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* Views expressed are those of the authors and do not necessarily reflect official positions of De Nederlandsche Bank.

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Abstract

How should policymakers respond to uncertainty shocks? To analyze the macroeconomic effects of uncertainty shocks associated with various conventional structural shocks, we develop a New Keynesian model with financial frictions and time-varying volatility, which features a monetary-macroprudential policy mix. We find that it matters whether the economy experiences heightened demand, supply or financial uncertainty. More specifically, the underlying source of uncertainty matters for the shocks' propagation, aggregate economic outcomes and appropriate policy responses. Financial uncertainty shocks appear to generate stronger effects and a broad complementarity between the interest rate response and the macroprudential policy stance. Supply-side and demand-side uncertainty shocks reveal important trade-offs between price stability and financial stability objectives, despite their quantitative effects being overall modest. Importantly, simulating a financial turmoil scenario reveals that heightened financial uncertainty exacerbates the negative macroeconomic effects triggered by a first-moment financial shock. Our results underscore the importance of timely and accurate identification of uncertainty surges, which is crucial for the appropriate design and calibration of the monetary-macroprudential policy mix.

Keywords: Uncertainty shocks, financial frictions, monetary policy, macroprudential policy

JEL Classification: E30, E32, E44, E47, E50

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1 Introduction

How should policymakers respond to uncertainty shocks? Addressing this question is of particular importance at the current juncture, since the unfolding COVID-19 pandemic poses new challenges for policies aimed at stabilizing the economy, amid persistently heightened uncertainty about pandemic development, economic outlook, and episodes marked by elevated financial distress. The unprecedented resulting increase in uncertainty at the outset of the pandemic was evident in various proxies used to measure it (Figure 1). These include text-based analysis of newspapers, stock market implied volatility, cross-sectional disagreement in forecasters' estimates about the economic outlook, or the model-based macroeconomic and financial uncertainty indexes as computed by Ludvigson et al. (2021).

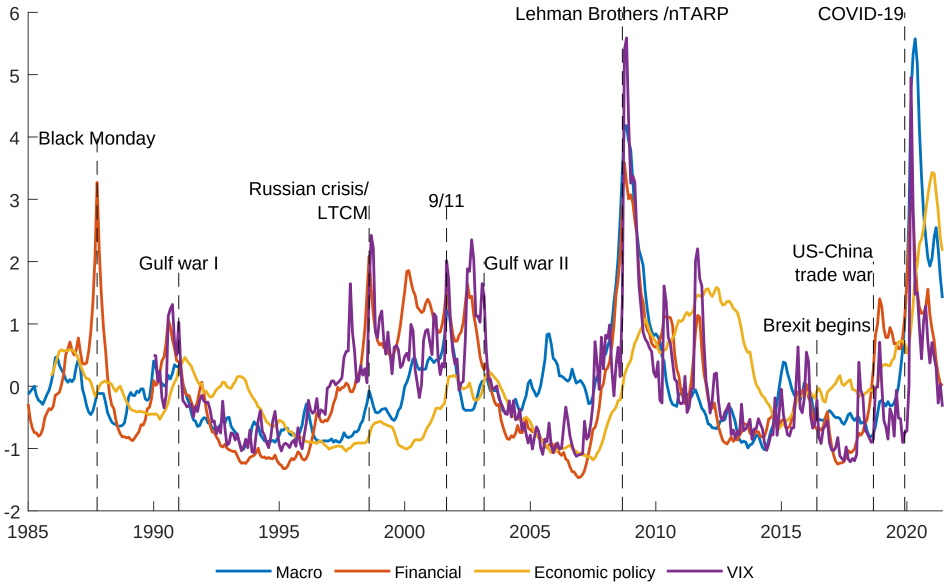

Figure 1: Alternative measures of uncertainty. Note: This figure plots the macroeconomic and financial uncertainty indexes calculated by Ludvigson et al. (2021), economic policy uncertainty calculated by Baker et al. (2016), and the CBOE S&P 500 VIX. All variables are standardized for the period Jan/85 to June/21. The economic policy uncertainty is plotted as a 12-month moving average.

Uncertainty shocks are second-moment perturbations, that can be formally defined as increases in the standard deviation of the shocks that hit the economy. While interest in the role of uncertainty and its time-variation in driving business cycles has been gaining momentum in both academic and policy circles, significantly less attention has been paid to the identification of the origin and nature of various uncertainty shocks, and how different economic policies should properly respond. In this paper, we study the effects of various uncertainty shocks – of supply-side, demand-side, or financial sector origin – in a New Keynesian model with financial frictions and a monetary-macroprudential policy mix. Our goal is to explore how the economic trade-offs revealed by each uncertainty shock interact with the adopted policy framework. Thus, our contribution relates to intersecting a comparative analysis of the effects of uncertainty shocks of different nature with an assessment of the stabilization role played by the monetary-macroprudential policy mix.

To conduct our quantitative analysis, we develop a dynamic, stochastic, general-equilibrium model with nominal rigidities and augmented with financial frictions. Alongside optimizing households and firms, our setting features policymakers who aim at stabilizing the economy using a set of two instruments. First, to achieve price stability, the central bank steers its short-term interest rate as prescribed by a Taylor rule. Second, to achieve financial stability, we assume that the authorities – either the central bank or a separate independent entity – are also in charge with the design and deployment of macroprudential policies (e.g. in the form of a "loan-to-value" type of instrument). In particular, in our setting policymakers respond to the build-up of financial imbalances. These are captured by the real credit gap, that is the credit activity's deviation from its long-run equilibrium. Our model features a costly enforcement type of financial frictions in the spirit of Kiyotaki and Moore (1997), which implies that the firms are collateral constrained and face a borrowing limit linked to the valuation of their assets. We consider three standard level shocks in our model to reflect various origins of economic perturbations: an intertemporal preference shock, a technology shock, and a financial shock (associated with the borrowing constraint). This distinction across structural shocks is all the more important given that the relevant literature did not reach a consensus regarding the economic impact of uncertainty shocks, given multiple and possibly counterbalancing propagation channels, as well as endogenous policy responses. For each of these first moment shocks, we allow for a time-varying second moment, capturing the degree of associated uncertainty.[1]

Our main results can be summarized as follows. First, we trace out the macroeconomic effects of various uncertainty shocks. We find that following productivity and preference uncertainty shocks, the qualitative responses resemble the effects of adverse supply and demand shocks, respectively, but the magnitudes are generally modest. When the economy is hit by financial uncertainty shocks, our analysis reveals that the effects are significantly larger, with output responding about ten times stronger compared to both productivity and preference uncertainty shocks. This result corroborates the strong nexus between financial markets and uncertainty, which appears to have powerful feedback effects. The impulse response analysis underscores the potential trade-offs between price stability and financial stability objectives revealed by each of the uncertainty shocks. In particular, both policy instruments are relaxed to lead, *ceteris paribus*, to a stimulative impact on aggregate economic activity after a financial uncertainty shock, complementing each other, but they pull in opposite directions in case of productivity and preference uncertainty shocks. Secondly, we document the dynamic responses to a simultaneous negative level financial shock and an increase in its associated uncertainty shock, which can be interpreted as a financial turmoil scenario similar to the onset of the global financial crisis (GFC). This exercise substantiates that heightened financial uncertainty exacerbates the negative macroeconomic effects triggered by the first-moment financial shock. In essence, this constellation of disturbances pushes firms against their

[1] This implies that we relax the commonly adopted assumption of homoscedastic innovations.

financing constraints, and, ultimately, generates a broad-based collapse in economic activity, driving the economy into a recession. In this crisis scenario, monetary and macroprudential policies complement each other, and given their timely response the economy is gradually stabilized.

Finally, we investigate how the economic trade-offs revealed by uncertainty shocks interact with the adopted policy framework. Our results stress the importance of carefully designing and calibrating the proper policy mix in response to uncertainty shocks conditional on the authorities' formally assigned mandates in terms of price stability and financial stability. We show that each uncertainty shock is unique and there is no single strictly preferred policy strategy. Therefore, a "one-size-fits-all" type of policy framework appears not adequate in dealing with uncertainty shocks. In the case of financial uncertainty shocks, we found that even if strong macroprudential policy provides a powerful stabilization mechanism, deploying such a tool would not necessarily be optimal in terms of private consumption and, implicitly, societal welfare.

Related literature. The uncertainty literature has benefited from mounting empirical evidence that documents two facts: uncertainty is (i) time-varying and (ii) countercyclical – times of high uncertainty are times of low economic activity. These findings appear to be robust and not to hinge on a particular modeling framework or data set.[2] Since the direction of causality is very hard to disentangle in the data, in this paper we assume that uncertainty fluctuations are exogenous. Nevertheless, we must emphasize that there is no theoretical consensus on whether the uncertainty that we observe during deep recessions is mainly a cause or an effect of declines in economic activity, or perhaps it entails both, within a complex endogenous feedback loop. As argued by Ludvigson et al. (2021), "uncertainty could co-move contemporaneously with real activity both because it is an exogenous impulse driving business cycles and because it responds endogenously to first moment shocks".

Our paper pertains to the stream of literature that analyzes the effects of *exogenous uncertainty* shocks based on structural models. Several pioneering studies have documented the propagation of uncertainty shocks to technology (Bloom, 2009; Leduc and Liu, 2016), preferences (Basu and Bundick, 2017; Pellegrino et al., 2021), the real interest rate (Fernández-Villaverde et al., 2011), monetary policy (Mumtaz and Zanetti, 2013), and fiscal policy (Born and Pfeifer, 2014a; Fernández-Villaverde et al., 2015). These theoretical models were extended in many directions, including to study specific transmission mechanisms and the importance of economic characteristics (such as nominal and real rigidities), but less so in terms of the role of macroprudential policy.[3] Models that feature uncertainty shocks and

[2] Fernández-Villaverde and Guerrón-Quintana (2020) provide a review on uncertainty shocks and business cycle research.

[3] Among others, Cho et al. (2021) study optimal monetary policy in response to uncertainty shocks when the precautionary pricing channel is operative; with a focus on inflation, Oh (2020) finds that depending on the pricing assumption, different dynamics emerge in response to uncertainty shocks; Fasani and Rossi (2018) show that under the Rotemberg pricing assumption, uncertainty shocks to productivity can have inflationary or deflationary effects depending on the monetary policy rule; Annicchiarico and Rossi (2015) employ a New Keynesian (NK)-AK model with three sources of uncertainty to explore the effects of uncertainty on growth under different Taylor-type rules, concluding that strong inflation targeting rules neutralize the negative effects of uncertainty.

financial market imperfections have also received comparatively less attention.[4] We aim to fill this gap by contributing to the literature with a comparative analysis of the effects of uncertainty shocks stemming from different sectors of the economy, and provide an assessment of the stabilization role played by the monetary-macroprudential policy framework.

