu-\rho} (1-\kappa) e_f^{\rho-1} \quad (\text{A.79})$$

$$p^g = a_0 \nu k_0^\alpha l_0^{1-\alpha-\nu} e_0^{\nu-\rho} \kappa e_g^{\rho-1} \quad (\text{A.80})$$

$$\psi = \left[\frac{\theta l^{\theta-1} x}{w} - \frac{\eta l^\theta}{\beta(1-\eta) - 1} \right]^{-1} \quad (\text{A.81})$$

$$\mu = \frac{(c - \psi l^\theta x)^{-\sigma} \psi l^\theta}{\beta(1-\eta) c^\eta x^{-\eta} - 1} \quad (\text{A.82})$$

$$\lambda = (c - \psi l^\theta x)^{-\sigma} + \mu \eta \quad (\text{A.83})$$

$$\frac{\text{cost}}{y} = \frac{q^n (\Delta_n - \hat{\delta}_n) k_n}{y} \quad (\text{A.84})$$

A.3 Additional quantitative results

A.3.1 Sensitivity to financial frictions

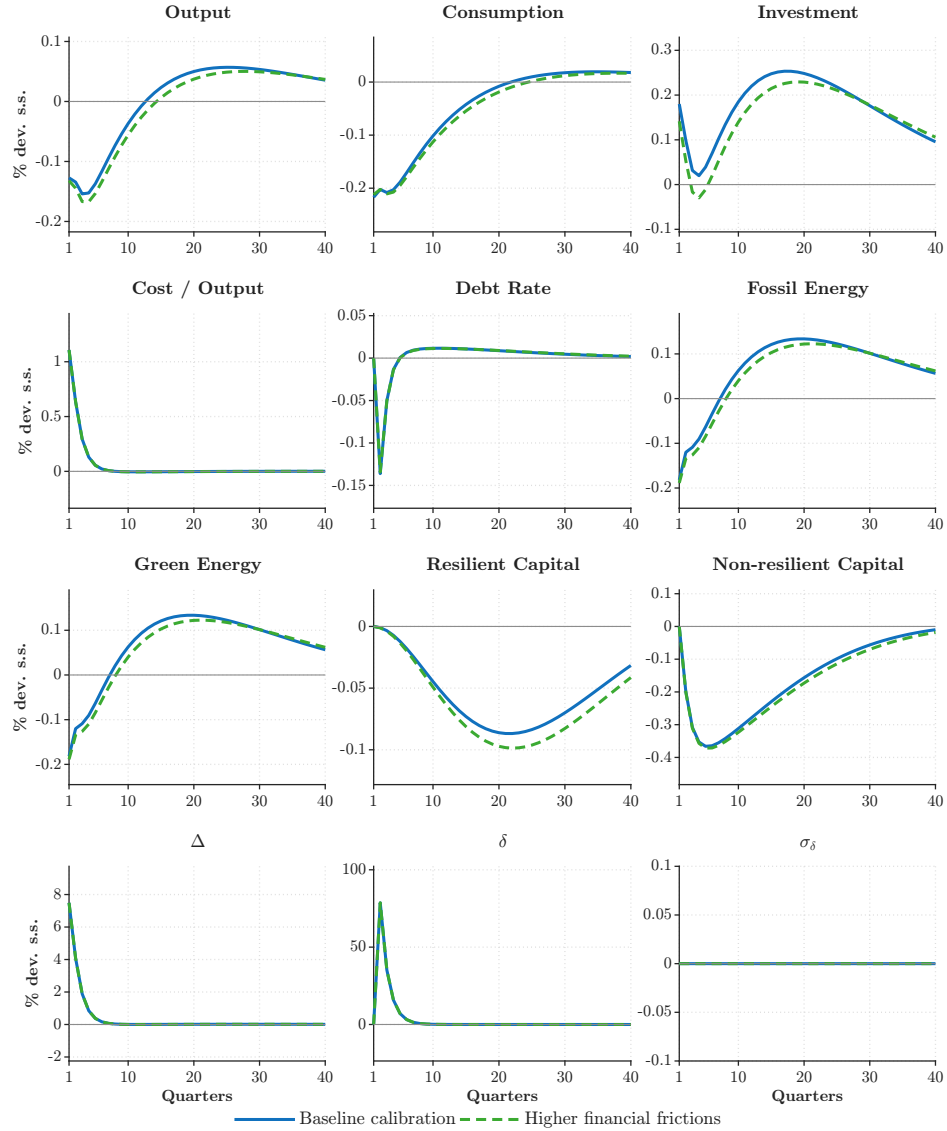


Figure 8: Generalized impulse responses to a one-standard-deviation climate-damage shock: sensitivity to financial frictions.

