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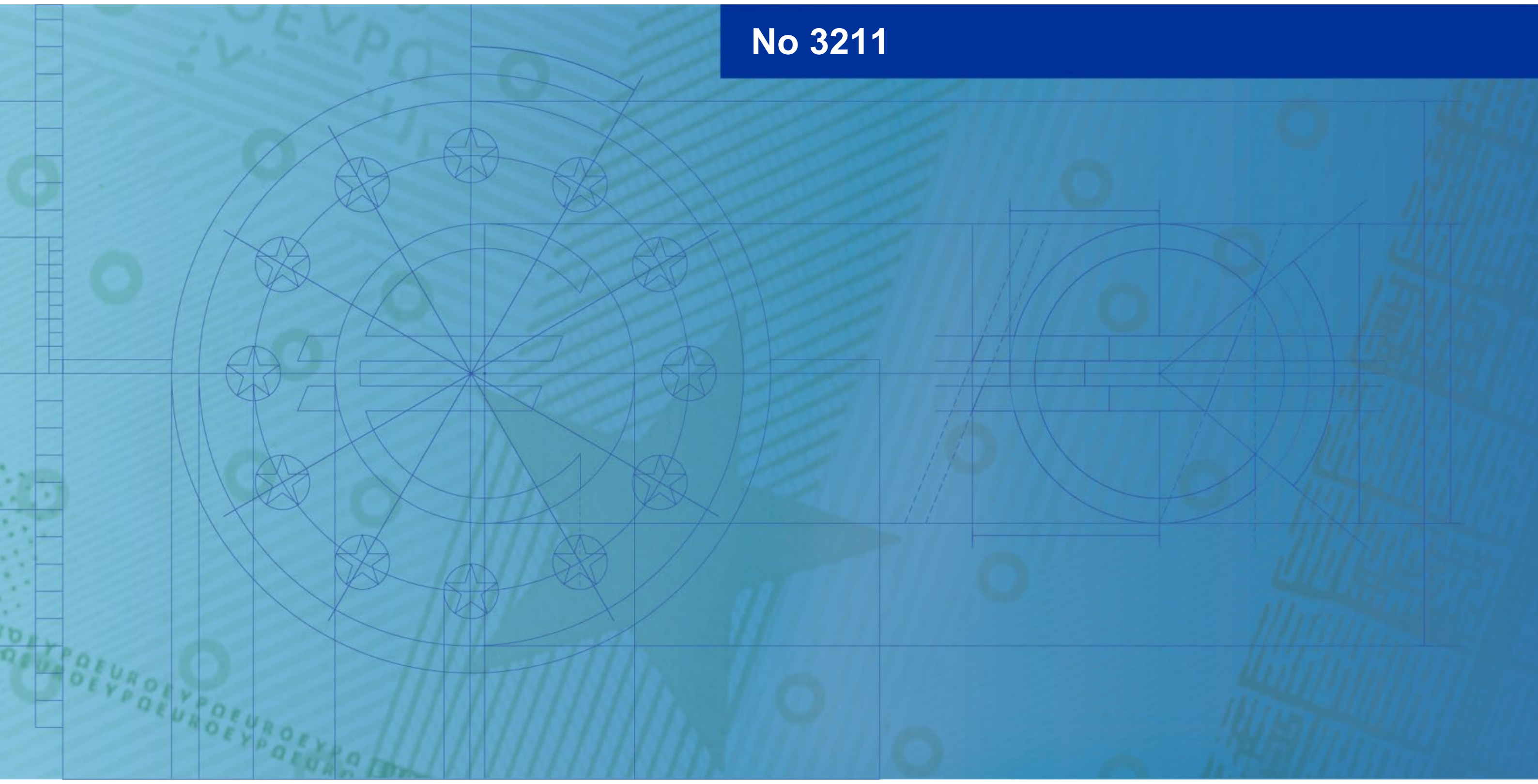
Severe weather and financial (in)stability



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Abstract

We quantify the effect of severe weather shocks on the US economy in an environment in which the economy can switch between periods of financial stability and financial instability, like the Great Recession. We estimate a New Keynesian dynamic stochastic general equilibrium model with banks and severe weather events. We show that severe weather shocks: 1) have a negative impact on real and financial US variables, sizable only in periods of financial instability, but muted effects on nominal variables; 2) are never a relevant source of business cycles fluctuations; 3) transmit mainly via a deterioration in the quality of capital.

Keywords: Severe weather shocks, Actuaries Climate Index, NK DSGE models, Financial frictions, Markov Switching

JEL classification: Q54, E32, E44

Non technical summary

Interest in the connections among severe weather events, the economy, and financial stability has risen among researchers and policymakers. While an expanding literature seeks to quantify the macroeconomic impact of severe weather on the US macroeconomy, there remains a paucity of research that formally integrates the financial system into these assessments. This paper aims to address this lacuna.

The first step of our analysis is to formalize the relationship between severe weather events, the US economy, and the US financial system. We develop a New Keynesian dynamic stochastic general equilibrium (NK DSGE) model which includes a role for US banks, along the lines of Gertler and Karadi (2011) which embeds the financial accelerator mechanism, and for severe weather events.

Our main goal and contribution is to quantify the effects of severe weather shocks on the US economy by addressing the literature's silence regarding the role that the financial system can play in the propagation of those shocks. To achieve this, we extend our framework beyond the mere integration of the financial accelerator mechanism into our NK DSGE model by explicitly accounting for the non-linear relationship that might exist between financial instability and severe weather events. In fact, it is reasonable to expect that periods of financial instability might be associated with a bigger impact of weather shocks. The intuition is that the negative consequences of shocks are more pronounced when banks are already under stress, i.e., when the banking sector is particularly vulnerable, at the moment the shock hits.

To capture all this, we estimate our NK DSGE model under the assumption that the economy can switch between two regimes, one characterized by financial instability and one by financial stability. We use a Markov Switching approach. The use of a NK DSGE model has the advantage of highlighting the channels of transmission through which severe weather shocks propagate, and providing a theory based interpretation of those channels. Moreover, given that we estimate our model, we can establish the most quantitatively relevant channels.

Our results show that severe weather shocks have a negative impact on the real economic activity, especially on investment. Consistently with that, banks net worth drops and credit premium increases. Severe weather shocks appear to be deflationary, although the effects on inflation are very modest. As a result, consistently with our estimated Taylor rule, monetary policy responds by decreasing the federal funds rate, by few basis as well. In periods characterized by financial instability, which the estimation identifies with the Great Recession in our sample, the effects of severe weather shocks are stronger for all the observed variables. Despite that, severe weather shocks are never a relevant source of business cycle fluctuations. The main channel of transmission is through shocks to the quality of capital. The destruction of physical capital impairs both goods producing firms, which produce less, and banks assets side, leading to a deterioration of their balance sheet and of the borrowing and lending activity. That gives rise to the accelerator mechanism. Finally, an analysis of different types of weather events comprising the ACI –temperatures, rainfall, drought, wind, and sea level– reveals that temperature and sea level shocks drive the largest GDP contractions.

1 Introduction

Interest in the connections among severe weather events, the economy, and financial stability has risen among researchers and policymakers. Lagarde (2021) notes that extreme weather events can impact output, inflation, and the financial system. Brunetti et al. (2021) point out that "vulnerabilities, which are underlying features of ... a financial system, ... can amplify the negative effects of ... climate-change related shocks." For example, "weather-related property destruction can lead to bank losses, leading to less lending, leading to reduced investment, and so on." Similar arguments can also be found in the November 2020 Financial Stability Report issued by the Board of Governors of the Federal Reserve System, and Brunetti et al. (2024), in a Federal Reserve Bank of New York Economic Policy Review, recently reemphasized them.[1]

At the same time, while an expanding literature, reviewed in the following subsection, seeks to quantify the macroeconomic impact of severe weather on the US macroeconomy, there remains a paucity of research that formally integrates the financial system into these assessments. This paper aims to address this lacuna.

The first step of our analysis is to formalize the relationship between severe weather events, the US economy, and the US financial system. The Brunetti et al. (2021) quote and the November 2020 Financial Stability Report highlight channels through which the financial system may amplify the effects of severe weather shocks, and it does that through second round effects. This means that severe weather shocks have a negative impact on the real US economy, which in turn has negative effects on banks, which in turn has further negative effects on the real US economy. This is all consistent with the financial accelerator theory in a general equilibrium framework (see Bernanke, Gertler and Gilchrist, 1999).

Therefore, we develop a New Keynesian dynamic stochastic general equilibrium (NK DSGE) model that includes a role for US banks, along the lines of Gertler and Karadi (2011) which also embeds the financial accelerator mechanism, and for severe weather events. To comply with our quantitative perspective, we estimate the model with US macroeconomic and financial data and the Actuaries Climate Index (ACI) for the period 1992M1-2019M12, a period where, according to Kim, Matthes and Phan (2025), weather shocks have been found to have stronger effects on the US economy.

Our main goal and contribution, then, is to quantify the effects of severe weather shocks on the US

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[1] See the box "The Implications of Climate Change for Financial Stability" in Board of Governors of the Federal Reserve System (2020).

economy by addressing the literature's silence regarding the role that the financial system can play in the propagation of those shocks.[2] To achieve this, we extend our framework beyond the mere integration of the financial accelerator mechanism into our NK DSGE model–an approach that, in itself, offers a way to address the silence of the literature– by explicitly accounting for the non-linear relationship that might exist between financial instability and severe weather events. In fact, it is reasonable to expect that periods of financial instability, identified as periods of high levels of banks' leverage in our analysis, might be associated with a bigger impact of weather shocks.[3] The intuition is that the negative consequences of shocks are more pronounced when banks are already under stress, i.e., when vulnerabilities are higher, at the moment the shock hits. To capture all this, we estimate our NK DSGE model under the assumption that the economy can switch between two regimes, one characterized by financial instability and one by financial stability. We use a Markov switching approach. The non-linear framework adds on the financial accelerator mechanism, leading to a further exacerbation of the effects of shocks on the economy in periods when the financial system is particularly vulnerable.

We contribute to the literature in two other ways. First, most quantitative papers use reduced-form econometric models. The use of a NK DSGE model has the advantage of allowing us to provide a structural interpretation of our results, highlighting the channels of transmission through which severe weather shocks propagate, and providing a theory-based interpretation of those channels. Moreover, given that we estimate our model, we can establish the most quantitatively relevant channels. Second, we contribute to the literature on the quantitative effects of severe weather shocks on US financial variables. We use the credit spread and banks' net worth as observed variables in our data set. The evidence on the stock market is quite developed, yet there is a dearth of research concerning the credit spread.

We introduce a role for severe weather shocks in our NK DSGE model in the following way. We model the ACI together with the global economic conditions indicator (GECON), developed by Baumeister, Korobilis and Lee (2022), as a two-variables vector autoregression (VAR) model. Then, the ACI enters into the US economy via the structural shocks of the NK DSGE model. In particular, we assume that each structural

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[2] Previous literature investigated the propagation of other shocks for the US economy through the lenses of the financial accelerator mechanism, e.g., De Graeve (2008), Gelain (2010), and Gelain and Lorusso (2025). However, no previous paper focused on weather-related shocks.

[3] Banks' leverage is one of the vulnerabilities of the financial system that can lead to the amplification of shocks. See Adrian, Covitz and Liang (2015).

US shock has its own conventional exogenous component plus a second component that is the ACI itself. In each shock, the ACI component is weighted by a different weight. Each weight is estimated together with the rest of the structural parameters. In that way, the data determine through which shock, or channel, the ACI propagates into the US economy. As detailed in subsequent sections, our framework is consistent with the damage function approach pioneered by William Nordhaus; see, e.g., Nordhaus (1992) and Nordhaus and Yang (1996). However, our methodology offers greater generality by accounting for a multiplicity of transmission channels of weather shocks, moving beyond the conventional focus on production-side damages that characterizes much of the existing literature.

Our results show that severe weather shocks have the following effects on US variables. They have a negative impact on real economic activity, especially on investment. Consistent with that, banks' net worth drops and credit premium increases. Severe weather shocks appear to be deflationary, although the effects on inflation are very modest, on the order of a few basis points. As a result, consistently with our estimated Taylor rule, monetary policy responds by decreasing the federal funds rate, by few basis points as well. Our findings regarding inflation and interest rates diverge somewhat from those of Kim, Matthes and Phan (2025), who report a positive response of inflation and a negative response of the federal funds rate.

In periods characterized by financial instability, which the estimation identifies with the Great Recession in our sample, the effects of severe weather shocks are stronger for all the observed variables. Despite that, severe weather shocks are never a relevant source of business cycle fluctuations. They explain at best 3 percent of the GDP growth variability in the financial instability regime. A similar percentage holds also for the other real, nominal and financial variables.

The main channel of transmission is through shocks to the quality of capital. The destruction of physical capital impairs both goods-producing firms, which produce less, and banks' assets side, leading to a deterioration in their balance sheet and in borrowing and lending activity. That gives rise to the accelerator mechanism.