Finally, a different stream of this literature studies alternative sources and propagation channels of *endogenous uncertainty*. Several prominent contributions are focused on (i) financial frictions or the zero lower bound constraint on the nominal interest rate (Brunnermeier and Sannikov, 2014; Plante et al., 2018; Adrian et al., 2020); (ii) incomplete information, where some examine learning mechanisms with aggregate shocks (Van Nieuwerburgh and Veldkamp, 2006; Fajgelbaum et al., 2017), while others study firm-specific shocks (Straub and Ulbricht, 2017; Ilut and Saijo, 2021); or (iii) search and matching frictions (Ilut et al., 2018).

The rest of the paper proceeds as follows. Section 2 describes the theoretical model with three types of uncertainty shocks. Section 3 briefly discusses the computation methods used to solve the model, while Section 4 reports the calibration of the model. Section 5 presents the quantitative analysis which delivers the main findings of the paper. Finally, Section 6 concludes.

2 Model

In this section we describe the economic environment based on a dynamic, stochastic, general-equilibrium model augmented with financial frictions. We develop this model to examine how uncertainty shocks propagate and the role played by the policy mix – monetary (interest rates) and macroprudential – in response to episodes of heightened uncertainty and financial disruptions. The model incorporates optimizing households and firms, while policymakers aim at stabilizing the economy using a set of two instruments. First, in order to achieve price stability, the central bank implements the interest rate policy as prescribed by a Taylor rule. Second, we assume that the authorities (either the central bank or a separate independent institution) are also in charge with the design and deployment of macroprudential policies in pursuit of achieving financial stability. We opt to include sticky prices using the quadratic-adjustment cost specification proposed by Rotemberg (1982), since this price setting has more empirical support for the propagation of uncertainty shocks than the Calvo-pricing approach (as documented by Oh, 2020). Our model features a costly enforcement type of financial frictions in the spirit of Kiyotaki and Moore (1997).[5] The underlying assumption is that, in the event of default, the lender can only recover a

[4]An exception is the work by Fernández-Villaverde and Guerrón-Quintana (2020), which proposes a standard real business cycle model augmented with financial frictions in the tradition of Kiyotaki and Moore (1997) to illustrate the main mechanisms linking uncertainty shocks and business cycles. However, this general-equilibrium model with flexible prices cannot reproduce a well established empirical finding that an uncertainty shock causes a fall in output, consumption, investment, and hours worked. As documented by Basu and Bundick (2017), uncertainty shocks are able to generate this co-movement when the model accounts for countercyclical markups via price stickiness.

[5]This approach can be viewed as modeling financial frictions in a reduced-form framework and it is motivated by tractability, since opting for a fully micro-founded setting requires allowing for some degree of market incompleteness and a certain level of heterogeneity in the model.

fraction of the debt, leading to an optimal contracting problem. This essentially implies that the firms are collateral constrained and can only borrow up to a fraction of the value of their assets. In this setting, asset price fluctuations affect the borrowing limit and the firm's investment decisions. We consider three standard level shocks in our model to capture both demand- and supply-side perturbations, as well as those of financial nature: an intertemporal preference shock, a technology shock and a financial shock. For each of these first moment shocks, we allow for a time-varying second moment, which captures the degree of associated uncertainty.

2.1 Households

We assume that the representative household in our economy is maximizing a utility function that features non-separability between the streams of consumption C_t and labor N_t as proposed by Greenwood et al. (1988) (GHH). This type of preferences implies that the wealth effect on labor supply is eliminated, since the labor optimality condition yields labor supply as a function of real wage only, with no direct effect coming through consumption.[6] Turning to its budget constraint, the household receives income W_t for each unit of labor N_t supplied to the intermediate goods-producing firms. The representative household saves in one-period riskless bonds B_t, which pay the gross nominal interest rate R_{t-1}, and owns the intermediate goods firm and receives its profits Π_t. Note that household savings in the form of riskless bonds are financing the borrowing undertaken by intermediate goods producers.

The representative household maximizes lifetime utility by choosing C_t, N_t, B_{t+1} for $t = 0, ...\infty$ by solving the following problem:

$$\max_{C_t,N_t,B_{t+1}} \quad \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \xi_t^C \frac{1}{1-\nu} \left(C_t - \gamma \frac{N_t^{1+\eta}}{1+\eta} \right)^{1-\nu} \tag{1}$$

subject to its intertemporal budget constraint in each period t:

$$C_t + B_{t+1} \leq W_t N_t + R_{t-1} B_t + \Pi_t \tag{2}$$

where $\beta < 1$ is the discount rate, ν captures the relative risk aversion (or the inverse of the intertemporal elasticity of substitution between consumption and labor), η denotes the inverse of Frisch labor supply elasticity, and γ represents a labor disutility scalar which controls for the number of hours worked in steady state. ξ_t^C is an intertemporal preference shock following a first order autoregressive process AR(1), with stochastic volatility (see subsection 2.5 for details), which we interpret as the degree of *ex ante* uncertainty about future aggregate demand.

The first order conditions are outlined in Appendix A. Note that under GHH preferences the house-

[6] A classical example is a positive technology shock which would shift out labor demand, but there would be no inward shift of labor supply driven by increasing consumption.

hold's stochastic discount factor Δ between periods t and $t+s$ reads as follows:

$$\Delta_{t+s} \equiv \frac{\partial U_{t+s}/\partial C_{t+s}}{\partial U_t/\partial C_t} = \beta^s \frac{\xi^C_{t+s}}{\xi^C_t} \left(\frac{C_{t+s} - \gamma \frac{N_{t+s}^{1+\eta}}{1+\eta}}{C_t - \gamma \frac{N_t^{1+\eta}}{1+\eta}} \right)^{-\nu}. \tag{3}$$

2.2 Intermediate goods producers

There is a continuum of intermediate goods producers, indexed by $i \in [0,1]$. Each firm i rents labor $N_t(i)$ from the representative household, which serves as input in the production of their goods. The intermediate-goods firms own their capital stock $K_t(i)$, and we assume that investment is subject to a convex adjustment cost as in Christiano et al. (2005). We allow firms to also choose the rate of utilization of their installed physical capital $u_t(i)$, which feeds into the depreciation rate; implicitly, the firm uses $K_t(i)u_t(i)$ capital services in the production process. Intermediate goods are produced in a monopolistically competitive market where firms need to pay a quadratic cost ψ_p if they want to adjust their nominal price $P_t(i)$, in the spirit of Rotemberg (1982). Firm i chooses $N_t(i)$, $I_t(i)$, $K_{t+1}(i)$, $u_t(i)$, and $P_t(i)$ to maximize its profits $\Pi_t(i)/P_t(i)$ given the demand for its variety $Y_t(i)$, the elasticity of substitution among intermediate goods ϵ, and the price P_t of the final good. We assume that each intermediate good firm i has access to the same technology represented by a Cobb-Douglas-type production function (with constant returns to scale), with A_t the level of aggregate productivity, and subject to a fixed cost of production FC. Finally, as one of the key ingredients in our setting, we assume that the intermediate-goods firms borrow to finance their wage bill and investment projects, what is often referred to as "working capital", via a one period loan with interest rate R_t to be paid at the end of the period. Moreover, we impose a collateral constraint and require that the loan cannot exceed a share of the firms' asset value, denoted ζ_t. This setup is sometimes known as the *costly enforcement* model: since a firm might default on its debt, a lender will only allow it to borrow up to a fraction of its assets. Hence, in our setting, an exogenous change in this share ζ_t captures a financial frictions shock.

Each firm maximizes current and future discounted profits using the household's stochastic discount factor:

$$\max_{N_t(i), I_t(i), K_{t+1}(i), u_t(i), P_t(i)} \quad \mathbb{E}_t \sum_{s=0}^{\infty} \Delta_{t+s} \frac{\Pi_{t+s}(i)}{P_{t+s}}, \tag{4}$$

where

$$\frac{\Pi_t(i)}{P_t} = \frac{P_t(i)}{P_t} Y_t(i) - R_t \left(\frac{W_t}{P_t} N_t(i) + I_t(i) \right) - \frac{\psi_p}{2} \left[\frac{P_t(i)}{\pi P_{t-1}(i)} - 1 \right]^2 Y_t(i) \tag{5}$$

where the terms on the right-hand side of the expression represent firm's income, expenses related to the repayment of the working capital loan (principal and interest), and price adjustment costs.[7]

The maximization problem is subject to several standard constraints, such as the production function, the capital accumulation equation, and the depreciation rate of capital (which depends on its utilization rate). A key additional constraint that we consider is the working capital assumption coupled with a borrowing limit (i.e. collateral constraint):

$$\frac{W_t}{P_t}N_t(i) + I_t(i) \le (\zeta_t - \upsilon_t)\, Q_t K_t(i) \tag{6}$$

where Q_t is the price of a marginal unit of installed capital (Tobin's Q, which varies over time). Importantly, we allow for macroprudential policy interventions, captured by υ_t, which we discuss in Subsection 2.4. The key idea is that the macroprudential authority responds to financial imbalances, releasing its instrument to tighten or loosen the borrowing limit and directly impacting credit activity. See Appendix A for the complete formulation of intermediate-goods producers' maximization problem, and for the full set of first order conditions which govern the behavior of each firm i. Here we show only the key optimality conditions:

$$\frac{W_t}{P_t}(R_t + \mu_t) = (1-\alpha)\mathcal{MC}_t A_t \left[K_t(i)u_t(i)\right]^{\alpha} N_t(i)^{-\alpha} \tag{7}$$

$$Q_t = \mathbb{E}_t \left\{ \Delta_{t+1} \left[u_{t+1}(i)\frac{R^K_{t+1}}{P_{t+1}} + Q_{t+1}\left(1 - \delta\left(u_{t+1}(i)\right) + \mu_{t+1}(\zeta_{t+1} - \upsilon_{t+1})\right) \right] \right\} \tag{8}$$

$$R_t + \mu_t = Q_t \left[1 - \frac{\psi_i}{2}\left(\frac{I_t(i)}{I_{t-1}(i)} - 1\right)^2 - \psi_i\left(\frac{I_t(i)}{I_{t-1}(i)} - 1\right)\frac{I_t(i)}{I_{t-1}(i)} \right] + \psi_i \mathbb{E}_t \left[\Delta_{t+1} Q_{t+1} \left(\frac{I_{t+1}(i)}{I_t(i)} - 1\right)\left(\frac{I_{t+1}(i)}{I_t(i)}\right)^2 \right] \tag{9}$$

where $\mathcal{MC}_t$ represents the real marginal cost of producing one additional unit of intermediate good i, μ_t denotes the Lagrange multiplier corresponding to the collateral constraint (which binds if $\mu_t > 0$, implying that equation (6) holds with equality), $\frac{R^K_t}{P_t}$ is the marginal revenue product per unit of capital services ($K_t u_t$).