Note: Responses are reported as percent deviations from steady state. The solid line corresponds to the baseline calibration, with leverage equal to 0.33. The dashed line corresponds to an alternative calibration with leverage equal to 0.5. Stronger financial frictions amplify the macroeconomic effects of the climate-damage shock.

A.3.2 Sensitivity to the share of resilient capital

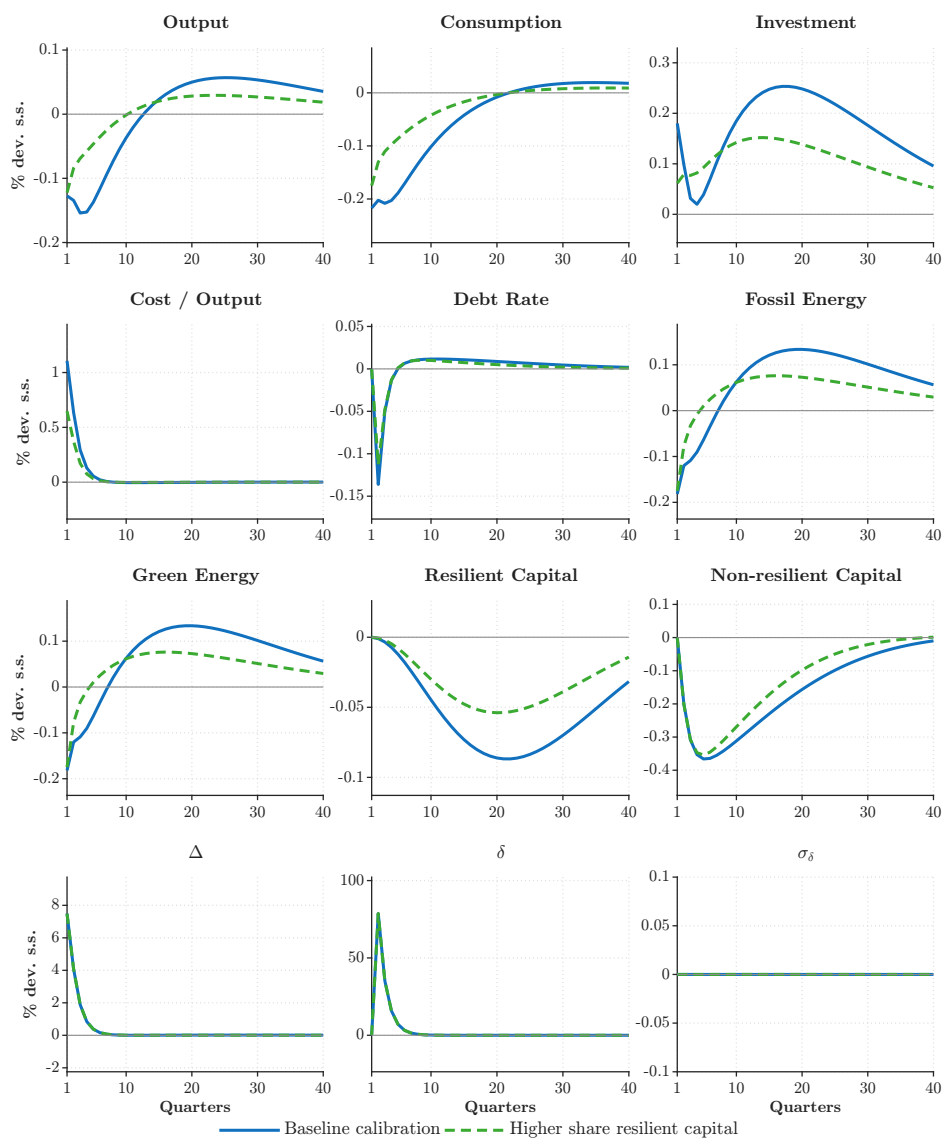


Figure 9: Generalized impulse responses to a one-standard-deviation climate-damage shock: sensitivity to the share of resilient capital.