Finally, an analysis of individual ACI components–including temperatures, rainfall, drought, wind, and sea level– reveals that temperature and sea level shocks drive the largest GDP contractions, with impacts exceeding those of the aggregate ACI. Nevertheless, variance decomposition confirms that individual weather shocks remain a secondary driver of the US business cycle relative to other structural disturbances.

Our paper is structured as follows. We review the relevant related literature in the next subsection. We then present the baseline model in Section 2. We move to the estimation details in Section 3. We present our results in Section 4, before our concluding remarks in Section 5.

1.1 Related Literature

Our study contributes to a broad and expanding body of empirical research that seeks to quantify the macroeconomic impacts of weather shocks, extreme weather events, and natural disasters in the United States using econometric models (e.g., see Kim, Matthes and Phan, 2025; Eickmeier, Quast and Schüler, 2024; Tran and Wilson, 2024; Natoli, 2023; Colacito, Hoffmann and Phan, 2019; Boldin and Wright, 2015) and other countries (see, e.g., Colombo and Ferrara, 2024; Kiley, 2024; Chang, Mi and Wei, 2023; Klusak et al., 2023; Alessandri and Mumtaz, 2022; Felbermayr et al., 2022; Carter et al., 2021; Pretis et al., 2018; Burke et al., 2015; Hsiang and Jina, 2014; Dell, Jones and Olken, 2012). Some studies also provide detailed reviews (see, e.g., Batten, 2018 and Dell, Jones and Olken, 2014).

Second, in line with previous literature, we use the ACI to identify extreme weather events. Accordingly, our paper is related to those studies also using that index. As noted earlier, one such study is Kim, Matthes and Phan (2025). In addition to this, a few other papers have also employed the ACI. Using a GVAR approach, Bacchiocchi, Bastianin and Moramarco (2024) estimate the effects of extreme weather disasters on local economic activity and cross-border spillovers that operate through economic linkages between US states. In particular, they use ACI as an alternative proxy of weather-related disasters. Zhou et al. (2024) provide an actuarial-focused survey of how weather change is measured and applied across insurance lines, including property/casualty, life, health, and agricultural insurance. They emphasize the utility of ACI in quantifying weather-related risk and informing industry decision-making globally. Pan, Porth and Li (2022) evaluate whether the ACI can effectively predict corn yields in the US Midwest and support insurance pricing and policy design. Using linear regressions, they find that the ACI can serve as a valuable weather-driven predictor for crop yields and yield loss likelihood, particularly with adaptable component weighting.

Finally, our paper is related to studies introducing weather shocks into DSGE models, in particular to four papers in which the approach of modeling the weather shock as an exogenous shock is similar in spirit to the one we adopt. Hashimoto and Sudo (2024) quantitatively assess the indirect effect of floods on the real economy and financial intermediation in Japan by estimating a DSGE model that incorporates a mechanism through which floods cause the capital stock and the public infrastructure to depreciate exogenously. Their results are in line with ours. In fact, they find that flood shocks dampen Japanese GDP. Moreover, the decline in Japanese GDP then impairs the balance sheets of firms and financial intermediaries, resulting in disruptions to financial intermediation and thus dampening GDP further. They do not account for the non-linear interaction between weather shocks and financial frictions, and they do not allow for other channels of transmission.

Gallic and Vermandel (2020) introduce a weather shock in a DSGE model for the New Zealand economy with an agriculture sector. Their weather shock is an exogenous shock to land productivity informed in the estimation by the drought index. The main difference with respect to our approach, apart from the focus on New Zealand rather than the US, is that they only look at the effect of weather on the agriculture sector, a sector that contributes very little to the overall economy in developed countries, while we evaluate its impact through different, possibly more relevant, channels. Finally, they do not look at the role of the financial sector or other non-linear effects.

Economides and Xepapadeas (2019) study how temperature changes affect the macroeconomic performance of a small open economy that cannot influence global weather outcomes but is fully exposed to their consequences. The authors develop a New Keynesian DSGE model with nominal rigidities and imperfect competition in which temperature changes enter the model as a permanent negative productivity shock through a damage function. The model is calibrated on the Greek economy. Results show that higher temperatures cause large and persistent output losses, and lead to a sharp deterioration in competitiveness, reflected in worsening terms of trade, as lower productivity raises domestic prices relative to foreign goods. The primary distinction of our study, beyond its focus on the US, is that their analysis is confined to the productivity channel, whereas we incorporate the role of the financial sector and other non-linear effects.

Bejarano and Rodríguez (2025) analyze how temperature changes affect macroeconomic outcomes and monetary policy in a small open economy, using Colombia as a case study. The authors develop and calibrate a

New Keynesian DSGE model where temperature changes are modeled as permanent and anticipated negative shocks to total factor productivity. Their results show that temperature changes lead to a gradual but persistent decline in potential output. Higher production costs raise domestic prices and cause a real exchange rate depreciation, weakening competitiveness. The timing of weather damage is crucial: if productivity losses materialize earlier, the short-term effects on inflation and interest rates are significantly amplified. Unlike our paper, which examines the US financial sector and non-linearities, their research focuses on Colombia and exclusively on the productivity channel.

2 Baseline Model

In this section, we describe our NK DSGE model which embeds financial frictions in line with Gertler and Karadi (2011). We include weather shocks in our model and we evaluate the impact of these shocks through different channels. We also consider the effects of world economic activity on the weather itself (see, e.g., Kim, Matthes and Phan, 2025).

2.1 Households

Members of each representative household are divided into workers and bankers. Workers supply labor and receive wages that return to the representative household. Bankers manage financial intermediaries, and they also return their earnings to the representative household. This implies that the representative household actually owns the financial intermediaries that its bankers manage. However, the deposits in financial intermediaries are not owned by the representative household. As in Gertler and Karadi (2011), we assume that there is perfect consumption insurance in each representative household.

We assume that the fraction of workers in the representative household corresponds to $1-d$, whereas the fraction of bankers is d. Over time, individuals can switch from workers to bankers and vice-versa. More specifically, the probability that a banker in the current period remains a banker in the next period is given by θ_t, which we also label a net worth shock. We assume that the retained earnings of the bankers that exit are given to the respective household. Also, the representative household provides its new bankers with some start-up funds.

The representative household maximizes the following utility function with respect to consumption, C_t, and labor, L_t:

$$\max E_t \sum_{i=0}^{\infty} b_t \beta^i \left[\ln \left(C_{t+i} - hC_{t+i-1} \right) - \frac{\chi_t}{1+\varphi} L_{t+i}^{1+\varphi} \right] \tag{1}$$

where : $0 < \beta < 1,\ 0 < h < 1, \varphi > 0$. In equation (1), β corresponds to the discount rate, φ the inverse Frisch elasticity of labor supply and h the habit consumption parameter. As in Justiniano, Primiceri and Tambalotti (2013), the representative household's preferences are subject to exogenous time variation captured by the intertemporal preference shock b_t. Moreover, χ_t denotes an exogenous shock to labor supply.

The representative household faces the following budget constraint:

$$C_t = W_t L_t + NP_t + T_t + R_t B_t - B_{t+1} \tag{2}$$

In equation (2), W_t denotes the real wage, NP_t the net payouts to the household from ownership of both non-financial and financial firms, T_t the lump-sum taxes, B_{t+1} the total quantity of short-term debt the household acquires and R_t the gross real interest rate. The first-order condition for consumption is:

$$E_t \beta \Lambda_{t,t+1} R_{t+1} = 1 \tag{3}$$

with

$$\Lambda_{t,t+1} \equiv \frac{\Psi_{t+1}}{\Psi_t}$$

$$\Psi_t \equiv b_t \left(C_t - hC_{t-1} \right)^{-1} - \beta h E_t \left[b_{t+1} \left(C_{t+1} - hC_t \right)^{-1} \right]$$

where Ψ_t is the marginal utility of consumption and Λ_t the stochastic discount rate.

2.2 Labor Market

The labor market has two layers. There is a unit measure of labor unions, indexed by $h \in [0, 1]$, that purchase labor from households and repackage it for resale to a labor packer at $W_t^N(h)$. Then a competitive labor packer combines union labor into a final labor input. The labor packer transforms union labor, $L_t(h)$, into final labor available for production via a CES technology:

$$L_t = \left(\int_0^1 L_t(h)^{\frac{1}{1+\Lambda_w}} \, dh \right)^{1+\Lambda_w} \tag{4}$$

The labor packer sells final labor input, L_t, to production firms at nominal wage W_t^N. It purchases union labor at $W_t^N(h)$. The elasticity of this aggregator Λ_w corresponds to the desired markup of wages over households' marginal rate of substitution between consumption and leisure. This is named a wage markup. The optimal decision gives rise to a standard downward-sloping demand curve for labor and an aggregate wage index:

$$L_t(h) = \left(\frac{W_t^N(h)}{W_t^N} \right)^{-\frac{1+\Lambda_w}{\Lambda_w}} L_t \quad \text{and} \quad \left(W_t^N\right)^{-\frac{1}{\Lambda_w}} = \int_0^1 W_t^N(h)^{-\frac{1}{\Lambda_w}} \, dh$$

Labor is purchased from the household at W_t^N. Unions are subject to a Calvo wage rigidity: each period, there is a $1 - \phi_w$ probability that a fraction of unions can adjust the nominal wage. Those that cannot adjust wages follow the indexation rule $W_t^N(h) = W_{t-1}^N(h)\Pi_{t-1}^{\iota_w}\Pi^{(1-\iota_w)}$.

The remaining fraction of unions chooses instead an optimal wage $W_t^{N,\#}$ by maximizing:

$$\max_{W_t^{N,\#}} \; \mathbb{E}_t \left\{ \sum_{j=0}^{\infty} \phi_w^j \beta^j \left[-b_{t+j}\chi_{t+j} \frac{L_{t+j}^{1+\varphi}}{1+\varphi} + \Psi_{t+j} W_t^N(h) L_{t+j} \right] \right\}$$

subject to the labor demand function above. The FOC is:

$$\mathbb{E}_t \left\{ \sum_{j=0}^{\infty} \phi_w^j \beta^j \Psi_{t+j} L_{t+j} \left[W_t^{N,\#} \Pi_{t,t+j}^w - (1+\lambda_w)\, b_{t+j}\chi_{t+j} \frac{L_{t+j}^{\varphi}}{\Psi_{t+j}} \right] \right\} = 0$$

with $\Pi_{t,t+j}^w = \prod_{k=1}^{j} \left[\Pi^{(1-\iota_w)} \Pi_{t+k-1}^{\iota_w} \right]$. The recursive formulation of the optimal decision is in Appendix B.

2.3 Financial Intermediaries

Financial intermediaries lend funds obtained from households to a non-financial final-goods-producing firm. Banker j has the following balance sheet:

$$Q_t S_{j,t} = N_{j,t} + B_{j,t+1} \tag{5}$$

In equation (5), Q_t corresponds to the price of financial assets, $S_{j,t}$ the quantity of financial claims on non-financial firms that the banker holds, $N_{j,t}$ the amount of wealth (net worth) that an intermediary has at the end of period t, and $B_{j,t+1}$ the deposits the banker obtains from households.

The evolution of the intermediary's equity capital is given by:

$$\begin{align} N_{j,t+1} &= R_{k,t+1} Q_t S_{j,t} - R_{t+1} B_{j,t+1} \tag{6} \\ &= \left(R_{k,t+1} - R_{t+1}\right) Q_t S_{j,t} + R_{t+1} N_{j,t} \tag{7} \end{align}$$

where $R_{k,t}$ is the return on capital.