2.3 Final goods producers

This second layer of production is standard and we provide all details in Appendix A. Here we focus only on the main elements characterizing this sector.

The final good Y_t with price P_t is assembled by a perfectly competitive final goods sector from the individual intermediate goods $Y_t(i)$ through a constant returns to scale technology (i.e. a CES

[7] Note that our specification of price adjustment costs is proportional to the individual firm output, which implies an additional term in our Phillips curve as compared to the assumption of these costs being proportional to aggregate output. However, our results, in terms of impulse responses following uncertainty shocks, are robust to this choice. These results are available upon request.

aggregator), $\left[\int_0^1 Y_t(i)^{\frac{\epsilon-1}{\epsilon}} di\right]^{\frac{\epsilon}{\epsilon-1}} \geq Y_t$, where ϵ represents the elasticity of substitution between any two input goods. Each intermediate input good $Y_t(i)$ is produced by one firm and sold for a price $P_t(i)$. Taking as given prices P_t and $P_t(i)$, the final goods producing-firms maximize profits by choosing quantities $Y_t(i)$ subject to its production function. This optimization problem yields the following optimality condition for each variety i, implying that the demand for the individual good $Y_t(i)$ depends negatively on the relative price and positively on aggregate output:

$$Y_t(i) = \left(\frac{P_t(i)}{P_t}\right)^{-\epsilon} Y_t. \tag{10}$$

Note that perfect competition results in zero profits, which delivers the following expression for the aggregate price index: $P_t = \left[\int_0^1 P_t(i)^{1-\epsilon} di\right]^{\frac{1}{1-\epsilon}}$.

2.4 Monetary and macroprudential policies

Monetary policy

We assume a cashless economy with a monetary authority that sets the short-term nominal interest rate R_t to stabilize inflation and output growth, consistent with an inflation targeting framework. More specifically, monetary policy is conducted by adjusting the nominal interest rate in accordance with the prescriptions of the following Taylor rule:

$$R_t = R_{t-1}^{\rho_r} \left[R \left(\frac{\pi_t}{\pi}\right)^{\kappa_\pi} \left(\frac{Y_t - Y_{t-1}}{Y_{t-1}}\right)^{\kappa_y} \right]^{1-\rho_r} e^{\varepsilon_t}, \tag{11}$$

where $\pi_t \equiv \frac{P_t}{P_{t-1}}$ represents gross inflation, with π denoting its steady-state value, and ε_t is the monetary shock, which is assumed to be independent and identically distributed (iid).

Macroprudential policy

Given the strong implications that financial markets have on other economic sectors – as demonstrated during the GFC – we augment the policymakers' mandate with an additional goal of financial stability. We assume that the central bank (or a separate authority) acts also as a macroprudential regulator, responding to the build-up of financial imbalances. In our setting, these are captured by the real credit gap, that is the credit activity's deviation from its long-run equilibrium. Therefore, we adopt the following functional form for the macroprudential policy rule:

$$\upsilon_t = \upsilon_{t-1}^{\rho_\upsilon} \left[\left(\frac{L_t}{L}\right)^{\kappa_{cr}} \right]^{1-\rho_\upsilon} e^{\nu_t}, \tag{12}$$

where $L_t \equiv \frac{W_t}{P_t} N_t + I_t$, L is its steady-state value, and ν_t is the macroprudential shock, which we assume to be iid. The coefficient κ_{cr} is positive, reflecting a counterciclical macroprudential policy.

By changing υ_t, the macroprudential authority affects the collateral constraint (6) and, implicitly, the accessibility to credit. In other words, when the private sector is willing to lend a certain fraction of the firm's underlying assets, the macroprudential regulator can tighten the borrowing constraint even further for financial stability concerns. If loan activity is too alert (above its long-run equilibrium), risking to generate a credit boom and endangers financial stability, υ_t is increased, implying tighter financing conditions and a decrease in credit demand, which feeds further into lower investment and aggregate demand. Our macroprudential instrument υ_t is analogous to a "loan-to-value" requirement implemented in practice by various national authorities. This can be easily seen by dividing expression (6) by the firm's asset value, implying in aggregate terms that $\frac{L_t}{Q_t K_t} \leq (\zeta_t - \upsilon_t)$.[8]

2.5 Shock processes

In this subsection, we describe the stochastic processes followed by the shocks included in the model. We assume that the intertemporal preference, productivity and financial shocks obey autoregressive of order one processes, with the corresponding non-stochastic means: $A = 1$, $\xi^C = 1$, and $\zeta = 0.05$, as follows:

$$A_t = (1 - \rho_a)A + \rho_a A_{t-1} + \sigma_t^A \epsilon_t^A \tag{13}$$

$$\xi_t^C = (1 - \rho_{\xi^C})\xi^C + \rho_{\xi^C}\xi_{t-1}^C + \sigma_t^{\xi^C} \epsilon_t^{\xi^C} \tag{14}$$

$$\zeta_t = (1 - \rho_\zeta)\zeta + \rho_\zeta \zeta_{t-1} + \sigma_t^\zeta \epsilon_t^\zeta, \tag{15}$$

where ϵ_t^A, $\epsilon_t^{\xi^C}$, and ϵ_t^ζ represent the corresponding innovations to the level of these exogenous stochastic processes, referred to as first-moment or level shocks. Importantly, we allow for time-varying volatility for all these processes – $\sigma_t^A \geq 0$, $\sigma_t^{\xi^C} \geq 0$ and $\sigma_t^\zeta \geq 0$ –, implying that we relax the widely adopted assumption of homoscedastic innovations. These are characterized by their own laws of motion (specified in terms of natural logarithm):

$$\ln \sigma_t^A = (1 - \rho_{\sigma_a}) \ln \sigma_a + \rho_{\sigma_a} \ln \sigma_{t-1}^A + \epsilon_t^{\sigma^A} \tag{16}$$

$$\ln \sigma_t^{\xi^C} = (1 - \rho_{\sigma_{\xi^C}}) \ln \sigma_{\xi^C} + \rho_{\sigma_{\xi^C}} \ln \sigma_{t-1}^{\xi^C} + \epsilon_t^{\sigma^{\xi^C}} \tag{17}$$

$$\ln \sigma_t^\zeta = (1 - \rho_{\sigma_\zeta}) \ln \sigma_\zeta + \rho_{\sigma_\zeta} \ln \sigma_{t-1}^\zeta + \epsilon_t^{\sigma^\zeta}, \tag{18}$$

where $\epsilon_t^{\sigma^A}$, $\epsilon_t^{\sigma^{\xi^C}}$, and $\epsilon_t^{\sigma^\zeta}$ capture the innovations to the corresponding volatility of the exogenous processes, referred to as uncertainty or second-moment shocks. In this paper we primarily focus on studying the propagation of these uncertainty shocks, which are assumed to originate from different sectors of the economy. Since uncertainty shocks are not all alike, differentiating among them is paramount to enhanc-

[8] Note that we do not analyze the potential strategic interactions between monetary and macroprudential policies, asymmetric information or coordination and communication frictions that could be relevant in practice, especially in a framework with two independent authorities. This work is left for future research.

ing our understanding about the role uncertainty plays in economic fluctuations and how policymakers can respond in order to restore the macroeconomic equilibrium.

2.6 Equilibrium and aggregation

We can model the production sector as a representative intermediate goods-producing firm because of our assumption of Rotemberg (1982) price setting behavior. The symmetric equilibrium characterizing this economy implies that all intermediate goods firms choose the same price ($P_t(i) = P_t$), investment ($I_t(i) = I_t$), capital stock ($K_t(i) = K_t$), capacity utilization rate ($u_t(i) = u_t$), and labor input ($N_t(i) = N_t$). Therefore, the aggregate production function reads as follows:

$$Y_t = A_t \left(K_t u_t\right)^{\alpha} N_t^{1-\alpha} - FC \tag{19}$$

Equilibrium in goods market yields the following aggregate resource constraint:

$$Y_t = C_t + I_t + \frac{\psi_p}{2}\left(\frac{\pi_t}{\pi} - 1\right)^2 Y_t \tag{20}$$

We also consider a measure of net output, or real GDP, which excludes the adjustment costs implied by the price setting behavior of firms, and being equal to the sum on consumption and investment demand: $GDP_t = C_t + I_t$. The full set of equilibrium conditions is provided in Appendix B. The economic environment is characterized by 24 equations in 24 aggregate variables: $Y_t, GDP_t, C_t, I_t, K_t, u_t, \delta_t, N_t, \Delta_{t+1}, \pi_t, Q_t, \mathcal{MC}_t, r_t^K, w_t, L_t, R_t, \upsilon_t, \mu_t, A_t, \xi_t^C, \zeta_t, \sigma_t^A, \sigma_t^{\xi^C}, \sigma_t^{\zeta}$, where $r_t^K \equiv \frac{R_t^K}{P_t}$ and $w_t \equiv \frac{W_t}{P_t}$. The dynamics are driven by five standard level stochastic shocks – intertemporal preference, productivity, financial, monetary and macroprudential –, to which we add three second-moment shocks to capture the uncertainty stemming from the demand-, supply-, and financial-side of the economy. Note that the monetary and macroprudential shocks are assumed to be iid.