Note: Responses are reported as percent deviations from steady state. The solid line corresponds to the baseline calibration, in which the share of resilient capital is 0.2301. The dashed line corresponds to an alternative calibration in which the share of resilient capital is 0.5. A larger share of resilient capital reduces the economy's exposure to climate-damage shocks.

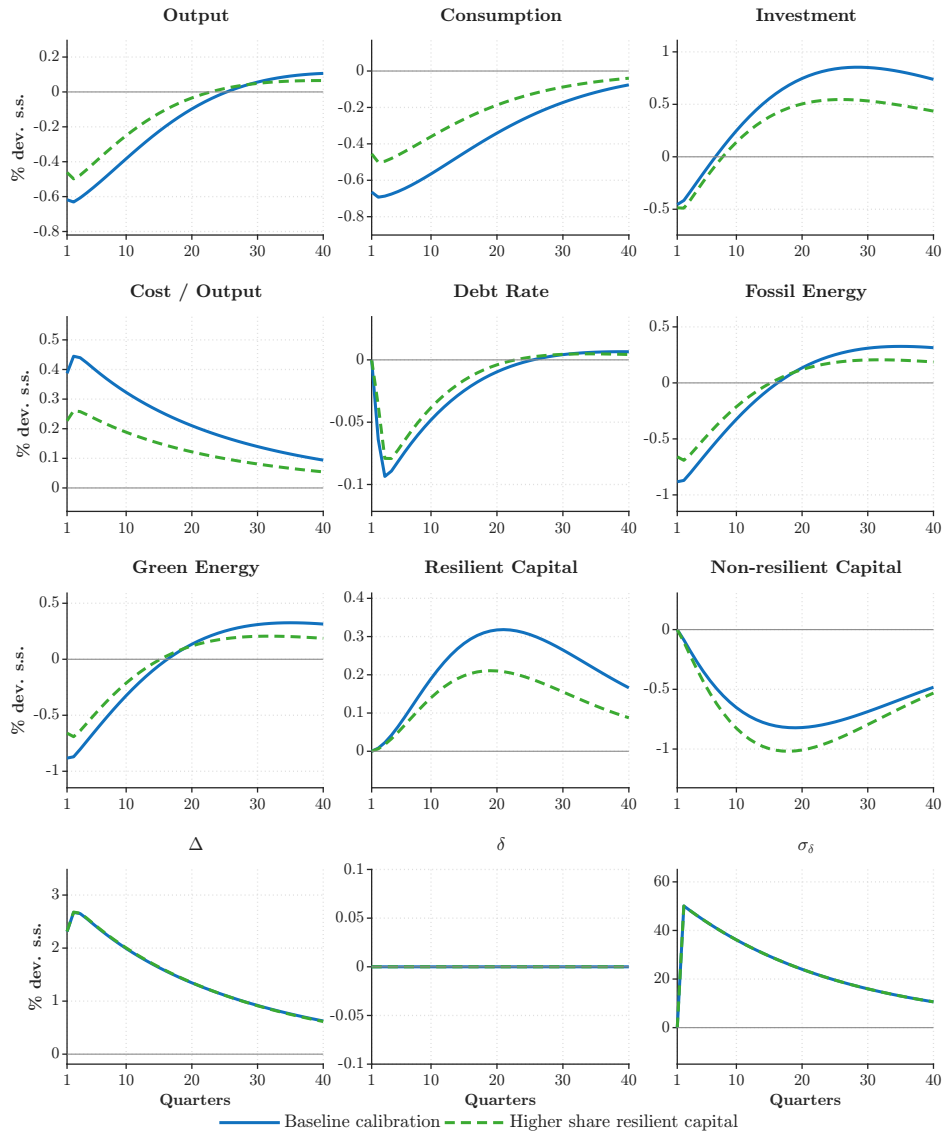


Figure 10: Generalized impulse responses to a one-standard-deviation shock to the volatility of climate damages: sensitivity to the share of resilient capital.

Note: Responses are reported as percent deviations from steady state. The solid line corresponds to the baseline calibration, in which the share of resilient capital is 0.2301. The dashed line corresponds to an alternative calibration in which the share of resilient capital is 0.5. A larger share of resilient capital reduces the economy's exposure to shocks to the volatility of climate damages.