The banker operates only if the following inequality holds:

$$E_t \beta^j \Lambda_{t,t+1+i} \left(R_{k,t+1+i} - R_{t+1+i}\right) \geq 0,\ i \geq 0 \tag{8}$$

The intermediary's aim is to maximize expected terminal wealth. Formally, this is given by:

$$\begin{align} V_{j,t} &= \max E_t \sum_{i=0}^{\infty} \left(1 - \theta_{t+i}\right) \theta_{t+i}^{i} \beta^{i+1} \Lambda_{t,t+1+i} N_{j,t+1+i} \\ &= \max E_t \sum_{i=0}^{\infty} \left(1 - \theta_{t+i}\right) \theta_{t+i}^{i} \beta^{i+1} \Lambda_{t,t+1+i} \begin{bmatrix} \left(R_{k,t+1+i} - R_{t+1+i}\right) \cdot \\ Q_{t+i} S_{j,t+i} + R_{t+1+i} N_{j,t+i} \end{bmatrix} \tag{9} \end{align}$$

The banker has the incentive to borrow additional funds from the representative household and expand its assets indefinitely, as long as equation (8) holds. To impose a limit on that, we introduce the following moral hazard/costly enforcement (or agency) problem. At the beginning of each period, the intermediary has the option of moving the time-varying fraction λ_t from the project to her representative household.[4] We label this a divert shock. This creates the right incentives because the cost to the banker is that depositors can force the intermediary into bankruptcy and recover the remaining fraction $1-\lambda_t$ of assets, but it is too costly for the depositors to recover the fraction λ_t. Accordingly, lenders supply funds to the intermediary only if the following incentive constraint is satisfied:

$$V_{j,t} \geq \lambda_t Q_t S_{j,t} \tag{10}$$

that is, the loss from diverting a fraction of assets is greater than the gain from doing so. In fact, the left-hand side represents the wealth a banker would lose if forced into bankruptcy, while the right-hand side is the amount of assets the bankrupt banker can retain because depositors cannot afford to recover them. Moreover, $V_{j,t}$ can be expressed as follows:

$$V_{j,t} = \nu_t Q_t S_{j,t} + \eta_t N_{j,t} \tag{11}$$

In the previous expression, we have that:

$$\nu_t = E_t \left\{ (1-\theta_t)\, \beta\Lambda_{t,t+1} \left(R_{k,t+1} - R_{t+1}\right) + \beta\Lambda_{t,t+1}\theta_{t+1}X_{t,t+1}\nu_{t+1} \right\} \tag{12}$$

$$\eta_t = E_t \left\{ (1-\theta_t) + \beta\Lambda_{t,t+1}\theta_{t+1}F_{t,t+1}\eta_{t+1} \right\} \tag{13}$$

In equations (12) and (13), ν_t can be interpreted as the expected discounted marginal gain to the banker of expanding assets $Q_t S_{j,t}$ by a unit, holding net worth $N_{j,t}$ constant, $X_{t,t+i} \equiv Q_{t+i}S_{j,t+i}/Q_t S_{j,t}$, η_t as the expected discounted value of having another unit of $N_{j,t}$, holding $S_{j,t}$ constant, and $F_{t,t+i} \equiv N_{j,t+i}/N_{j,t}$.

The incentive constraint can be rewritten as:

$$\eta_t N_{j,t} + \nu_t Q_t S_{j,t} \geq \lambda_t Q_t S_{j,t} \tag{14}$$

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[4] Other papers that make a similar assumption about the time-varying nature of this parameter are Sims and Wu (2021), Gelain and Ilbas (2017), Dedola, Karadi and Lombardo (2013), and Bean et al. (2010).

Given this constraint, and assuming that it is binding, the equity capital of the intermediary determines the assets she can buy:

$$Q_t S_{j,t} = \frac{\eta_t}{\lambda_t - \nu_t} N_{j,t} = \phi_t N_{j,t} \tag{15}$$

In equation (15), ϕ_t represents the private leverage ratio, that is, the ratio of privately intermediated assets to equity. The constraint (15) limits the intermediaries' leverage ratio to the point where the banker's incentive to cheat is exactly balanced by the cost. In this respect the agency problem leads to an endogenous capital constraint on the intermediary's ability to acquire assets.

Over time, the net worth of the intermediary evolves according to:

$$N_{j,t+1} = \left[\left(R_{k,t+1} - R_{t+1} \right) \phi_t + R_{t+1} \right] N_{j,t} \tag{16}$$

Moreover, we have that:

$$F_{t,t+1} = \frac{N_{j,t+1}}{N_{j,t}} = \left(R_{k,t+1} - R_{t+1} \right) \phi_t + R_{t+1} \tag{17}$$

$$X_{t,t+1} = \frac{Q_{t+1} S_{j,t+2}}{Q_t S_{j,t+1}} = \left(\frac{\phi_{t+1}}{\phi_t} \right) \left(\frac{N_{j,t+1}}{N_{j,t}} \right) = \left(\frac{\phi_{t+1}}{\phi_t} \right) F_{t,t+1} \tag{18}$$

In order to determine the banker's total demand for assets we sum across individual demands. Therefore, we have that:

$$Q_t S_t = \phi_t N_t \tag{19}$$

where S_t denotes the aggregate quantity of the banker's assets and N_t indicates the aggregate intermediary capital.

We assume that the banker's aggregate capital is given by the sum of the net worth of existing bankers, $N_{e,t}$, and the net worth of entering bankers, $N_{n,t}$:

$$N_t = N_{e,t} + N_{n,t} \tag{20}$$

We know that the fraction θ_t of intermediaries at $t-1$ survives until t. This implies $N_{e,t}$ evolves according to:

$$N_{e,t} = \theta_t \left[\left(R_{k,t} - R_t \right) \phi_{t-1} + R_t \right] N_{t-1} \tag{21}$$

The total final period assets of exiting intermediaries at t is $(1-\theta_t)\, Q_t S_{t-1}$. We also assume that each period, the household transfers a fraction $\frac{\omega}{1-\theta_t}$ of this value to its entering bankers. In aggregate terms we have that:

$$N_{n,t} = \omega Q_t S_{t-1} \tag{22}$$

In equation (22), ω is the proportional transfer to the entering intermediaries.

Finally, we combine equations (21) and (22) in order to get an equation of motion for N_t:

$$N_t = \theta_t \left[\left(R_{k,t} - R_t \right) \phi_{t-1} + R_t \right] N_{t-1} + \omega Q_t S_{t-1} \tag{23}$$

2.4 Goods Production

There are two layers in production. Final-good producers, or retailers, produce the final output Y_t, which is a CES composite of a continuum of mass unity of differentiated retail firms that use intermediate output as the sole input. The final output composite is given by:

$$Y_t = \left(\int_0^1 Y_{ft}^{\frac{1}{1+\Lambda_{\pi,t}}} df \right)^{1+\Lambda_{\pi,t}} \tag{24}$$

where Y_{ft} is output by retailer f. From the cost minimization by the users of final output we have:

$$Y_{ft} = \left(\frac{P_{ft}}{P_t} \right)^{-\frac{1+\Lambda_{\pi,t}}{\Lambda_{\pi,t}}} Y_t \quad \text{and} \quad P_t^{-\frac{1}{\Lambda_{\pi,t}}} = \int_0^1 P_{ft}^{-\frac{1}{\Lambda_{\pi,t}}} df$$

The curvature $\Lambda_{\pi,t}$ of the aggregator determines the degree of substitutability across intermediate goods in the production of each of these intermediates. It is modelled as an exogenous stochastic process and it is called a price markup shock. The final good firm earns no profit.

Retailers simply re-package intermediate output. One unit of intermediate output makes up a unit of retail output. The marginal cost is thus the relative price of the intermediate output P_{mt}. In each period a firm is able to freely adjust its price with probability $(1 - \phi_\pi)$. In between these periods, the firm is able to index its price to the lagged rate of inflation with intensity ι_π. The retailers' pricing problem then is to choose the optimal reset price $P_t^{\#}$ to solve its maximization problem:

$$\max_{P_t^{\#}} E_t \sum_{i=0}^{\infty} \phi_\pi^i \beta^i \Lambda_{t,t+1} \left[\frac{P_t^{\#}}{P_{t+i}} \prod_{k=1}^{i} (1 + \pi_{t+k-1})^{\iota_\pi} - P_{mt+i} \right] Y_{ft+i} \tag{25}$$

where π_t is the rate of inflation. The FOC is given by:

$$E_t \sum_{i=0}^{\infty} \phi_\pi^i \beta^i \Lambda_{t,t+1} \left[\frac{P_t^{\#}}{P_{t+i}} \prod_{k=1}^{i} (1 + \pi_{t+k-1})^{\iota_\pi} - (1 + \Lambda_{\pi,t}) P_{mt+i} \right] Y_{ft+i} \tag{26}$$

The recursive formulation of the optimal choice is in Appendix B.

In the second layer, firms that produce intermediate goods work in a perfectly competitive environment. As in Gertler and Karadi (2011), we assume that at the end of period t, the firm buys capital K_{t+1} that it uses in the following period. After production takes place, in period $t+1$, the firm can sell the capital in the open market.

In order to acquire capital, the firm uses funds from the bankers. The firm issues S_t claims equal to the number of units of capital that it bought, K_{t+1}. The price of each claim is exactly equal to the price of a unit of capital, Q_t. Accordingly, the value of capital acquired is given by $Q_t K_{t+1}$, whereas the value of claims is given by $Q_t S_t$. Thus, the arbitrage condition is given by:

$$Q_t K_{t+1} = Q_t S_t \tag{27}$$

As in Gertler and Karadi (2011), we assume that there are no frictions in the process of non-financial final-goods-producing firms obtaining funding from intermediaries. The intermediary has perfect information about the firm and has no problem enforcing payoffs. This contrasts with the process of the intermediary obtaining funding from households. Thus, within the model, only intermediaries face capital constraints on obtaining funds. These constraints, however, affect the supply of funds available to non-financial final-goods-producing firms and hence the required rate of return on capital these firms must pay. Conditional on this required return, however, the financing process is frictionless for non-financial final-goods-producing firms. The firm is thus able to offer the intermediary a perfectly state-contingent security, which is best thought of as equity (or perfectly state-contingent debt).

At each time t, the firm produces output Y_t, using capital and labor L_t, and by varying the utilization rate of capital, U_{t+1}. Then production is given by:

$$Y_t = (Z_t L_t)^{\alpha} (U_t \xi_t K_t)^{1-\alpha} \tag{28}$$

In equation (28), the share of labor input is denoted by α. Moreover, Z_t represents exogenous labor-augmenting technological progress or, equivalently, a neutral technology factor. The level of neutral technology is non-stationary and its growth rate ($z_t \equiv \Delta ln Z_t$) follows an AR(1) process. In equation (28), U_t is the capital utilization and ξ_t the quality of capital shock (so that $\xi_t K_t$ is the effective quantity of capital at time t). The shock ξ_t is meant to provide a simple source of exogenous variation in the value of capital.[5] We assume that the depreciation rate is given by:

$$\delta(U_t) = \delta_c + \frac{b}{1+\zeta} U_t^{1+\zeta} \tag{29}$$

At time t, the firm chooses the utilization rate and the labor demand as follows:

$$P_{mt}(1-\alpha)\frac{Y_t}{U_t} = b U_t^{\zeta} \xi_t K_t \tag{30}$$

$$W_t = P_{mt} \alpha \frac{Y_t}{L_t} \tag{31}$$

Given that the firm earns zero profits state by state, because there are no adjustment costs and thus the firm's capital choice problem is always static, it simply pays out the ex post return to capital to the intermediary.

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[5] Gourio (2012) elaborates as follows on the quality of capital shock: "Capital destruction is clearly realistic for wars or natural disasters, but obviously not for economic depressions. The assumption requires in this case a broader interpretation as a shock to the quality of capital. Perhaps it is not the physical capital but the intangible capital (customer and employee value) that is destroyed during prolonged economic depressions. Moreover, economic crises often lead to microeconomic volatility and large reallocation, implying that some specialized capital goods may become worthless. Finally, expropriation of capital may be equivalent to capital destruction, if the capital is taken away and not used as effectively".

Accordingly R^k_{t+1} is given by:

$$R^k_{t+1} = \frac{\xi_{t+1}\left[\ P_{mt+1}\left(1-\alpha\right)\frac{Y_{t+1}}{\xi_{t+1}K_{t+1}} + Q_{t+1} - \delta\left(U_{t+1}\right)\ \right]}{Q_t} \tag{32}$$

2.5 Capital-Producing Firms

Capital-producing firms are perfectly competitive. At the end of period t, they buy capital from final-goods-producing firms. Then, they repair the depreciated capital and build new capital. In turn, they sell both the new and the repaired capital. The worn-out capital can be replaced at a cost of unity. We denote by Q_t the value of a new unit of capital. Following Gertler and Karadi (2011), we assume that there are no adjustment costs associated with refurbishing capital, whereas there are adjustment costs in the production of new capital. Since the households own the capital-producing firms, they receive their profits. Net investment is given by:

$$I_{n,t} = I_t - \delta\left(U_t\right)\xi_t K_t \tag{33}$$

where I_t is gross investment. The capital accumulation equation is given by:

$$K_{t+1} = \xi_t K_t + I_{n,t} \tag{34}$$

Therefore, we can write the discounted profits for a capital producer as:

$$\max E_t \sum_{\tau=t}^{\infty} \beta^{T-t}\Lambda_{t,\tau}\left\{\ \left(Q_\tau - 1\right)I_{n,\tau} - f\left(\frac{I_{n\tau}+I}{I_{n\tau-1}+I}\right)\left(I_{n,\tau}+I\right)\ \right\} \tag{35}$$

where $I_{n,t} = I_t - \delta\left(U_t\right)\xi_t K_t$, $f\left(1\right) = f^{'}\left(1\right) = 0$ and $f^{''}\left(1\right) > 0$, and where $\delta\left(U_t\right)\xi_t K_t$ is the quantity of capital refurbished.