3 Model solution

Since our NK DSGE model has no closed-form solution, we need to solve it numerically. To this end, we use third-order perturbation methods and the pruning techniques proposed by Andreasen et al. (2018).[9] Note that using at least a third-order approximation or global solutions is required since we are interested in capturing how changes in the standard deviation of shocks influence the model's dynamics, which do not play any role if employing a lower order approximation. The computation method is rather standard, and it can be summarized as follows: (i) solve for the non-stochastic steady state of the model – the deterministic point of the optimality conditions characterizing the model's dynamics,

[9] The authors show that this technique performs well in dealing with the trade-off between computational speed and accuracy.

where the volatility of all shocks is zero; (ii) employ a third-order approximation in levels of the system of equations characterizing the equilibrium around this deterministic steady state[10]; and finally (iii) compute the generalized impulse response functions (GIRFs) of variables of interest following specific shocks. As is customary with non-linear solutions, we compute GIRFs because the responses to shocks are state-dependent, which means that they depend on the sign and magnitude of the shock, as well as on the initial point in the state space characterizing the economy when the shock hits. In our simulations, this is considered to be the ergodic mean (i.e. theoretical mean based on the third-order pruned state space), following the approach by Andreasen et al. (2018). Note that in this case GIRFs have closed-form expressions and, hence, we do not rely on simulations for their computation.[11]

Opting for perturbation solutions is motivated by the fact that models with uncertainty shocks are typically highly-dimensional, given that the time-varying volatilities are additional state variables, which we need to keep track of.[12] Therefore, because of high computational demands linked to the curse of dimensionality inherent to global techniques such as projection methods, we discard the option of solving the model fully non-linearly.

4 Model calibration

Instead of taking the model to the data, which is complicated given the inherent non-linearities, we opt to implement a standard calibration, using the relevant literature contributions. For completeness, we report in Table 1 all calibrated parameters (corresponding to a quarterly frequency), but below we focus on the more novel ones, underlying the uncertainty shocks processes.

All structural parameters – the household discount factor, coefficients in the capital depreciation rate function, capital's share in the production function, the inverse of the Frisch elasticity of labor supply, etc. – are borrowed from the literature. These values are rather standard: some are extensively documented in previous work, while for others there is broad consensus on their conventional values. However, a few remarks are in order. Note that we set the disutility weight on labor, γ, such that hours worked are 1/3 in the non-stochastic steady state (based on US data). Also, we set the utilization rate to 1 in the non-stochastic steady state. Regarding the monetary policy parameters, we adopt a rather standard and

[10]For this higher-order perturbation solution, we need to apply pruning techniques as proposed by Andreasen et al. (2018) to tackle the potential problem of explosive sample paths. In a nutshell, pruning entails leaving out terms in the solution that have higher-order effects than the approximation order. Furthermore, as explained in Fernández-Villaverde and Guerrón-Quintana (2020), it is recommended to perturb the system around the deterministic steady state, even when we account for uncertainty shocks which might move the stochastic steady state (defined as the fixed point characterizing the equilibrium conditions of the model when the realization of all shocks within the period is zero).

[11]An alternative would be to compute GIRFs around the stochastic steady state (also referred to as the ergodic mean in the absence of shocks). This approach relies on simulations and is used by Fernández-Villaverde et al. (2011); Born and Pfeifer (2014b); Basu and Bundick (2017), among others. Nevertheless, it is worth highlighting, as discussed in the online appendix of Born and Pfeifer (2014b), in section IV "IRFs at the Ergodic Mean", computing the non-linear IRFs not as the expected difference in responses as proposed by Koop et al. (1996), but also conditioning on future shocks and setting them to 0, only partly captures the economic effects of uncertainty shocks.

[12]Our setting is characterized by eleven state variables: capital, investment, the nominal interest rate, output, the macroprudential instrument, the three level shocks, and the corresponding three uncertainty shocks.

Parameter	Value
Panel A. Structural parameters	
β, preference discount factor	0.994
δ_0, capital depreciation rate	0.02
δ_1, slope depreciation function	0.03
δ_2, curvature depreciation function	0.03
α, capital share in the production function	1/3
η, labor supply elasticity	0.5
γ, disutility weight on labor	2.8
ν, controls risk aversion (inverse of EIS)	2
ψ_i, investment adjustment cost	2
ϵ, elasticity of substitution among varieties	5
ψ_p, price adjustment cost	50
π, steady state gross inflation rate	1.005
Policy parameters	
κ_π, policy weight on inflation	1.5
κ_y, policy weight on output growth	0.2
ρ_r, interest rate smoothing parameter	0.8
κ_{cr}, policy weight on credit imbalances	0.1
ρ_v, macroprudential smoothing parameter	0.5
Panel B. First- and second-moment shocks, standard deviations	
ρ_{ξ^C}, persistence of preferences	0.9
ρ_a, persistence of technology (TFP)	0.9
ρ_ζ, persistence of financial friction	0.75
$\rho_{\sigma_{\xi^C}}$, persistence of uncertainty preference shock	0.75
ρ_{σ_a}, persistence of uncertainty TFP shock	0.75
ρ_{σ_ζ}, persistence of uncertainty financial shock	0.75
ζ, mean-reversion borrowing limit	0.05
σ_{ξ^C}, volatility of preference uncertainty	0.0325
σ_a, volatility of TFP uncertainty	0.007
σ_ζ, volatility of financial friction uncertainty	0.008

Table 1: Calibrated parameters

empirically plausible Taylor rule with interest rate smoothing: $\kappa_\pi = 1.5$, $\kappa_y = 0.2$, $\rho_r = 0.8$.[13] Turning to the macroprudential policy parameters, we acknowledge there is less guidance in the literature, and we calibrate the response to credit imbalances to $\kappa_{cr} = 0.1$, assuming there is also a degree of smoothing when deploying this instrument, $\rho_v = 0.5$. Since we are also interested in investigating how the economic trade-offs emerging following different uncertainty shocks interact with the adopted policy framework, in subsection 5.4 we conduct a joint sensitivity analysis with respect to two key policy parameters – the response to inflation deviation from target (κ_π) and the response to financial imbalances (κ_{cr}).

Next, we calibrate the parameters governing the shock processes following previous work by Basu and Bundick (2017), Fernández-Villaverde and Guerrón-Quintana (2020), and Cesa-Bianchi and Fernandez-Corugedo (2018). For the persistence of the first-moment shocks, we opt for a value of 0.9 for technology and preferences, which is in the range revealed by empirical estimates (see Christiano et al., 2014; Fernández-Villaverde et al., 2015, among others), while for the financial friction perturbation our working assumption is a lower persistence of 0.75. Based on the mean estimates by Fernández-Villaverde et al. (2015), we calibrate all persistence parameters of uncertainty shocks to 0.75. Mean parameters in the preference, productivity and financial uncertainty shocks are taken from estimations by Fernández-Villaverde et al. (2015), Cooley and Prescott (2021) and Guerron-Quintana and Jinnai (2019), respectively.

[13] As noted in Fasani and Rossi (2018), the interest rate smoothing parameter ρ_r is estimated in the interval $0.79 - 0.85$ by many studies, including Clarida et al. (2000), Benati and Surico (2008), Benati and Surico (2009), Christiano et al. (2014), Christiano et al. (2016), Justiniano and Primiceri (2008), Fernández-Villaverde et al. (2010).

5 Results

5.1 Key mechanisms and intuition

In this section we focus on describing the key mechanisms at work in our model following uncertainty shocks: (i) precautionary behavior, (ii) the Oi-Hartman-Abel effect, and (iii) the real rigidities implied by financial frictions. We aim to clarify that there are different driving forces, some of them working in opposite directions, which make the overall effect *a priori* ambiguous. Here we focus on the channels, and we postpone some of the nuances associated to the dynamics of specific uncertainty shocks to the next subsection. Note that despite a generalized consensus in the economics profession regarding the high-level effects of first moment shocks, there is an a priori ambiguity about the direction and size of second moment shocks, as noted in Fernández-Villaverde and Guerrón-Quintana (2020): "economic theory, in general, does not impose constraints regarding the sign of the effects of uncertainty shocks: they can be either expansionary or contractionary"; and in Born and Pfeifer (2014a): "Scientific evidence on the aggregate effects of uncertainty is still inconclusive" given "different effects working in opposite directions, thereby making the overall effect ambiguous".

In our model, agents exhibit precautionary behavior in the form of savings and pricing decisions. We start with precautionary savings, and then discuss the upward pricing bias channel, arising due to nominal price rigidities.

It is well established in the literature that precautionary behavior depends on the third derivative of the utility function: if $U''' > 0$ agents will save more, everything else equal. In other words, given the convexity of marginal utility, households exhibit prudence and prefer to avoid ample fluctuations in marginal utility across different states of the world by saving in order to self-insure against this risk. For example, following an adverse uncertainty shock of any nature, consumers characterized by prudence respond, *ceteris paribus*, by increasing their precautionary savings.[14] As emphasized by Fernández-Villaverde and Guerrón-Quintana (2020), part of the mitigation of the precautionary saving effects of uncertainty shocks stems from the fact that in this stylized economic environment agents have access to one asset (in positive net supply) to save in, and that is physical capital. When uncertainty rises and the precautionary behavior is triggered, since physical capital represents the only asset in which agents can save, it also becomes riskier. There are two possible explanations for this evolution: (i) there is heightened productivity uncertainty or (ii) higher discount factor (i.e. a demand shifter) uncertainty. Therefore, two opposing forces are at play – a higher demand for savings in the form of physical capital, due to precautionary motives, concurrently with a lower demand for capital, due to valuation risk –, and which one dominates is not necessarily clear *ex ante*.

[14] Note that the qualification "everything else equal" or "*ceteris paribus*" is important, since agents' labor supply will also typically increase in general equilibrium, which, in turn, will increase consumption via the income effect; however, this effect is not operating under GHH preferences.

As documented by Fernández-Villaverde et al. (2015), nominal price rigidities can amplify the consequences of uncertainty shocks and prompt firms to engage in precautionary behavior in their pricing decisions. They argue that a higher level of uncertainty induces an upward pricing bias by increasing the dispersion of where the relative price will fall ex-post. The key transmission mechanism is a rise in markups, which is explained by two channels – an aggregate demand channel and an upward pricing bias channel. The first channel is rather standard, following the reasoning from above in terms of precautionary behavior. In the presence of sticky prices, output is demand-determined in the short run. Therefore, due to heightened uncertainty agents would cut back on their consumption and investment, but with nominal rigidities prices do not fully and immediately adjust to accommodate the lower demand. Thus, markups rise and output declines. The upward pricing bias channel prompts firms to set prices higher than in the absence of uncertainty. With Rotemberg adjustment costs, the current price determines how costly it will be for firms to change next period's price. Since for firms it is costlier to set a price that is too low relative to its competitors rather than setting it too high (as implied by the asymmetric profit function), they bias their pricing decision upward in the current period. Real marginal costs decline because firms invest less (this lowers the cost with capital) and hire less workers, given the fall in output. As labor demand falls, and since labor supply is fixed, due to GHH preferences, the labor market clears through a reduction in real wages. Higher prices and lower real marginal costs generate a rise in markups.