The first-order condition for net investment is given by:

$$Q_t = 1 + f\left(\cdot\right) + \left(\frac{I_{n,t}+I}{I_{n,t-1}+I}\right)f^{'}\left(\cdot\right) - E_t\beta\Lambda_{t,t+1}\left(\frac{I_{n,t+1}+I}{I_{n,t}+I}\right)^2 f^{'}\left(\cdot\right) \tag{36}$$

2.6 Global Economic Activity and Weather

We model global economic activity and extreme weather conditions through the following bi-variate structural VAR (SVAR):

$$A_0 \begin{bmatrix} GECON_t \\ ACI_t \end{bmatrix} = c + \sum_{j=1}^{p} A_j \begin{bmatrix} GECON_{t-j} \\ ACI_{t-j} \end{bmatrix} + \begin{bmatrix} \varepsilon_t^{GECON} \\ \varepsilon_t^{ACI} \end{bmatrix} \tag{37}$$

where $GECON_t$ denotes the Monthly Global Economic Conditions indicator (see Baumeister, Korobilis and Lee, 2022), and ACI_t is the Actuaries Climate Index. The two innovations ε_t^{GECON} and ε_t^{ACI} are independently and identically distributed $N(0, \Omega_\varepsilon)$, with $\Omega_\varepsilon = E(\varepsilon_t \varepsilon_t')$, and $\varepsilon_t = [\varepsilon_t^{GECON}, \varepsilon_t^{ACI}]'$. Moreover, A_0 is a lower triangular matrix, implying a lagged response of global economic conditions to an innovation in extreme weather conditions, whereas extreme weather conditions can respond contemporaneously to an innovation in global economic activity. The number of lags is 6.

The ordering of variables within the VAR is immaterial, as the ACI is strictly exogenous to global economic activity—a feature well-documented in the literature (e.g., Kim, Matthes and Phan, 2025). This exogeneity is confirmed ex-post by our estimates, which reveal near-zero shock correlations and autoregressive coefficients with offsetting signs and magnitudes. Consequently, modeling the ACI as an independent AR(p) process would yield substantially similar results.

2.7 Resource Constraint and Government Policy

The aggregate resource constraint of the economy is given by:

$$Y_t = C_t + I_t + G_t + f\left(\frac{I_{n,t} + I}{I_{n,t-1} + I}\right)(I_{n,t} + I) \tag{38}$$

where output is divided between consumption, investment, and government consumption, G_t. The last term on the right-hand side captures the resources used for the adjustment costs in the production of new capital.

The government budget constraint is given by:

$$G_t = T_t \tag{39}$$

where government expenditure is financed by lump-sum taxes.

Finally, following Justiniano, Primiceri and Tambalotti (2013), we assume that monetary policy is modeled as the following Taylor-type rule for the nominal interest rate:

$$i_t^{mp} = \rho_i i_{t-1}^{mp} + (1-\rho_i) \begin{bmatrix} R + \frac{\kappa_\pi}{4}\left(\pi_t + \pi_{t-1} + \pi_{t-2} + \pi_{t-3} - \ln \pi_t^*\right) + \\ \frac{\kappa_y}{4}\left(\ln Y_t - \ln Y_{t-4}\right) \end{bmatrix} + \sigma_{mp}\varepsilon_t^{mp} \tag{40}$$

where ε_t^{mp} is a monetary policy shock and π_t^* is the inflation target shock.

2.8 Exogenous Shocks

In addition to the stationary technology shock already mentioned, the other shocks in the model follow AR(1) processes. They are the quality of capital shock, the government spending shock, the divert shock, the consumption preference shock, the labor supply shock, the price markup shock, the inflation target shock, the monetary policy shock, and the net worth shock. To account for the effects of extreme weather shocks on the US economy, we specify the US shock processes as follows:

$$\Psi_t = C + \Delta\Psi_{t-1} + \Omega\epsilon_t + \Omega_{ma}\epsilon_{t-1} + \Theta ACI_t \tag{41}$$

where $\Psi_t = \begin{bmatrix} z_t \\ \ln \xi_t \\ \ln G_t \\ \ln \lambda_t \\ \ln b_t \\ \ln \chi_t \\ \lambda_{\pi,t} \\ \ln \pi_t^\star \\ \ln mp_t \\ \ln \theta_t \end{bmatrix}$, $C = \begin{bmatrix} (1-\rho_z)\gamma \\ 0 \\ (1-\rho_g)\ln g \\ (1-\rho_\lambda)\ln\lambda \\ 0 \\ (1-\rho_\chi)\ln\chi \\ \left(1-\rho_{\lambda_\pi}\right)\lambda_\pi \\ 0 \\ 0 \\ (1-\rho_\theta)\ln\theta \end{bmatrix}$, $\Delta = \begin{bmatrix} \rho_z & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \rho_\xi & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \rho_g & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \rho_\lambda & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \rho_b & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \rho_\chi & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \rho_{\lambda_\pi} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \rho_{\pi^\star} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \rho_\theta \end{bmatrix}$,

$$\Omega = \begin{bmatrix} \sigma_z & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \sigma_\xi & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \sigma_g & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \sigma_\lambda & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \sigma_b & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \sigma_\chi & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \sigma_{\lambda_\pi} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \sigma_{\pi^\star} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \sigma_{mp} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \sigma_\theta \end{bmatrix}, \ \epsilon_t = \begin{bmatrix} \varepsilon_t^z \\ \varepsilon_t^\xi \\ \varepsilon_t^g \\ \varepsilon_t^\lambda \\ \varepsilon_t^b \\ \varepsilon_t^\chi \\ \varepsilon_t^{\lambda_\pi} \\ \varepsilon_t^{\pi^\star} \\ \varepsilon_t^{mp} \\ \varepsilon_t^\theta \end{bmatrix},$$

$$\Omega_{ma} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \mu_{\lambda_\pi} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix},$$

$$\Theta = \begin{bmatrix} \lambda_z \\ \lambda_\xi \\ \lambda_g \\ \lambda_\lambda \\ \lambda_b \\ \lambda_\chi \\ \lambda_{\lambda_\pi} \\ \lambda_{\pi^\star} \\ \lambda_{mp} \end{bmatrix} \begin{bmatrix} (1-\rho_z) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \left(1-\rho_\xi\right) & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & (1-\rho_g) & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & (1-\rho_\lambda) & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & (1-\rho_b) & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & (1-\rho_\chi) & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \left(1-\rho_{\lambda_\pi}\right) & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & (1-\rho_{\pi^\star}) & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

All shocks vary exogenously over time in response to independently and identically distributed $N(0,1)$ innovations ε_t^i, $i = z, \xi, g, \lambda, b, \chi, \lambda_\pi, \pi^\star, mp, \theta$. All λ_i are estimated together with the other parameters. In that way, the data determine through which shock, or channel, the ACI propagates into the US economy.

Moreover, this is also equivalent to the approach based on the damage function used in the previous literature, e.g., Gallic and Vermandel (2020), Hashimoto and Sudo (2024), and Bilal and Känzig (Forthcoming), and it also represents its generalization. In fact, to save on notation, we do not explicitly highlight the relationship between our model's structural shocks and the weather shock directly in the model equations where structural shocks appear. We reveal such dependence only when we specify the functional form of the shocks in the system of equations (41). Therefore, it might seem that we do not rely on the damage function approach even if we do. To clarify this point with an example, we could mimic, for instance, Gallic and Vermandel (2020) by specifying our production function as follows:

$$Y_t = \left[Z_t(ACI_t)L_t\right]^\alpha \left(U_t\xi_t K_t\right)^{1-\alpha}$$

where $Z_t(ACI_t)$ would highlight that productivity is a function of weather. We could follow Gallic and Vermandel (2020) also in selecting the functional form as follows:

$$\Delta \ln Z_t\left(ACI_t\right) \equiv z_t = \lambda_z ACI_t$$

This would limit the determinants of productivity to weather only. However, we believe that this is not a realistic assumption. Therefore, we allow for a more general specification where productivity varies over time in response to its own innovations and to weather as follows:

$$\Delta \ln Z_t \left(ACI_t \right) \equiv z_t = \left(1 - \rho_z \right) \gamma + \rho_z z_{t-1} + \left(1 - \rho_z \right) \lambda_z ACI_t + \sigma_z \varepsilon_t^z$$

This specification allows the data to discriminate what part of productivity is explained by its own innovations and what part by weather. These arguments generalize to all the other structural shocks.

2.9 Markov Switching

We assume that there are two financial regimes, one characterized by financial stability and one characterized by financial instability. This is done by assuming that the steady state value of the private leverage ratio, ϕ, changes according to a Markov chain, i.e., (S^{ϕ}), where the Markov chain is given by:

$$S_t^{\phi} \in \{\text{Financial stability, Financial instability}\}$$

We estimate the transition probabilities from one regime to the other. We report them in Table 1. We also report the estimated values for ϕ in the two regimes.

3 Estimation

In this section, we discuss the data we use to estimate our model and we provide some details of the estimation procedure. Then, we describe how we calibrate some of the model parameters and how we estimate the remainder.

3.1 Data

Our model is estimated using Bayesian methods for the sample period 1992M1-2019M12. We use the following observed variables: real per capita GDP growth, real per capita consumption growth, real per capita investment growth, the spread between the BAA corporate bond yield and the 10-year government bond yield, the Dow Jones US bank stock market index growth, the inflation rate, the federal funds rate, wage growth, hours worked, the GECON index and the ACI. A detailed description of the data and their transformation is in Appendix A. We plot them in Figure A1. The measurement equations are as follows:

$$\begin{aligned}
\text{Output growth} &= \ln\left(y_t\right) - \ln\left(y_{t-1}\right) + z_t \\
\text{Consumption growth} &= \ln\left(c_t\right) - \ln\left(c_{t-1}\right) + z_t \\
\text{Investment growth} &= \ln\left(i_t\right) - \ln\left(i_{t-1}\right) + z_t \\
\text{Net worth growth} &= \ln\left(n_t\right) - \ln\left(n_{t-1}\right) + z_t \\
\text{Spread} &= E_t[\ln\left(R^k_{t+1}\right) - \ln\left(R_{t+1}\right)] \\
\text{Fed funds rate} &= i_t \\
\text{Inflation rate} &= \pi_t \\
\text{Hours worked} &= L_t \\
\text{Wage growth} &= \ln w_t - \ln w_{t-1} + z_t
\end{aligned}$$

where lower-case letters correspond to stationary variables as defined in Appendix B. We estimate the model using the RISE toolbox (see Maih, 2015).

The ACI is a standardized indicator designed to measure changes in weather extremes across the United States. The ACI aggregates six distinct components, each measured relative to a fixed historical reference period (1961–1990). These components include the frequency of unusually high daily temperatures (above the 90th percentile), the frequency of unusually low daily temperatures (below the 10th percentile), extreme precipitation measured as the maximum rainfall over any consecutive five-day period, drought measured by the maximum number of consecutive dry days, the frequency of high-wind events, and anomalies in sea level. Each component is standardized into deviations from its reference-period mean, allowing heterogeneous weather phenomena with different physical units to be combined into a single composite index.

3.2 Calibrated Parameters and Prior Distributions

Production. The depreciation rate of capital, δ, corresponds to an annual capital depreciation of 10 percent. The monthly trend growth rate of GDP, γ, is computed as the average growth rate of real per capita GDP over our sample period and it is equal to 1.001255. The steady state price and wage markup, λ_π and λ_w, are 0.32 and 0.1, respectively.

Financial Intermediaries. We calibrate the steady state value of the gross external finance premium, R^k/R, based on the monthly average of the observed gross premium in the sample, i.e., 1.0020. Moreover, we set the proportional transfer to entering bankers, ω, equal to that assumed by Gertler and Karadi (2011), i.e., 0.0022.

Policy. We calibrate the government spending to output ratio at 0.2. We set the autoregressive coefficient of the inflation target shock, ρ_{π^*}, at 0.975 as in Christiano, Motto and Rostagno (2014).

Priors of Estimated Parameters. Table 1 reports the priors of the estimated parameters. Priors are standard and mostly follow Justiniano, Primiceri and Tambalotti (2013), with the exception of the persistence of the labor supply shock ρ_χ. Following Faccini and Melosi (2022), we set a strict prior with mean equal to 0.995 and standard deviation 0.001 to account for the low frequency movements in hours worked.

In both regimes, we assign to the steady state leverage ratio a prior distribution with a mean equal to 4, the calibrated value in Gertler and Karadi (2011), and a standard deviation equal to 1.

As for the prior distributions of the SVAR parameters, we estimate the reduced-form parameters. We estimate the standard deviations of the ACI and GECON shocks, σ_{ACI} and σ_{GECON}, respectively, and the coefficients of the lagged structure denoted by $b_{i,j}$, together with the other parameters of our NK DSGE model. To get a sense of how to set their prior distribution moments, we first estimate the SVAR separately by OLS. We then assume Normal prior distributions for all those parameters centered at the OLS estimates.

4 Results

In this section, we discuss our results. We start by looking at the estimated smoothed probabilities reported in Figure 1. The only financial instability period identified by our estimation substantially coincides with the Great Recession. The probability of being in that regime is always equal to 1 in the official NBER recession dates (2007M12-2009M6). Our estimation attaches a small probability of 0.47 to be in that regime in November 2007. All other months are identified as months of financial stability. It is worth highlighting that in our sample there is another NBER classified recession, i.e., the period 2001M3-2001M11. This recession is not captured by our estimation, as that period lacked the characteristics of financial instability and was not associated with elevated levels of bank leverage.

Leverage Estimates. As shown in Table 1, the estimated steady state leverage is 1.37 in the financial stability regime, and 6.28 in the financial instability regime. The leverage ratio is key for the accelerator mechanism. In the extreme case in which the leverage ratio is zero, we would be in a Modigliani-Miller world (see Miller and Modigliani, 1958), where banks' net worth position is irrelevant for the real economy. In the presence of a positive leverage, financial frictions matter and fluctuations in the worth matter for the real economy. The higher the leverage is, the higher the risk involved in banks' activities, and the stronger the financial accelerator is.

Our data contain useful information to estimate those values, especially banks' net worth and the credit spread. Together, they are sufficient to characterize banks' leverage ratio dynamics, even if we do not observe the ratio directly. In fact, our leverage ratio dynamics in the two regimes are consistent with the behavior of banks' leverage over our sample as shown by Coimbra, Kim and Rey (2022). They show that the asset-weighted leverage of large intermediaries, i.e., roughly those in our stock market index, was substantially stable outside the Great Recession, while it increased sharply over that period.[6] Further empirical support for this cyclical behavior is provided by the Chicago Fed's National Financial Conditions Index. Its movements offer a broader perspective on the US banking sector, reinforcing the narrative that systemic leverage and financial constraints tightened significantly during the Great Recession, in line with the evidence documented by Coimbra, Kim and Rey (2022).

Impulse Response Functions. Turning to the effect of a severe weather shock on US variables, we show the impulse response functions to a one estimated standard deviation severe weather shock in Figure 2. We report the financial stability regime dynamics in blue, while the financial instability dynamics are in dashed red. Overall, variables move little in the former regime. For instance, GDP growth drops less than 0.05 percent, and investment less than 1 percent. Inflation decreases less than 2 basis points. Consistent

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[6] See their Figure 1.

with the drop in inflation, the federal funds rate decreases less than 1 basis point. Financial variables barely move. Banks' net work goes down about 1 percent and the credit spread increases by a few basis points, in keeping with the financial accelerator theory.

These variables exhibit significantly higher volatility in the financial instability regime in response to the same shock. GDP and investment growth drop more than 0.2 percent and more than 4 percent, respectively. Inflation and the federal funds rate still decrease only a few basis points. It is for this reason that, even if severe weather shocks tend to be slightly deflationary, they move inflation so little that we conclude they are neither inflationary nor deflationary. This is related to the recent policy discussions among advanced countries' central banks, which see some potential risks for price stability associated with weather shocks.[7] Our analysis suggests that those risks are immaterial. Finally, banks' net worth moves down a solid 15 percent, while the credit spread soars about 35 basis points.

How do our results relate to the existing empirical evidence? The most comparable paper in terms of the effects of severe weather shock on the macroeconomy is Kim, Matthes and Phan (2025). They show that US industrial production drops 0.12 percent in response to a shock that increases the ACI by about 0.45 percent. Re-scaling our impulse response functions, this shock would imply a decrease in GDP growth of about 0.12 percent in the financial stability regime in our model. In terms of the effects on financial variables, although we cannot be sure that the size of the shock is entirely comparable, Eickmeier, Quast and Schüler (2024) show that the US stock market drops about 1 percent and the credit spread increases a few basis points in response to a one standard deviation disaster shock using a local projection framework with monthly data, all consistent with our signs and sizes in the financial stability regime. Overall, the literature finds a negative effect on the US stock market.

One might contend that our inference regarding the financial instability regime is limited by the relatively small number of observations available for this state. However, the financial instability regime includes 19 monthly observations. Although these numbers might seem negligible, the Great Recession represents an unquestionable period of financial instability characterized by significant data volatility, with all indicators converging toward the same crisis dynamics. Moreover, this is consistent with the broader difficulties of characterizing US business cycles in a state-dependent framework. As Hamilton (2016) observes, estimating

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[7] See, for instance, Lagarde (2021) for the ECB, and Batten, Sowerbutts and Tanaka (2020) for the Bank of England.

US recessions “with postwar quarterly data ... would mean about 50 observations from which to estimate all the parameters operating during recessions. ... For this reason researchers may want to limit the focus to a few of the most important parameters that are likely to change.” Following this recommendation, we only allow the steady state leverage ratio to switch.

Variance Decomposition. In Table 2, we show the variance decomposition of US GDP growth for both regimes. The first result to stress is that the severe weather shock accounts for only 0.2 percent of GDP growth variability in the financial stability regime. The rest of the variance decomposition for this regime is fairly standard for a model with financial frictions, with supply shocks explaining the bulk of the variability, as in Gelain and Lorusso (2025).

As for the financial instability regime, the severe weather shock, consistent with the larger variables' response in Figure 2, is somewhat more relevant, but it does not explain more than 3 percent. A similar pattern emerges across the other real, nominal, and financial variables. We therefore conclude that, irrespective of the prevailing regime, weather-related shocks do not constitute a significant driver of business cycle fluctuations, highlighting that those shocks might not represent a threat to financial stability. Our findings are broadly consistent with the findings in Kim, Matthes and Phan (2025), who find a limited role for this type of shock. They find, without distinguishing across different regimes, that “the posterior median for the effects of the ACI shock on macroeconomic variables is between 1 and 3 percent”. Notably, the capital quality shock accounts for over 60 percent of the variability during the Great Recession. We interpret this as a validation of our empirical strategy, as this specific shock is designed to capture the core dynamics of the 2008 financial crisis, consistent with the framework of Gertler and Karadi (2011).

Channels of Transmission. Another interesting analysis is to evaluate the channels of transmission of the severe weather shock into the US economy. Our model is rich in channels of transmission and it encompasses some that are popular in the literature, such as the effect on productivity. Moreover, we have some that are not contemplated in the literature, such as the effect on households' preferences for consumption and the disutility of labor supply, banks' risk attitude, government spending, the quality of capital, firms' market power, and monetary policy.

In Figure 3, we decompose the response of GDP growth in the financial instability regime into the underlying channels. We focus on that because the variations are meaningful. In the stability regime, the decomposition is similar. The dashed red line is the overall response as in Figure 2. To isolate the individual channels, we set to zero all the estimated weights, λ_i, but the one corresponding to the desired channel. As Figure 3 shows, a single channel effectively accounts for the overall dynamics, namely, the channel associated with the quality of capital shock. This is consistent with the quote in the introduction, according to which "weather-related property destruction can lead to bank losses, leading to less lending, leading to reduced investment, and so on". In our model, the destruction of physical capital has negative consequences for the goods-producing firms, which are forced to reduce production. But also for banks' balance sheet. In fact, banks' net worth drops as well, but more than the initial drop in the effective capital because of the leverage constraint as in equation (15). There is an increase in the credit spread associated with the drop in intermediaries' capital, given the resulting disruption in borrowing and lending activity. Firms face a higher cost of borrowing and they have to reduce their demand for capital and investments, which magnifies the initial negative shock, giving rise to the financial accelerator effect. This second-round effect transmits also to production. All the other channels play a minor role.

ACI Components. Finally, we explore the dynamics implied by the different ACI components. In Figure 4, we report the GDP growth response to shocks in each individual component of the ACI, distinguishing between financial stability and financial instability regimes. We estimate five different versions of our baseline model, each with a component at a time instead of the aggregate ACI.[8] In terms of magnitudes, the responses are heterogeneous across components. Temperature and sea level shocks generate the largest contractions in GDP growth, particularly during financial instability episodes, where the decline reaches roughly 0.4–0.6 percent at peak, somewhat larger than the overall response of 0.25 percent to the aggregate ACI shock shown in Figure 2. In contrast, drought and wind shocks produce noticeably smaller effects, generally below 0.1 percent in normal times and only modestly larger during instability. These differences suggest that temperature- and sea-related disturbances are more directly linked to capital destruction. An interesting exception is rainfall, which appears to generate a mild positive effect on GDP growth. One plausible explanation is that moderate increases in rainfall may benefit agricultural output or ease supply-side constraints without causing

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[8] There are six ACI components, but we ran five estimations because for temperature we created a unique measure by taking the difference between high and low temperatures, which also reflects the way they are treated when they are aggregated to form the ACI.

significant capital damage, especially in the absence of extreme flooding. Alternatively, rainfall shocks may proxy for milder climatic conditions that temporarily boost certain sectors of activity.

Figure 4 also shows that the macroeconomic effects of the different weather shocks are markedly stronger during episodes of financial instability, confirming the amplification effect already visible in Figure 2. Despite some responses being larger in magnitude, the variance decomposition suggests that all types of weather shocks contribute very little to the business cycle, always less than 3 percent.[9] Overall, our findings therefore reinforce the paper's central message that the macroeconomic consequences of severe weather shocks depend crucially on prevailing financial conditions but remain quantitatively small relative to other structural disturbances.

5 Conclusions

This paper investigates the relationship between severe weather events and the US financial system, a topic of growing interest but one for which the current literature lacks quantitative modeling. We aim to bridge this gap by developing and estimating a NK DSGE model that incorporates both the financial accelerator mechanism and severe weather shocks, using monthly data from 1992 to 2019.

We introduce non-linearity via a Markov switching framework to distinguish between periods of financial stability and instability, finding that the negative impact of weather shocks is stronger during unstable periods, such as the Great Recession. Weather shocks are modeled through the ACI, which enters as a component of structural economic shocks.

Our main results are that severe weather reduces real economic activity, especially investment. Banks' net worth falls and credit spreads rise. The effect on inflation is small but deflationary, prompting monetary easing. The main transmission channel is via the quality of capital—damaged capital affects both production and banks' balance sheets. Despite these effects, weather shocks account for only a small portion (up to 3 percent) of GDP variability. Finally, the analysis based on the single components of the ACI highlights similar findings.

Our study contributes to the growing literature on the effects of severe weather shocks by offering a

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[9] Estimated parameters and variance decomposition are available upon request.

structural, theory-based model to analyze how those shocks propagate through the financial system—an area previously underexplored.

Tables and Figures

Table 1: **Prior and posterior distributions in Markov switching model**

Parameter	Description	Prior	Mean	St. Dev.	Post. Mode
σ_z	St. Dev. Technology	IG	0.1	3	0.7455
σ_ξ	St. Dev. Capital Quality	IG	0.1	3	1.6673
σ_g	St. Dev. Gov. Exp.	IG	0.1	3	1.4494
σ_b	St. Dev. Preference	IG	0.1	3	6.8472
σ_λ	St. Dev. Divert	IG	0.1	3	0.5246
σ_{mp}	St. Dev. Monetary Policy	IG	0.1	3	0.0132
σ_{λ_π}	St. Dev. Price Markup	IG	0.1	3	6.2079
σ_χ	St. Dev. Labor Supply	IG	0.1	3	10.9139
$\sigma_{\pi^\star}$	St. Dev. Infl. Target	IG	0.05	0.03	0.0828
σ_θ	St. Dev. Net Worth	IG	0.1	3	0.0386
σ_{GECON}	St. Dev. GECON	N	0.057	0.001	0.0573
σ_{ACI}	St. Dev. ACI	N	0.189	0.01	0.1899
$corr(\varepsilon_t^{ACI}, \varepsilon_t^{GECON})$	VAR Shocks Correl.	N	0.0063	0.0001	0.0063
ρ_z	Auto. Technology	B	0.5	0.2	0.0319
ρ_ξ	Auto. Capital Quality	B	0.5	0.2	0.6675
ρ_g	Auto. Gov. Exp.	B	0.5	0.2	0.9564
ρ_b	Auto. Preference	B	0.5	0.2	0.0421
ρ_λ	Auto. Divert	B	0.5	0.2	0.6226
ρ_{λ_π}	Auto. Price Markup	B	0.5	0.2	0.9730
ρ_χ	Auto. Labor Supply	B	0.995	0.001	0.9977
ρ_θ	Auto. Net Worth	B	0.5	0.2	0.9767
μ_{λ_π}	MA Price Markup	B	0.5	0.2	0.6945
$\widetilde{\beta}$	Aux. Discount Factor	B	0.25	0.1	0.1387
h	Habit Formation	G	0.5	0.2	0.9611
η_i	Invest. Adj. Costs	B	4	1	1.4211
ϕ_π	Price Stickiness	B	0.5	0.2	0.8559
ι_π	Price Indexation	B	0.5	0.2	0.5057
ρ_i	Interest Rate Smooth.	B	0.5	0.2	0.9573
κ_π	Taylor Rule Reaction Infl.	N	1.7	0.3	2.0488
κ_y	Taylor Rule Reaction Growth	N	0.4	0.3	0.4036
α	Lab. Share in Prod. Fun.	N	0.64	0.05	0.9004
φ	Inv. Frisch El.	G	2	0.75	4.8348
ζ	El. Utiliz. Rate	G	5	1	4.9152
ϕ_w	Wage Stickiness	B	0.5	0.2	0.6241
ι_w	Wage Indexation	B	0.5	0.2	0.0491
$b_{1,1}$	VAR Auto.	N	0.6268	0.01	0.6279
$b_{1,2}$	VAR Auto.	N	0.1883	0.01	0.1899
$b_{1,3}$	VAR Auto.	N	0.0283	0.001	0.0283
$b_{1,4}$	VAR Auto.	N	-0.0345	0.0001	-0.0345
$b_{1,5}$	VAR Auto.	N	0.0029	0.0001	0.0029
$b_{1,6}$	VAR Auto.	N	0.0194	0.0001	0.0194
$b_{2,1}$	VAR Auto.	N	-0.0998	0.01	-0.1001
$b_{2,2}$	VAR Auto.	N	0.0966	0.001	0.0964
$b_{2,3}$	VAR Auto.	N	-0.0201	0.01	-0.0203
$b_{2,4}$	VAR Auto.	N	0.3433	0.01	0.3370
$b_{2,5}$	VAR Auto.	N	0.1414	0.01	0.1517
$b_{2,6}$	VAR Auto.	N	0.2407	0.01	0.2413
λ_z	Weather Weight - Technology	N	0	1	0.2627
λ_ξ	Weather Weight - Capital Quality	N	0	1	-1.3763
λ_g	Weather Weight - Gov. Exp.	N	0	1	-0.1382
λ_b	Weather Weight - Preference	N	0	1	-0.7681
λ_λ	Weather Weight - Divert	N	0	1	-1.5186
λ_{mp}	Weather Weight - Monetary Policy	N	0	1	-0.0032
λ_{λ_π}	Weather Weight - Price Markup	N	0	1	-0.7953
λ_χ	Weather Weight - Labor Supply	N	0	1	-0.0118
$\lambda_{\pi^\star}$	Weather Weight - Infl. Target	N	0	1	-0.4774
$\phi(S_t^\phi = \text{Financial instability})$	Banks' Leverage Fin. Inst.	N	4	1	6.2780
$\phi(S_t^\phi = \text{Financial stability})$	Banks' Leverage Fin. Stab.	N	4	1	1.3688
$p_{-}\{\text{Fin Stab, Fin Inst}\}$	Transition Prob.	B	0.5	0.2	0.0052
$p_{-}\{\text{Fin Inst, Fin Stab}\}$	Transition Prob.	B	0.5	0.2	0.0013