Next, we focus on how uncertainty can affect the production decisions of the economy. The frequently cited mechanism is the Oi-Hartman-Abel effect, which can be outlined with the following example. When the production function of firms is characterized by decreasing returns to scale, by endogenously choosing their size, firms can benefit from higher productivity uncertainty: when favorable shocks hit the economy, firms can expand, while when adverse shocks arrive, they can scale down. The concavity of the production function warrants that such decision rules deliver higher profits when technology fluctuates due to uncertainty shocks than when it is held constant.[15] However, this effect entirely dies out when the size of the firm becomes indeterminate, as it is the case under constant-returns-to-scale. However, in our model firms are facing investment adjustment costs, which prevent constant-returns-to-scale firms from fully adjusting to shocks, and allows us to recover a quasi-Oi-Hartman-Abel effect.

Finally, we discuss the real rigidities channel implied by financial frictions. Given that our model features financial frictions in the form of a borrowing limit, uncertainty shocks affect the probability of the collateral constraint binding in the future or the severity of this constraint (by changing the distribution of future realizations). Therefore, agents react already in the current period to protect themselves against such future realizations. For example, in our setting firms have an incentive to accumulate more capital because this relaxes their financing constraints, and, therefore, they will undertake more investment projects in the current period in the form of precautionary investment.

[15] Note that a mean-preserving rise in productivity's volatility will increase, everything else equal, the *ex post* dispersion of input demands, profits, and output.

5.2 Macroeconomic effects of uncertainty shocks

In this subsection we document the propagation of uncertainty shocks within our model. For each shock, we study the impact on the economic environment of a doubling in its standard deviation, which implies a doubling of the volatility of the corresponding first moment shock. The stream of literature on uncertainty shocks typically focuses on tracing out the macroeconomic effects of relatively large (i.e. two- or three-standard deviation) shocks. Despite this increase in the volatility of level shocks – entailing an increased probability of larger future changes – there is no actual change in fundamentals. This feature of the model implies that unrealistically large uncertainty shocks are required in order to push the economy in a state where firms are against their collateral constraints if the simulations are initiated at the non-binding steady state. Therefore, in this subsection we focus on a hypothetical economic environment in which the collateral constraint is always binding. This assumption is relaxed in the next subsection, when analyzing joint financial first- and second-moment shocks. We reveal the macroeconomic effects of uncertainty shocks using GIRFs, given that we employ non-linear methods to solve our model.

5.2.1 Productivity uncertainty shock

Figure 2 shows the impact of a technology uncertainty shock. A doubling of TFP uncertainty shock's standard deviation (equivalent to about 0.7 log-points on impact, as shown in the very last panel in the figure) resembles the effects of an unfavorable aggregate supply shock. As opposed to the RBC model proposed by Fernández-Villaverde and Guerrón-Quintana (2020), in which TFP uncertainty shocks are expansionary, mainly on account of strong investment, in our model with nominal price rigidities and collateral constraints output declines, matching qualitatively the results in New Keynesian models of Born and Pfeifer (2014a), Fasani and Rossi (2018) and Cesa-Bianchi and Fernandez-Corugedo (2018) (the latter also includes financial frictions in the spirit of Bernanke et al., 1999). Overall, the magnitude of the effects on key macroeconomic variables is relatively small – with net output declining by 0.02% on impact – but within the range of results delivered by the New Keynesian models of (i) Born and Pfeifer (2014a), where output declines by about 0.007% in the face of a doubling standard deviation of TFP and investment-specific uncertainty shocks, and (ii) Cesa-Bianchi and Fernandez-Corugedo (2018), where output declines by almost 0.02% on impact in response to an increase of 15% in TFP volatility. The small impact of TFP uncertainty shocks is due to various propagation mechanisms working in opposite directions, including precautionary savings motives, nominal rigidities and quasi-Oi-Hartman-Abel effects, as explained in a previous subsection. In addition, unlike the relevant literature, we also include macroprudential policy as an active macro-stabilization tool, which further dampens the amplitude of business cycle fluctuations.

In response to heightened uncertainty regarding future TFP dynamics, households typically resort to lower consumption and wish to save and work more. Under demand-determined output (due to sticky prices), lower consumption leads to downward pressure on both real marginal costs and demand for

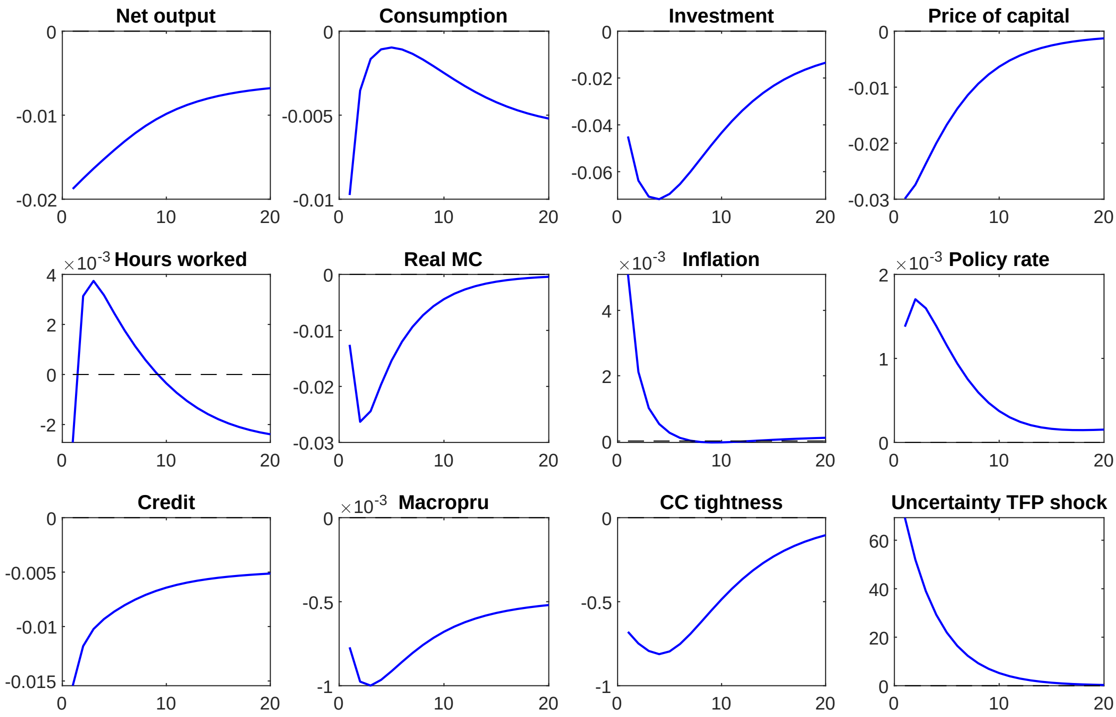

Figure 2: Impact of a doubling in TFP uncertainty shock. Note: The GIRFs are computed at the ergodic mean following Andreasen et al. (2018). All variables correspond to percentage deviations from their deterministic steady state.

production inputs. Given GHH preferences, labor supply is fixed initially, resulting in a decline in hours worked and real wages on impact.[16] Lower costs are reflected in higher markups; in addition, via the quasi-Oi-Hartman-Abel effect and convex marginal profit curves, firms want to self-insure against being stuck with too low unit prices when future TFP innovations arrive (upward pricing bias). Consequently, the inflation rate increases. At the same time, given lower aggregate demand, investment declines while utilization rate increases to compensate partly for subdued capital accumulation. Lower investment leads to a negative impact on credit demand, which is reflected into a more relaxed collateral constraint. Concurrently, reductions in asset prices, including because capital is now perceived as riskier, imply tighter lending conditions.

In order to restore macroeconomic equilibrium, policymakers implement a mix of measures consisting of higher interest rates, directly addressing above-target inflation and price stability concerns, and relaxed macroprudential policy in response to weak credit activity. Note that *ceteris paribus* the two policies have an opposite impact on economic developments: while higher interest rates will decline output, a looser macroprudential stance will stimulate production via higher investment. Accordingly, a sensible policy framework in the face of productivity (supply-side) uncertainty shocks would consist of the two instruments pulling in opposite directions, given the trade-offs between price stability and financial stability objectives that this shock reveals.

[16] As explained previously (subsection 5.1), the precautionary labor supply effect emerging via the income channel is not operative under GHH preferences.

5.2.2 Preference uncertainty shock

The effects of doubling the standard deviation of preference shocks are displayed in Figure 3. Overall, the direction of dynamic responses resembles an unfavorable demand shock. Unlike the RBC model of Fernández-Villaverde and Guerrón-Quintana (2020), which under a strong precautionary savings channel (absent price rigidities) makes demand uncertainty expansionary, in our case this second-moment shock leads to lower output. This outcome is in line with the results provided by Basu and Bundick (2017), who document empirically that heightened demand uncertainty leads to lower output and inflation, and then design a New Keynesian model to match this evidence.

Increased uncertainty about future consumption preferences rises the probability of large swings in marginal utility, which – under the convexity of the marginal utility function – induces a strong precautionary savings motive. Accordingly, households cut back on their consumption by around 0.03% at its trough and save more, while firms increase investment by more than 0.01%. Under sticky prices and demand-determined production, output declines by a maximum of 0.01%, thus reducing equilibrium hours worked (lower demand for inputs dominates the outward-shifting labor supply) and limiting the increase in investment demand arising under precautionary capital accumulation, since this activity entails more risk. The latter mechanism raises the price of capital, which relaxes the collateral constraint and boosts credit demand, while capital utilization declines since firms value capital services more and want to maintain it into the future (when the economy might experience a more favorable preference disturbance). On the account of reductions in both input prices – real wages and the marginal revenue product per unit of capital services –, to which adds a more relaxed working capital financing, real marginal costs decrease. As opposed to productivity uncertainty shocks, the upward pricing bias in the case of demand uncertainty is less pronounced, and subdued aggregate demand effects end-up dominating, leading to lower inflation.

Policymakers respond with interest rate cuts and a tighter macroprudential stance, given below-target inflation and above-equilibrium credit development, respectively. Note that similarly to the TFP uncertainty shock, the ensuing trade-off between price stability and financial stability objectives leads to a policy mix implementation that requires setting the two instruments to have, *ceteris paribus*, opposite effects on output. However, the roles are now reversed, with looser monetary policy (given too low inflation) and tighter macroprudential policy (given too alert credit activity).