Notes: The table shows the modes of the posterior distributions of the estimated parameters in the Markov switching environment. We also report the means and standard deviations of the prior distributions. Regarding the prior distributions, B, N, G and IG stand for Beta, Normal, Gamma and Inverse Gamma, respectively. The discount rate is defined as $\beta = (\frac{\widetilde{\beta}}{100} + 1)^{-1}$.

Table 2: **GDP growth variance decomposition**

Shock	Financial Stability	Financial Instability
1 month ahead		
Technology	23.37	3.99
Quality of capital	2.78	64.45
Government	12.39	3.53
Preference	5.79	1.69
Monetary policy	0.16	0.21
Divert	0.26	0.03
Price markup	16.87	6.12
Labor supply	26.41	2.09
Inflation target	11.61	15.13
Net worth	0.20	0.00
ACI	0.17	2.75
GECON	0.00	0.01
Unconditional		
Technology	17.08	3.40
Quality of capital	1.67	60.58
Government	5.94	2.02
Preference	2.82	0.97
Monetary policy	0.14	0.21
Divert	0.17	0.03
Price markup	24.78	8.70
Labor supply	36.30	5.68
Inflation target	10.39	15.41
Net worth	0.21	0.00
ACI	0.48	3.00
GECON	0.00	0.01

Notes: The table shows the GDP growth variance decomposition. For each horizon we display two sets of values: the first column shows the variance explained when the economy is in the financial stability regime, and the second column shows the variance explained when the economy is in the financial instability regime.

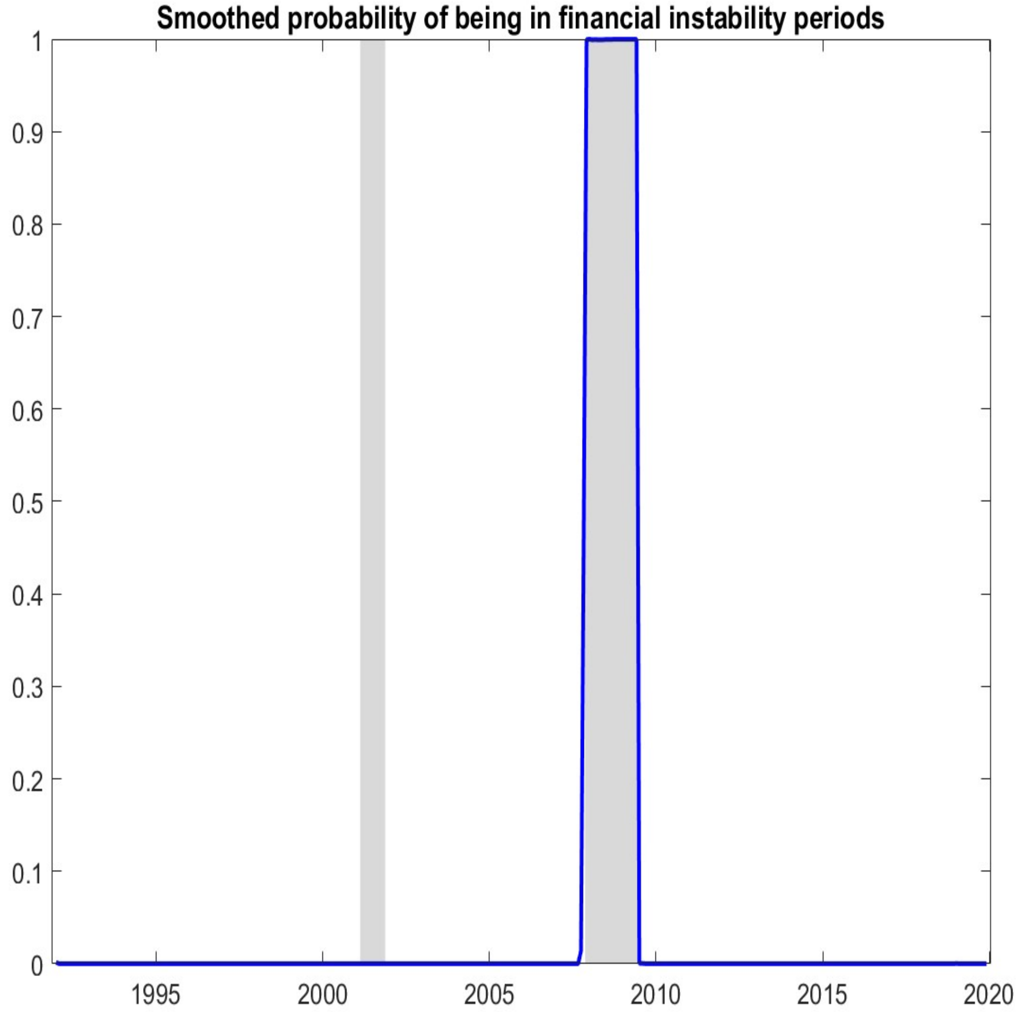

Figure 1: **Smoothed probability**

Notes: The figure shows the smoothed probability of being in periods of financial instability. The shaded areas correspond to US recessions as identified by the NBER.

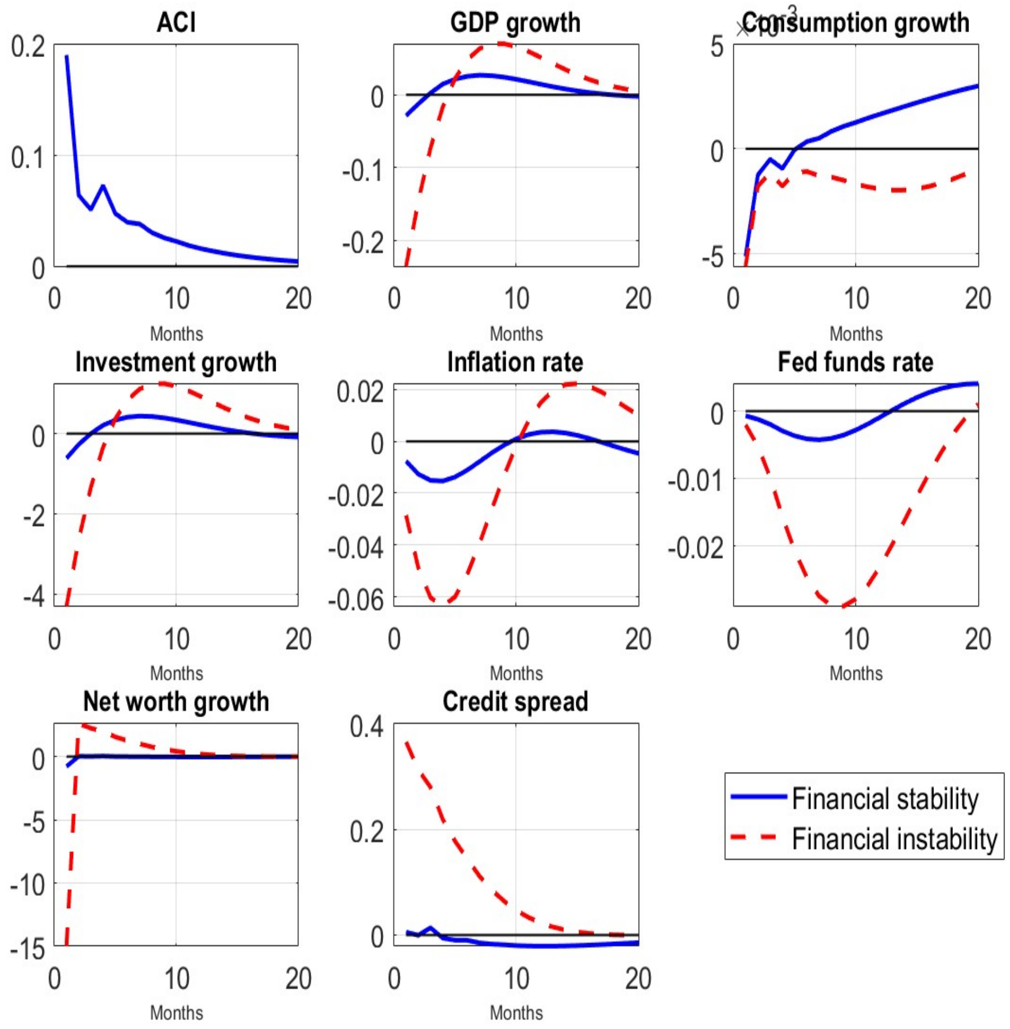

Figure 2: **Response of observed variables to Actuaries Climate Index**

Notes: The figure shows the impulse response functions of all observed variables to an estimated one standard deviation shock to the ACI. The solid blue lines represent the impulse response functions when the economy is in the financial stability regime, and the dashed red lines represent the impulse response functions when the economy is in the financial instability regime.

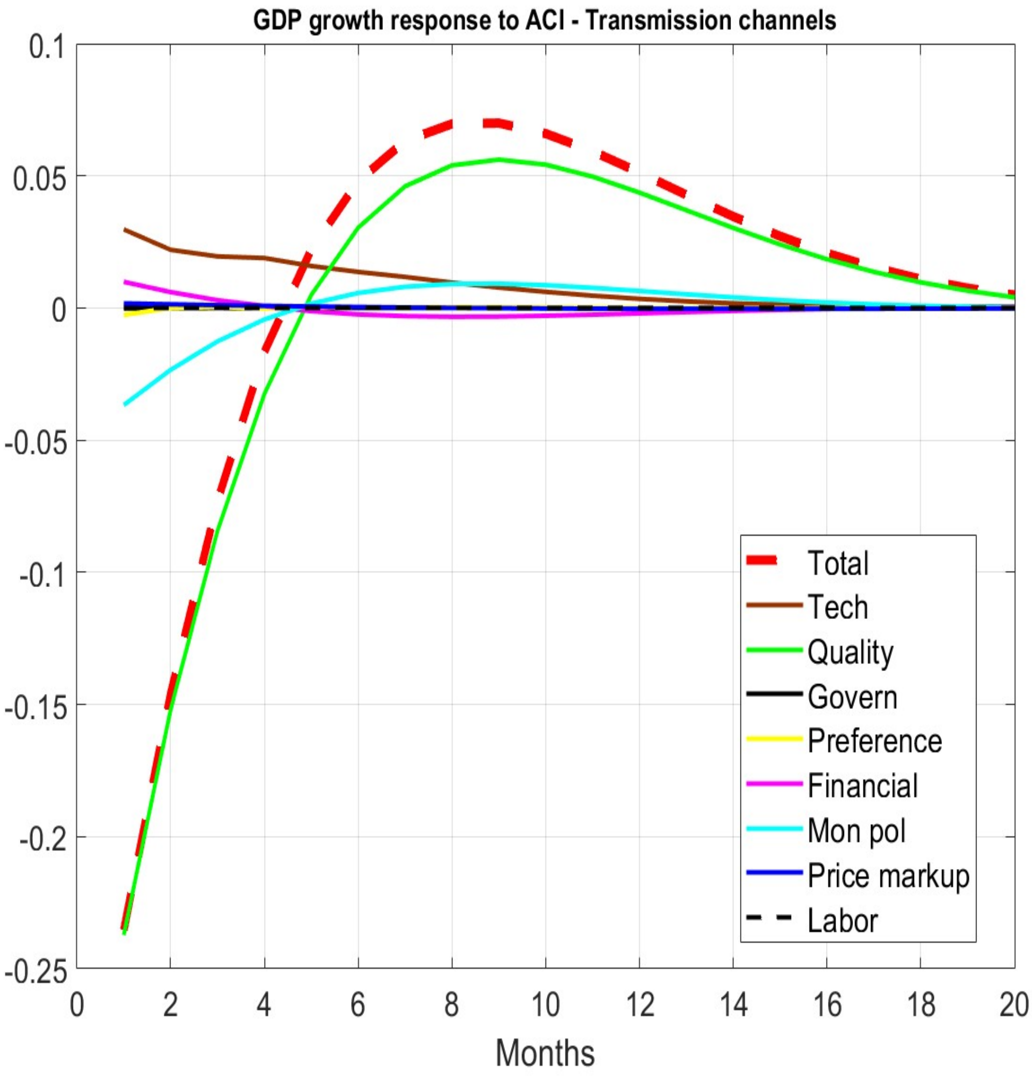

Figure 3: **Severe weather shocks' channels of transmission**

Notes: The figure shows the response of GDP growth to the channels of transmission of the severe weather shock during the period of financial instability. The red line represents GDP growth's response to the ACI shock, the brown line represents the technology channel, the green line represents the capital quality channel, the black line represents the government expenditure channel, the yellow line represents the consumers' preference channel, the purple line represents the financial channel, the light blue line represents the monetary policy channel, and the dark blue line represents the price markup channel, the dashed black line represents the labor supply channel.

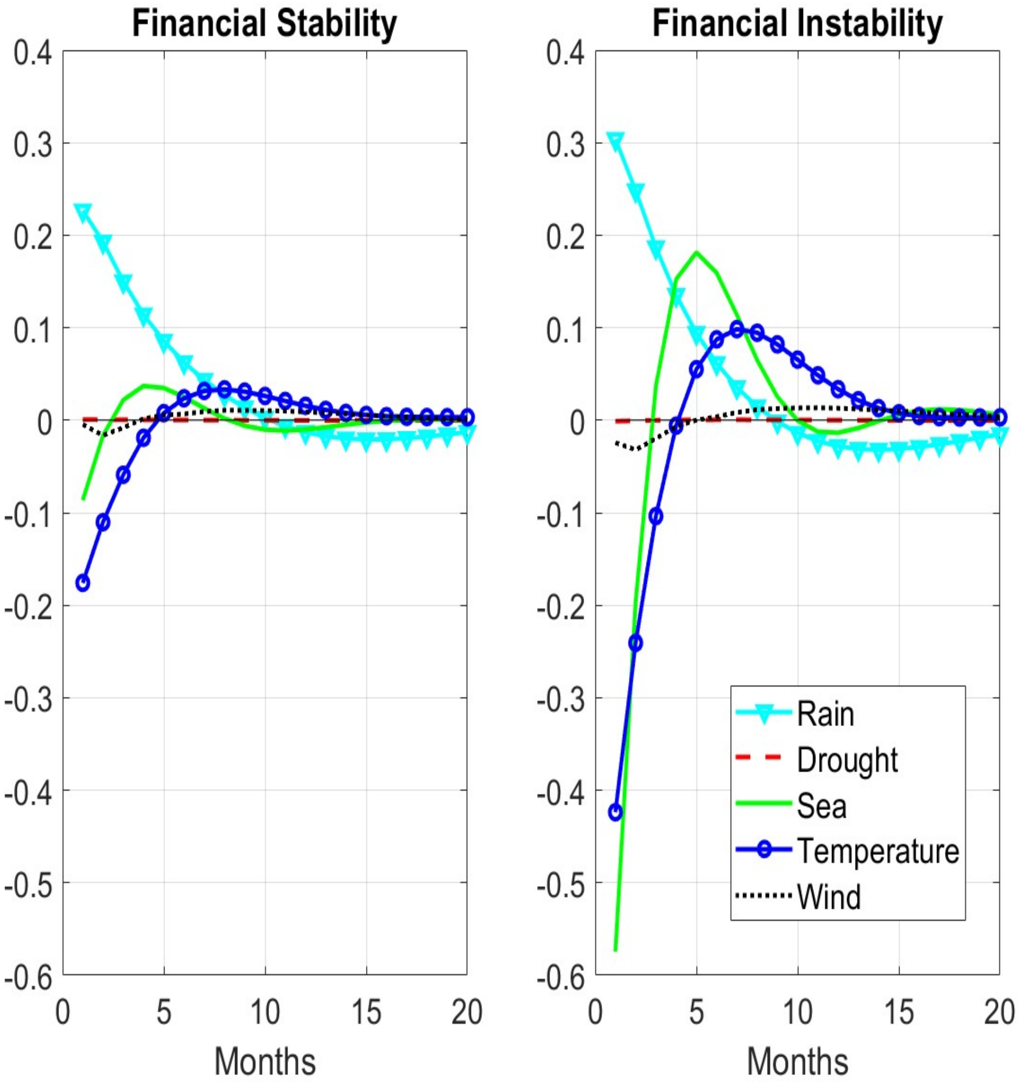

Figure 4: **Severe weather shocks: ACI components**

Notes: The figure shows the response of US GDP growth to a shock to each of the ACI components in financial stability (left panel) and financial instability times (right panel). The ACI components are: rain (light blue with triangle markers), drought (dashed red lines), sea (solid green lines), temperature (blue with circular markers), wind (dotted black lines).

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Appendices

A Data

As we described in the main body of the paper, the data are monthly and the model is estimated for the sample period 1992:M1-2019:M12. In this Appendix, we provide the original sources and construction methods of the observed series.

Real GDP is the IHS monthly GDP index (GDPIHS), which is conceptually consistent with real gross domestic product in the National Income and Product Accounts. The series of nominal personal consumption expenditures is the sum of personal consumption expenditures of non-durable goods released by the US BEA (Personal Consumption Expenditures: Non-durable Goods [PCND], downloaded from `https://fred.stlouisfed.org/series/PCND`) and personal consumption expenditures of services released by the US BEA (Personal Consumption Expenditures: Services [PCESV], downloaded from `https://fred.stlouisfed.org/series/PCESV`). The series of nominal private investment is the sum of personal consumption expenditures of durable goods released by the US BEA (Personal Consumption Expenditures: durable Goods [PCDG], downloaded from `https://fred.stlouisfed.org/series/PCDG`) and gross private domestic investment released by the US BEA (Gross Private Domestic Investment [GPDI], downloaded from `https://fred.stlouisfed.org/series/GPDI`). The civilian non-institutional population is released by the US BLS (Population Level [CNP16OV], downloaded from `https://fred.stlouisfed.org/series/CNP16OV`) and is transformed in LNSINDEX. The annualized Moody's Seasoned Baa Corporate Bond Yield spread over the 10-Year Treasury Note Yield at Constant Maturity is taken from the Federal Reserve Bank of St. Louis (Moody's Seasoned Baa Corporate Bond Yield Relative to Yield on 10-Year Treasury Constant Maturity [BAA10Y], downloaded from `https://fred.stlouisfed.org/series/BAA10Y`). The DJGL US banks' stock market index is taken from `https://markets.businessinsider.com/index/historical-prices/dow-jones-us-banks`. The GDP deflator is released by the US BEA (Gross Domestic Product: Implicit Price Deflator [GDPDEF], downloaded from `https://fred.stlouisfed.org/series/GDPDEF`). Let Δ denote the temporal difference operator. Then the variables are transformed as follows:

$$\begin{aligned}
\text{Output growth} &= 100\Delta LN(GDPIHS/LNSINDEX)\\
\text{Consumption growth} &= 100\Delta LN(((PCND + PCESV)/GDPDEF)/LNSINDEX)\\
\text{Investment growth} &= 100\Delta LN(((PCDG + GPDI)/GDPDEF)/LNSINDEX)\\
\text{Spread} &= (1/12) * (BAA\ CORPORATE - 10\ YEAR\ TREASURY)\\
\text{Net worth growth} &= 100\Delta LN((DJGL/GDPDEF)/LNSINDEX)
\end{aligned}$$

The GECON index is based on a set of 16 indicators that cover a broad range of variables tied to energy demand. The variables represent different data categories spanning multiple dimensions of the global economy: real economic activity, commodity prices, financial indicators, transportation, uncertainty, expectations, weather, and energy-related measures. Baumeister, Korobilis and Lee (2022) extract the first principal component from this unbalanced panel of 16 variables by applying the EM algorithm recursively. The source of this series is Baumeister's website (`https://sites.google.com/site/cjsbaumeister/research`).

We also use the monthly average federal funds rate [DFF], downloaded from `https://fred.stlouisfed.org/series/DFF`, the monthly Personal Consumption Expenditures: Chain-type Price Index [PCEPI], downloaded at `https://fred.stlouisfed.org/series/PCEPI`, the average monthly hours of production and nonsupervisory employees for total private industries [AWHNONAG], downloaded at `https://fred.stlouisfed.org/series/AWHNONAG`, and the monthly compensation per hour for the non-farm business sector [COMPNFB], downloaded at `https://fred.stlouisfed.org/series/COMPNFB`. Those variables are transformed as follows:

$$\text{Federal funds rate} = (1/12) * (DFF)$$

$$\text{Inflation} = 100\Delta LN(PCEPI)$$

$$\text{Hours worked} = 100LN((AWHNONAG * CE16OV/100)/LNSINDEX)$$

$$\text{Real wage growth} = 100\Delta LN(COMPNFB/GDPDEF)$$

where [CE16OV] is the employment level, downloaded at `https://fred.stlouisfed.org/series/CE16OV`.

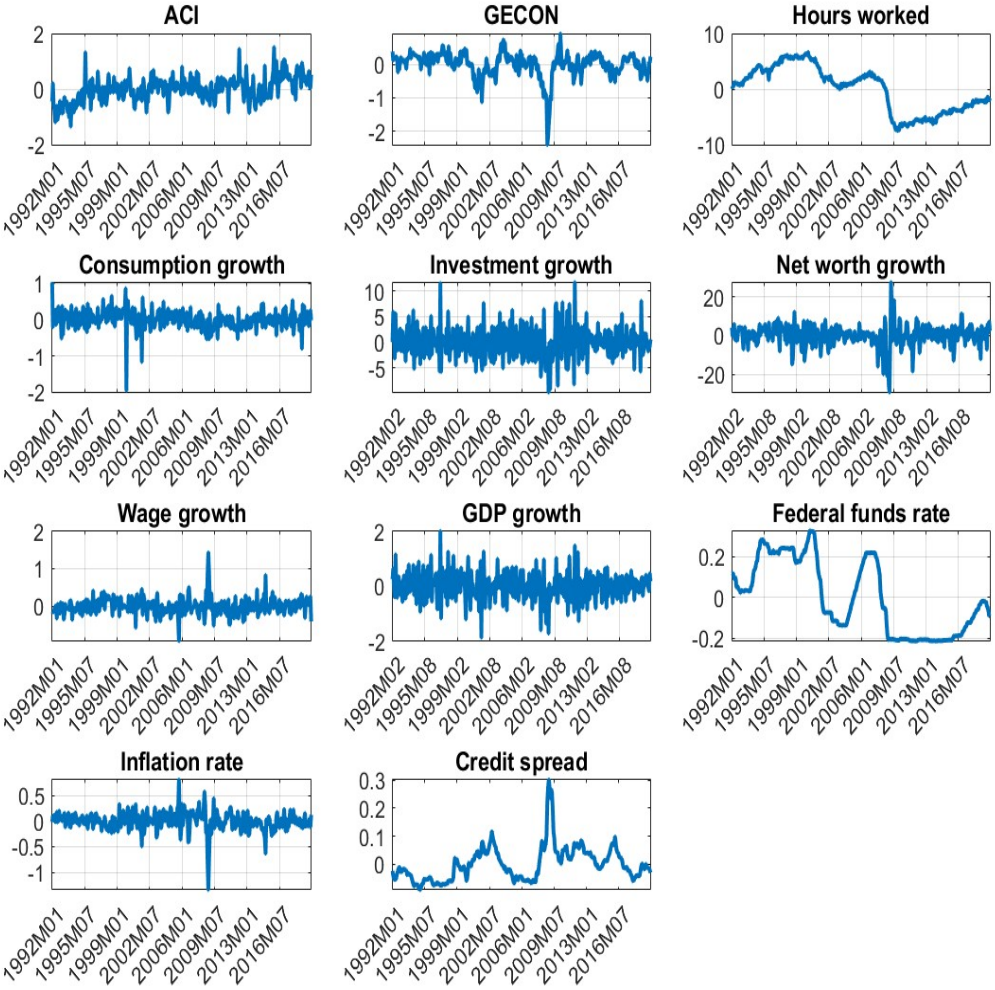

Figure A1: **Observed data**

Notes: Data used in the estimation. The sample is 1992M1:2019M12.