5.2.3 Financial uncertainty shock

Figure 4 presents the dynamic responses to a two standard deviations increase in financial uncertainty shocks. Intuitively, this measure of uncertainty quantifies the magnitude of unpredictability about the future developments in financial conditions. A notable difference vis-à-vis the two second moment shocks from above is that the effects are generally much larger, with output responding about ten times stronger

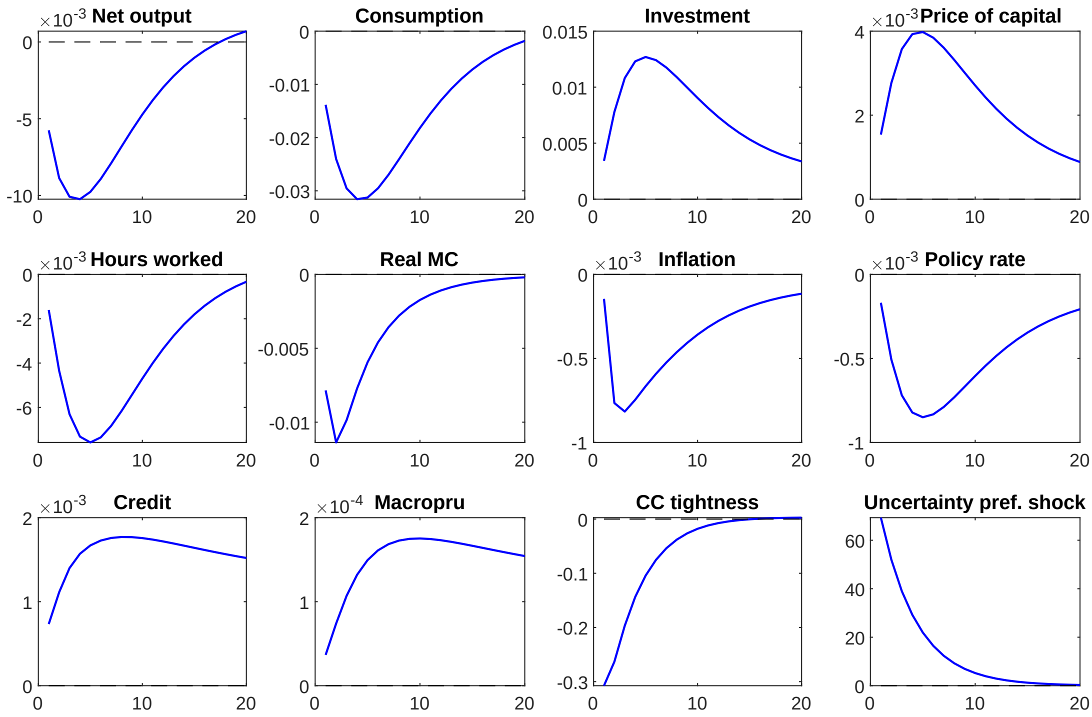

Figure 3: Impact of a doubling in preference uncertainty shock. The GIRFs are computed at the ergodic mean following Andreasen et al. (2018). Note: All variables correspond to percentage deviations from their deterministic steady state.

as compared to both TFP and demand uncertainty shocks. This result highlights the strong nexus between financial markets and economic uncertainty, which is at the heart of macro-financial linkages. Similar relative magnitudes in the responses of the key macroeconomic variables are also observed in: (i) Fernández-Villaverde and Guerrón-Quintana (2020), where financial frictions uncertainty shocks are more potent as compared to demand and TFP uncertainty shocks and (ii) Cesa-Bianchi and Fernandez-Corugedo (2018), where microeconomic uncertainty, captured by the cross-sectional dispersion of idiosyncratic productivity (feeding into the financial accelerator mechanism introduced by Bernanke et al., 1999), generates much larger effects relative to macroeconomic uncertainty associated with aggregate TFP.

Overall, output and inflation decline, similar to demand uncertainty shocks. However, the comovement of consumption and investment with aggregate output is inverted (so the substitution between consuming and investing reverses across the two shocks), providing an unambiguous identification of financial uncertainty and preference uncertainty shocks. In response to heightened financial uncertainty, agents assign larger probabilities to both looser and tighter financial frictions in the future. Given our adopted functional forms of preferences, the scenario of more relaxed financing conditions dominates, so that pledging capital is expected to be easier, investment is postponed (decreases by 0.7%), while consumption increases (by over 0.2%). In addition, in order to avoid too fast capital depreciation and extend it into the future – when investment is expected to become more profitable – capital utilization decreases. Under nominal rigidities, output is determined by the demand for investment and consump-

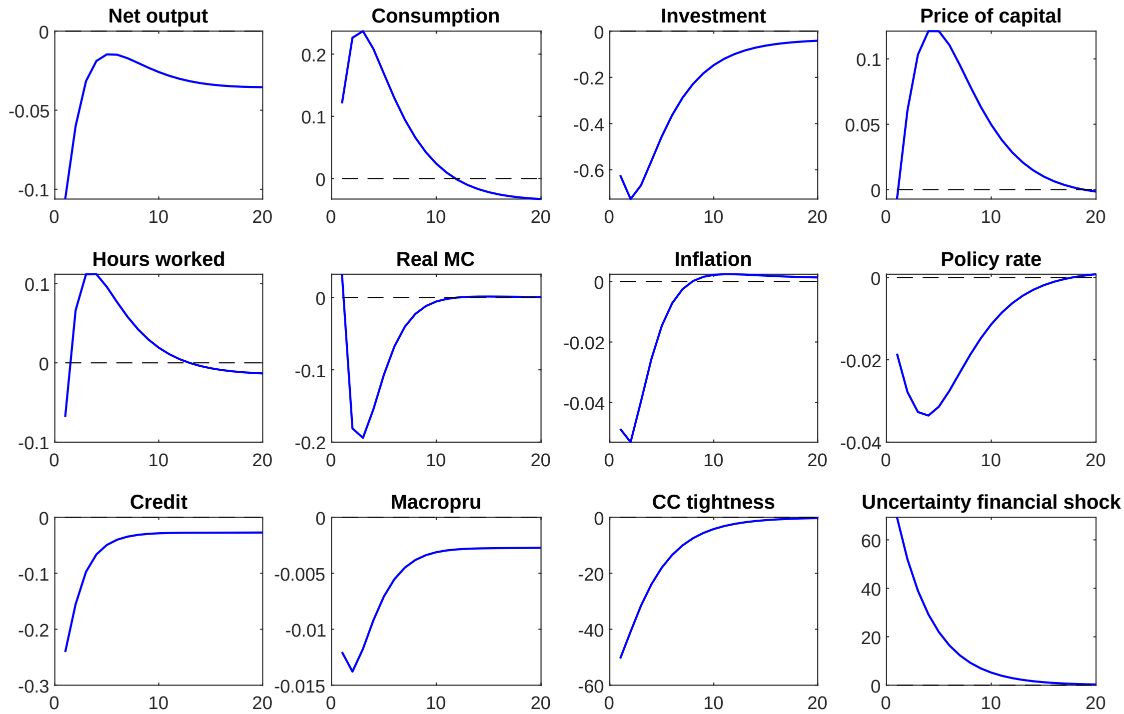

Figure 4: Impact of a doubling in financial uncertainty shock. The GIRFs are computed at the ergodic mean following Andreasen et al. (2018). Note: All variables correspond to percentage deviations from their deterministic steady state.

tion goods. Given that the fall in investment outweighs the pick-up in consumption, aggregate output declines by 0.1% on impact. The subsequent up-and-down dynamics of output reflects differences – in terms of magnitude and persistence – of consumption and investment responses.

Restoring the equilibrium between investment supply and demand schedules requires an increase in the price of capital, which relaxes the tightness of the collateral constraint, allowing credit to decline relatively less as compared to investment. Looser collateral constraint is reflected in lower marginal costs (except on impact), via the working capital mechanism embedded in our model, despite input costs (wage and cost of capital) increasing moderately in the medium term. This allows firms to charge lower prices, with inflation decreasing by around 20 annualized basis points (ABP).

Authorities' response to financial uncertainty shocks is consistent with loosening both interest rate policy and macroprudential stance. Given the primacy of price stability goal embedded in the Taylor rule and below-target inflation, interest rates decline by maximum 15 ABP. Lower credit activity leads to a relaxation of macroprudential stance. Note that, unlike the two previous uncertainty shocks, both policy instruments produce, ceteris paribus, a stimulative impact on aggregate economic activity. Thus, in the case of financial uncertainty shocks, the policies are complementing each other, given there are no trade-offs between price stability and financial stability goals. This outcome can, in principle, rationalize a scenario in which only one of the instruments – either interest rates or the macroprudential policy – could be employed to restore macroeconomic equilibrium; however, the needed reaction would likely be more intense as compared to the unconstrained policy space analyzed in our simulations; see subsection

5.4 for additional results on policy frameworks.

5.3 A financial distress scenario

Motivated by the observation that during the GFC we witnessed a sharp tightening of financial conditions coupled with heightened volatility in many of the key macroeconomic and financial variables, in this subsection we propose the following exercise. We consider a simultaneous negative level financial shock and an adverse financial uncertainty shock, which implies a tightening of the borrowing constraint coupled with an increase in the volatility of financial conditions. Even though this simulation does not fully capture the shifting in distributions implied by a change in the skewness of shocks' density, we show that it delivers important insights for our analysis.

Importantly, this exercise allows to study in a coherent framework the interplay between financial frictions and their corresponding uncertainty, while also modeling the borrowing limit as an occasionally binding constraint. This, in turn, helps capture the underlying uncertainty stemming from the occasional nature of the borrowing limit. While in the previous subsection we treat the collateral constraint as always binding, here we relax this assumption by considering that it is only occasionally binding.[17] In this setting, following an adverse financial level shock the economy is pushed in a recession, and in this state of the world the collateral constraint starts to bind and the agents face uncertainty regarding whether and for how long the constraint will bind in the future.

To implement this exercise, we first compute the correlation between a financial shock and its corresponding time-varying measure of uncertainty estimating a data-driven model of the US economy. This empirical exercise is based on a time-varying parameter Bayesian VAR with stochastic volatility as proposed by Primiceri (2005). We follow Plante et al. (2018) and use a standard set of key macroeconomic variables for the US – *per capita* real GDP growth, the inflation rate, the federal funds rate – to which we add the credit spread computed by Gilchrist and Zakrajšek (2012) to proxy financial conditions.[18] We are interested in estimating the volatility of all the shocks included in the model, and in particular the one characterizing financial conditions. We use a pre-pandemic data sample, covering the period between 1975Q1 to 2019Q4.[19] The *ex post* estimated correlation coefficient between the posterior mean of the financial shock and the posterior mean of its stochastic volatility is positive and around 0.22, implying that a tightening in financial conditions is coupled with a simultaneous increase in financial un-

[17] We solve this version of the model using the algorithm proposed by Holden (2016), and the accompanying toolbox DynareOBC.