B The Stationary System

To get a stationary system, we use the following variable transformations: $c_t = \frac{C_t}{Z_t}$, $\psi_t = \Psi_t Z_t$, $y_t = \frac{Y_t}{Z_t}$, $k_t = \frac{K_t}{Z_t}$, $w_t = \frac{W_t}{Z_t}$, $i_{n,t} = \frac{I_{n,t}}{Z_t}$, $i_t = \frac{I_{,t}}{Z_t}$, $n_t = \frac{N_t}{Z_t}$, $n_{e,t} = \frac{N_{e,t}}{Z_t}$, $n_{n,t} = \frac{N_{n,t}}{Z_t}$, $f_t = \frac{F_t}{Z_t}$, $\widetilde{\Lambda}_{t,t+1} = \frac{\Lambda_{t,t+1}}{Z_t}$. With these definitions the stationary system is as follows.

The marginal utility of consumption is given by:

$$\psi_t = b_t \left[\left(c_t - h \frac{c_{t-1}}{e^{z_t}} \right) \right]^{-1} - \beta h E_t \left[b_{t+1} \left(c_{t+1} e^{z_{t+1}} - h c_t \right)^{-1} \right] \tag{42}$$

The Euler equation is given by:

$$E_t b_t \beta \frac{\psi_{t+1}}{\psi_t e^{z_{t+1}}} R_{t+1} = 1$$

Stochastic discount rate:

$$\widetilde{\Lambda}_{t,t+1} = \frac{\psi_{t+1}}{\psi_t e^{z_{t+1}}}$$

Labor market:

$$f_{1,t} = e^{\lambda_{w,t}} \chi_t b_t L_t^{1+\varphi} + \phi_w \beta \mathbb{E}_t \left\{ \left[\left(\frac{\Pi_t e^{z_t}}{\Pi e^z} \right)^{\iota_w} \left(\frac{\Pi_{t+1} e^{z_t+1}}{\Pi e^z} \right)^{-1} \left(\frac{w_{t+1}}{w_t} \right)^{-1} \right]^{-\frac{(1+\varphi)(1+\lambda_w)}{\lambda_w}} f_{1,t+1} \right\} \tag{43}$$

$$f_{2,t} = \psi_t L_t w_t + \phi_w \beta \mathbb{E}_t \left\{ \left[\left(\frac{\Pi_t e^{z_t}}{\Pi e^z} \right)^{\iota_w} \left(\frac{\Pi_{t+1} e^{z_{t+1}}}{\Pi e^z} \right)^{-1} \left(\frac{w_{t+1}}{w_t} \right)^{-1} \right]^{-\frac{1}{\lambda_w}} f_{2,t+1} \right\} \tag{44}$$

$$w_t^{\#} = w_t \left(\frac{f_{1,t}}{f_{2,t}} \right)^{\frac{\lambda_w}{\lambda_w + \varphi(1+\lambda_w)}} \tag{45}$$

$$1 = (1 - \phi_w) \left(\frac{w_t^{\#}}{w_t} \right)^{-\frac{1}{\lambda_w}} + \phi_w \left[\left(\frac{\Pi_{t-1} e^{z_{t-1}}}{\Pi e^z} \right)^{\iota_w} \left(\frac{\Pi_t e^{z_t}}{\Pi e^z} \right)^{-1} \frac{w_{t-1}}{w_t} \right]^{-\frac{1}{\lambda_w}} \tag{46}$$

The value of banks' capital is given by:

$$\nu_t = E_t \left\{ (1 - \theta_t) \beta \frac{\psi_{t+1}}{\psi_t e^{z_{t+1}}} \left(R_{kt+1} - R_{t+1} \right) + \beta \frac{\psi_{t+1}}{\psi_t} \theta_{t+1} \frac{\phi_{t+1}}{\phi_t} f_{t,t+1} \nu_{t+1} \right\}$$

The value of banks' net worth is given by:

$$\eta_t = E_t \left\{ (1-\theta_t) + \beta \frac{\psi_{t+1}}{\psi_t} \theta_{t+1} f_{t,t+1} \eta_{t+1} \right\}$$

The optimal leverage is given by:

$$\phi_t = \frac{\eta_t}{\lambda_t - \nu_t}$$

The growth rate of banks' capital is given by:

$$f_{t,t+1} e^{z_{t+1}} = \left(R_{k,t+1} - R_{t+1}\right) \phi_t + R_{t+1}$$

The growth rate of banks' net worth is given by:

$$X_{t,t+1} = \frac{\phi_{t+1}}{\phi_t} f_{t,t+1} e^{z_{t+1}}$$

The aggregate capital is given by:

$$Q_t k_{t+1} e^{z_{t+1}} = \phi_t n_t$$

Banks' net worth is given by:

$$n_t = n_{e,t} + n_{n,t}$$

Existing banks' net worth accumulation is given by:

$$n_{e,t} = \theta_t \left[\left(R_{k,t} - R_t\right) \phi_{t-1} + R_t \right] \frac{n_{t-1}}{e^{z_t}}$$

New banks' net worth is given by:

$$n_{n,t} = \omega Q_t \xi_t k_t$$

The production function of final-goods-producing firms is given by:

$$y_t = L_t^{\alpha} \left(U_t \xi_t k_t\right)^{1-\alpha} \tag{47}$$

The FOC for U_t is given by:

$$P_{mt}\left(1-\alpha\right)\frac{y_t}{U_t} = bU_t^{\zeta}\xi_t k_t \tag{48}$$

The FOC for W_t:

$$w_t = P_{mt}\alpha\frac{y_t}{L_t} \tag{49}$$

The return to capital:

$$R_{k,t+1} = \frac{\xi_{t+1}\left[\;P_{mt+1}\left(1-\alpha\right)\frac{y_{t+1}}{\xi_{t+1}e^{z_{t+1}}k_{t+1}} + Q_{t+1} - \delta\left(U_{t+1}\right)\;\right]}{Q_t} \tag{50}$$

The optimal investment decision is given by:

$$\begin{aligned}Q_t = 1 &+ \frac{\eta_i}{2}\left(\frac{i_{n,t}+i}{\frac{i_{n,t-1}}{e^{z_t}}+i} - e^z\right)^2 + \eta_i\left(\frac{i_{n,t}+i}{\frac{i_{n,t-1}}{e^{z_t}}+i} - e^z\right)\frac{i_{n,t}+i}{\frac{i_{n,t-1}}{e^{z_t}}+i} \\ &- \beta\frac{\psi_{t+1}}{\psi_t e^{z_{t+1}}}\eta_i\left(\frac{i_{n,t+1}+i}{\frac{i_{n,t-1}}{e^{z_t}}+i} - e^z\right)\left(\frac{i_{n,t+1}e^{z_{t+1}}+i}{i_{n,t}+i}\right)^2\end{aligned}$$

The depreciation rate is given by:

$$\delta\left(U_t\right) = \delta_c + \frac{b}{1+\zeta}U_t^{1+\zeta}$$

The net investment is given by:

$$i_{n,t} = i_t - \delta\left(U_t\right)\xi_t k_t$$

The capital accumulation equation is given by:

$$k_{t+1}e^{z_{t+1}} = \xi_t k_t + i_{n,t} \tag{51}$$

The Phillips curve:

$$x_{1,t} = e^{\lambda_{\pi,t}}y_t P_{mt} + E_t\left\{\beta\phi_\pi\widetilde{\Lambda}_{t,t+1}\left[\Pi_t^{\iota_\pi}\Pi_{t+1}^{-1}\right]^{-\frac{1+\lambda_\pi}{\lambda_\pi}}x_{1,t+1}\right\} \tag{52}$$

$$x_{2,t} = y_t + E_t \left\{ \beta \phi_\pi \widetilde{\Lambda}_{t,t+1} \left[\Pi_t^{\iota_\pi} \Pi_{t+1}^{-1} \right]^{-\frac{1}{\lambda_\pi}} x_{2,t+1} \right\} \tag{53}$$

$$\Pi_t^{\#} = (1 + \lambda_\pi) \frac{x_{1,t}}{x_{2,t}} \Pi_t \tag{54}$$

$$P_t = \left[(1 - \phi_\pi) \left(P_t^{\#} \right)^{-\frac{1}{\lambda_\pi}} + \phi_\pi \left(\Pi_{t-1}^{\iota_\pi} P_{t-1} \right)^{-\frac{1}{\lambda_\pi}} \right]^{-\lambda_\pi} \tag{55}$$

The aggregate resource constraint is given by:

$$y_t = c_t + i_t + G_t + \frac{\eta_i}{2} \left(\frac{i_{n,t} + i}{\frac{i_{n,t-1}}{e^{z_t}} + i} - e^z \right)^2 (i_{n,t} + i) \tag{56}$$

The Taylor rule:

$$i_t^{mp} = \rho_i i_{t-1}^{mp} + (1 - \rho_i) \left[R + \frac{\kappa_\pi}{4} \left(\pi_t^{ma} - \ln \pi_t^* \right) + \frac{\kappa_y}{4} \left(\ln y_t - \ln y_{t-4} \right) + z_t^{ma} - 4z \right] + \sigma_{mp} \varepsilon_t^{mp}$$

where $\pi_t^{ma} = \pi_t + \pi_{t-1} + \pi_{t-2} + \pi_{t-3}$, and $z_t^{ma} = z_t + z_{t-1} + z_{t-2} + z_{t-3}$.

Finally, the structural shocks:

$$\Psi_t = C + \Delta \Psi_{t-1} + \Omega \epsilon_t + \Omega_{ma} \epsilon_{t-1} + \Theta ACI_t \tag{57}$$

where $\Psi_t = \begin{bmatrix} z_t \\ \ln \xi_t \\ \ln G_t \\ \ln \lambda_t \\ \ln b_t \\ \ln \chi_t \\ \lambda_{\pi,t} \\ \ln \pi_t^\star \\ \ln mp_t \\ \ln \theta_t \end{bmatrix}, C = \begin{bmatrix} (1 - \rho_z)\gamma \\ 0 \\ (1 - \rho_g) \ln g \\ (1 - \rho_\lambda) \ln \lambda \\ 0 \\ (1 - \rho_\chi) \ln \chi \\ \left(1 - \rho_{\lambda_\pi}\right) \lambda_\pi \\ 0 \\ 0 \\ (1 - \rho_\theta) \ln \theta \end{bmatrix}, \Delta = \begin{bmatrix} \rho_z & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \rho_\xi & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \rho_g & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \rho_\lambda & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \rho_b & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \rho_\chi & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \rho_{\lambda_\pi} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \rho_{\pi^\star} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \rho_\theta \end{bmatrix},$

$$\Omega = \begin{bmatrix} \sigma_z & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \sigma_\xi & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \sigma_g & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \sigma_\lambda & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \sigma_b & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \sigma_\chi & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \sigma_{\lambda_\pi} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \sigma_{\pi^\star} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \sigma_{mp} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \sigma_\theta \end{bmatrix}, \ \epsilon_t = \begin{bmatrix} \varepsilon_t^z \\ \varepsilon_t^\xi \\ \varepsilon_t^g \\ \varepsilon_t^\lambda \\ \varepsilon_t^b \\ \varepsilon_t^\chi \\ \varepsilon_t^{\lambda_\pi} \\ \varepsilon_t^{\pi^\star} \\ \varepsilon_t^{mp} \\ \varepsilon_t^\theta \end{bmatrix},$$

$$\Omega_{ma} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \mu_{\lambda_\pi} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\Theta = \begin{bmatrix} \lambda_z \\ \lambda_\xi \\ \lambda_g \\ \lambda_\lambda \\ \lambda_b \\ \lambda_\chi \\ \lambda_{\lambda_\pi} \\ \lambda_{\pi^\star} \\ \lambda_{mp} \end{bmatrix} \begin{bmatrix} (1-\rho_z) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \left(1-\rho_\xi\right) & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & (1-\rho_g) & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & (1-\rho_\lambda) & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & (1-\rho_b) & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & (1-\rho_\chi) & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \left(1-\rho_{\lambda_\pi}\right) & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & (1-\rho_{\pi^\star}) & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

All shocks vary exogenously over time in response to independently and identically distributed $N(0,1)$ innovations ε_t^i, $i = z, \xi, g, \lambda, b, \chi, \lambda_\pi, \pi^\star, mp, \theta$.

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