[18] Our result is similar to the one obtained if using the shadow interest rate, as computed by Krippner (2013), to capture a more accurate picture of the monetary policy stance.

[19] The first 10 years train the prior distributions of the parameters, and since we consider a two-quarter lag structure, our estimates are based on data from 1986Q1 to 2019Q4. The model is estimated with Bayesian Monte Carlo Markov Chain (MCMC) methods; our estimates are based on 100,000 draws from the posterior distribution, after a burn-in of 50,000 draws and keeping every 100th draw. More details about the model's structure and its estimation can be found in Plante et al. (2018). Nevertheless, we do acknowledge that using a recursive identification scheme comes with limitations (i.e. timing restrictions and ordering), and an approach as proposed by Ludvigson et al. (2021) would be more appropriate. Since this is not the focus of our paper, we leave this endeavor for future research. Figure 9 in Appendix C displays the strong correlation between the credit spread and its corresponding model-based volatility.

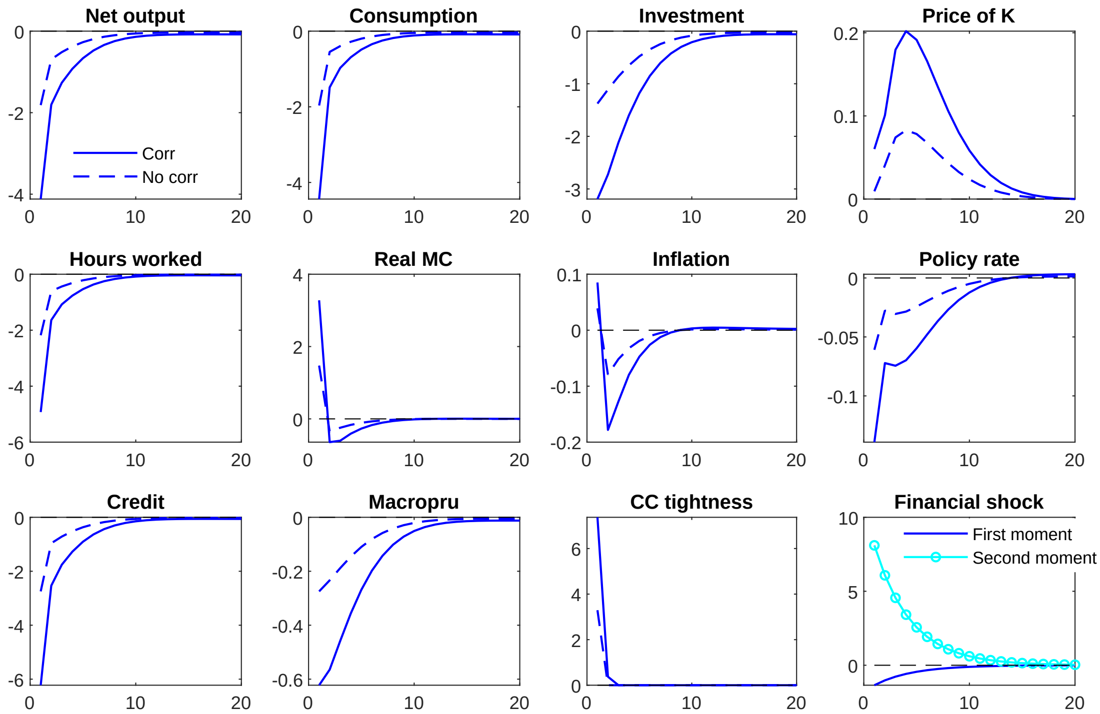

Figure 5: Impact of simultaneous financial first and second moment shocks. Note: The solid blue line captures responses in the financial distress scenario (assuming correlation between first and second moment financial shocks), while the dashed blue line depicts responses following only a financial level shock (i.e. no correlation). The GIRFs are computed at the ergodic mean following Andreasen et al. (2018). All variables correspond to percentage deviations from their deterministic steady state.

certainty.[20] We next impose this empirical correlation in our simulations and study the macroeconomic effects revealed by this constellation of simultaneous financial first and second moment shocks.[21]

Figure 5 displays with solid blue lines the dynamic responses to a simultaneous negative level financial shock (a reduction in ζ_t, i.e. the fraction of collateral firms can borrow against to acquire working capital) and an adverse uncertainty shock (an increase in σ_t^ζ by a factor of 1.084). Note that the underlying assumption is that uncertainty responds contemporaneously to first moment financial shocks, which is depicted by the light blue circled line (last panel in the last row). The negative financial friction shock, which limits the borrowing capacity of firms, pushes them against their collateral constraint for several periods (second panel in the last row). As a result, firms hire less labor and undertake fewer investment projects, which imply lower credit activity. These developments lead to a decline in output, which reduces the gains from owning capital, since the marginal revenue of capital falls. The decline in the desired capital stock feeds further into a lower level of investment. In parallel, as the capital stock diminishes, its price gradually goes up, which prompts a relaxation of the borrowing constraint that ultimately becomes not binding. Price stickiness and the strong decline in output result in lower inflation, which raises the real interest rate (relative to the flexible-price benchmark) and further depresses consumption. Concurrently, higher uncertainty about how much firms can borrow reduces the demand for consumption

[20] For the other variables included in our model the corresponding *ex post* correlation coefficients are close to zero.

[21] Note that in contrast to the empirical exercise, where an adverse financial shock implies a credit spread increase, in our theoretical model, a tightening of financial conditions implies a fall in the borrowing limit. Hence, in our simulations the calibrated correlation is negative.

goods, which lowers output directly, since under the assumption of price stickiness aggregate demand determines output in the short run. This constellation of simultaneous perturbations generates a broad-based decline in activity, pushing the economy into a downturn. Therefore, in order to stabilize the economy, the monetary authority promptly reduces interest rates and the macroprudential regulator acts such that to ease financing conditions. These targeted instruments complement each other and their timely deployment ensures that policymakers are able to achieve their price and financial stability objectives.

Additionally, Figure 5 shows with dashed blue lines the responses following only an adverse financial shock (i.e. there is no correlation between first and second moment financial shocks). The decline in all key macroeconomic variables – output, consumption, and investment – is still sizable, but on impact the fall is less than half its value under financial turmoil. This alternative scenario helps clarify that financial uncertainty matters and it has strong amplification effects when it increases simultaneously with a deterioration in financing conditions. Also, by comparing the solid and dashed blue lines, we can observe that even though both monetary and macroprudential policies react more strongly under the financial distress scenario, the recovery phase is more protracted.

5.4 Uncertainty shocks, economic trade-offs, and policy frameworks

In this subsection we explore how the economic trade-offs revealed by uncertainty shocks interact with the adopted policy framework. Our model embeds two policy instruments aiming at implementing the dual mandate of price stability and financial stability: the interest rate rule is deployed to bring inflation rate to the target, while the macroprudential tool is directly targeting the return of credit to its long-run equilibrium. We showcase how the effects of uncertainty shocks vary across policy frameworks, as embedded in the calibration of the two policy rules. The results underscore the importance of carefully designing and calibrating the proper policy mix in response to uncertainty shocks conditional on the authorities' formally assigned mandates in terms of price stability and financial stability, given that each shock is unique and there is no single strictly preferred policy strategy. Accordingly, our analysis substantiates that a "one-size-fits-all" type of policy framework appears not adequate in dealing with uncertainty shocks.

We start by discussing the financial uncertainty shock, which in our model produces quantitatively larger effects on the economy as compared to the other uncertainty disturbances. In Figure 6 we plot the impact effect of the shock across a grid of three values for the inflation parameter in the Taylor rule (κ_π) and five values for the credit parameter in the macroprudential rule (κ_{cr}).[22] For each panel, the lines correspond to three central banks which differ in their tolerance for off-target inflation, from high (blue line, $\kappa_\pi = 1.05$) to average (red line, $\kappa_\pi = 1.5$, which corresponds to the standard calibration

[22]Our baseline calibration corresponds to the combination $\kappa_\pi = 1.5$ and $\kappa_{cr} = 0.1$. The results are broadly consistent if instead of the impact effect we look at the accumulated effect over initial several quarters.

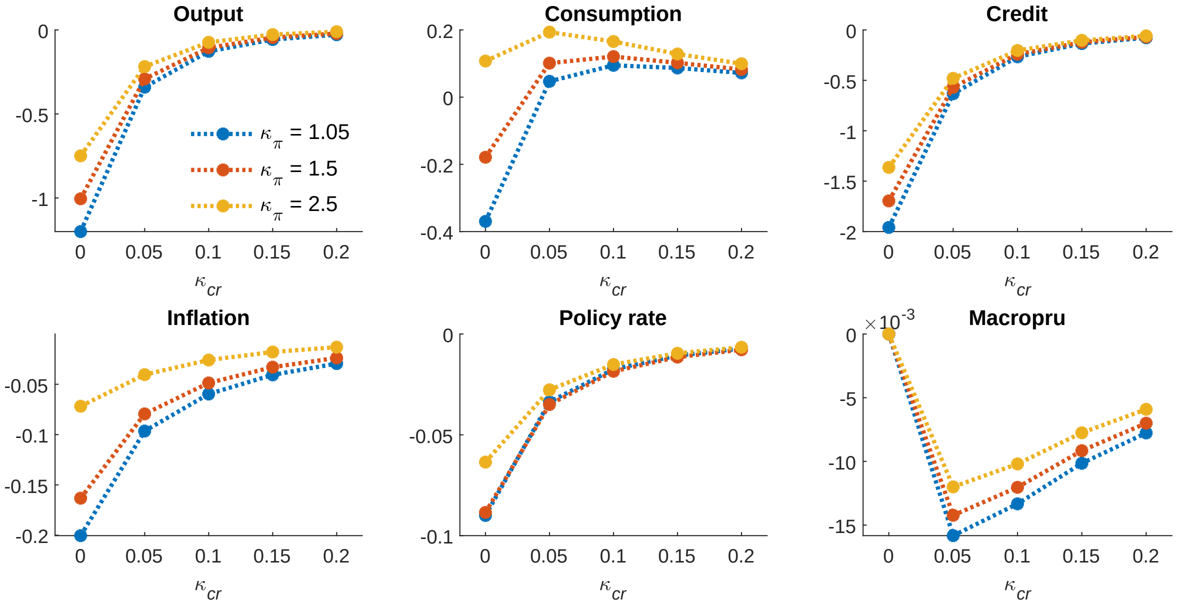

Figure 6: Impact effect of financial uncertainty shocks across policy frameworks

in the literature) to low (yellow line, $\kappa_\pi = 2.5$). For each central bank behavior, we assign five different macroprudential strategies, which differ in their tolerance for credit imbalances, ranging from low ($\kappa_{cr} = 0.2$, implying a strong macroprudential response) to no macroprudential policy at all ($\kappa_{cr} = 0$, corresponding to a pure inflation targeting framework). Note that we abstract from the practical issue of whether interest rate policy and macroprudential policy are assigned to a single institution (e.g. the central bank), or to different decision bodies; in our model the two instruments are set according to the assigned rules, reacting to the stated arguments with specific intensities embedded in the model's parameterization.

A weaker interest rate policy is generally associated with larger declines in output, credit and inflation in response to financial uncertainty shocks. Macroprudential policy provides a significant stabilization mechanism, with a vigorous macroprudential reaction (higher κ_{cr}) being able to insulate the economy even in case of a weak inflation targeting policy (low κ_π). Even the implementation of a weak macroprudential policy produces a large stabilization effect: compare the magnitudes of effects for $\kappa_{cr} = 0$ and $\kappa_{cr} = 0.05$. In addition, the weaker the interest rate re-activeness, the larger the burden placed on the shoulders of macroprudential policy and, hence, the more it should be relaxed.

However, note the concave pattern of consumption responses, with both strong and absent reaction to credit imbalances being inferior in terms of household consumption to a strategy of mild macroprudential policy. As such, the authorities are subject to a significant trade-off when designing the appropriate policy framework in response to financial uncertainty: while a strong reaction to risks of both price stability and financial stability would avoid volatility in production, credit, or inflation, it would not necessarily be optimal in terms of private consumption and, implicitly, societal welfare.

Technology uncertainty shocks (Figure 7) do not appear to pose a trade-off between aggregate output

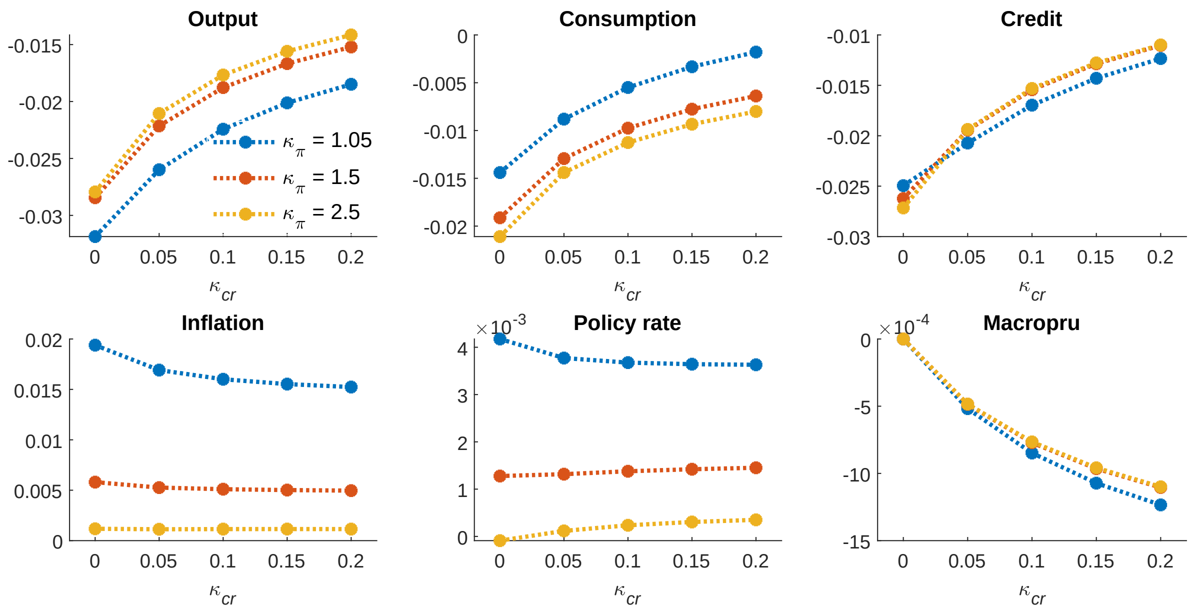

Figure 7: Impact effect of technology uncertainty shocks across policy frameworks

and inflation in terms of preferred policy framework: stronger commitment to both price stability and financial stability (higher κ_π and κ_{cr}) generally results in milder output decline and lower above-target inflation.[23] However, note that the ranking of the frameworks by tolerance to inflation is reversed in case of consumption as compared to the one for output or inflation. In other words, for a given calibration of the macroprudential rule, the interest rate framework that allows for a milder decline in output is also producing a larger drop in consumption. This underscores the trade-off authorities face in the event of supply-side uncertainty between supporting consumption versus investment, or implicitly between households versus businesses.

Depending on the policy framework, demand-side uncertainty shocks imply very stark differences in terms of impact effect on several variables, as displayed in Figure 8. While output and consumption decline for all analyzed calibrations, the response of inflation, credit (implicitly investment) and the two policy variables is highly-dependent on the central bank's attitude toward inflation. For a weak inflation-targeter prices increase (with the shock now resembling a supply-side disturbance) and credit declines, making the macroprudential policy act toward loosening; in the baseline calibration – and more generally when the reactiveness to inflation in the Taylor rule is high enough – inflation declines, credit increases, and macroprudential policy is tightened. Note also that the $\kappa_\pi = 1.05$ case matches qualitatively the co-movement of consumption and investment that Basu and Bundick (2017) document in case of preferences uncertainty shocks, in contrast to our baseline results where the two demand components are negatively correlated.

[23] The fact that inflation appears to be low for the strong inflation-targeting central bank ($\kappa_\pi = 2.5$) despite a very modest increase in the interest rates (or equivalently that inflation is relatively quite high despite stronger interest rate reaction for the weak inflation-targeting central bank) is the outcome of the rational expectations property embedded in the model. Agents have perfect knowledge and understanding of policy functions, including interest rate and macroprudential rules, and full credibility in the policymakers' capacity to efficiently respond to shocks, implying that only small changes in the two instruments are sufficient to minimize the effect of shocks.

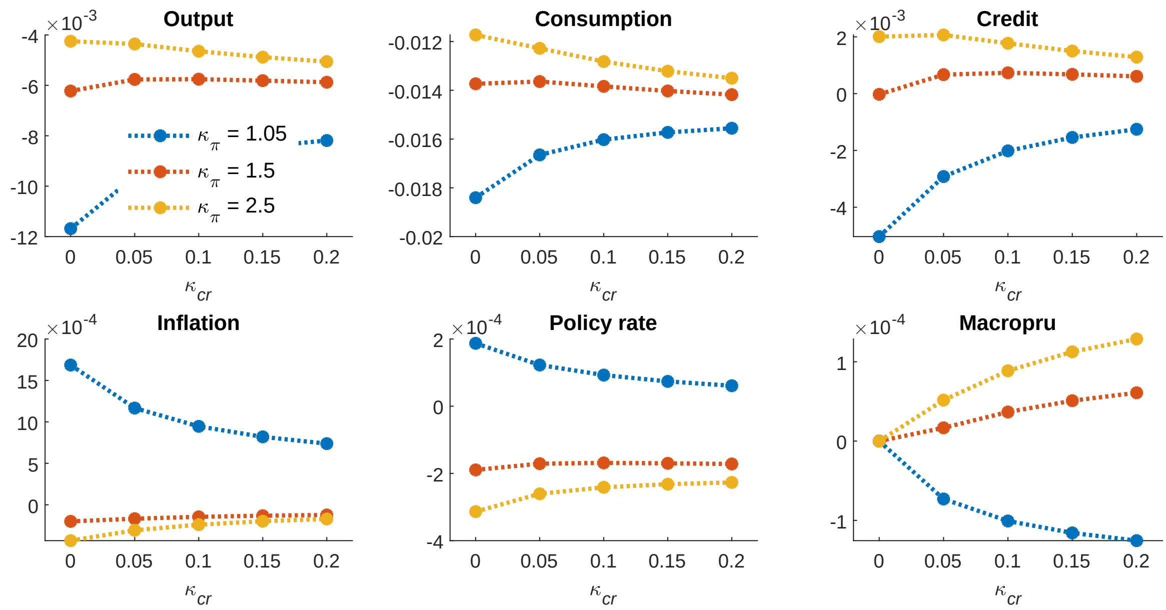

Figure 8: Impact effect of preferences uncertainty shocks across policy frameworks

6 Conclusion

Interested in the conduct of both monetary and macroprudential policies in the presence of financial frictions and heightened uncertainty, we designed a monetary DSGE model with collateral constraints, in the spirit of Kiyotaki and Moore (1997), and allowing for time-varying volatility of structural shocks. This structure is applied to three fundamental shocks, which enables us to analyze the macroeconomic effects of uncertainty shocks stemming from different sectors of the economy. We first documented the dynamic effects of the model economy in reaction to uncertainty shocks, highlighting the main propagation channels and monetary-macroprudential policy responses. When the economy is hit by financial uncertainty shocks, our analysis revealed generally much larger effects, with output responding about ten times stronger as compared to both productivity and preference uncertainty shocks. Overall, we found that following productivity and preference uncertainty shocks, the qualitative responses resemble the effects of adverse supply and demand shocks, respectively. This finding substantiates the strong nexus between financial markets and economic uncertainty. Based on our model economy, we also documented the emerging trade-offs or complementarities between price stability and financial stability objectives revealed by each of the uncertainty shocks and their implications for the appropriate policy mix. In the case of financial uncertainty shocks, both interest rate and macroprudential policies are relaxed, thus complementing each other and implying, *ceteris paribus*, a stimulative impact on aggregate economic activity. On the contrary, given the trade-off between off-target inflation and credit imbalances revealed in the face of both productivity and preference uncertainty shocks, the two policy instruments are required to adjust in opposite directions.

Then, we focused on tracing out the dynamic responses of a simultaneous level financial shock and an adverse financial uncertainty shock – a scenario resembling the narrative during the GFC. This exercise revealed that heightened uncertainty exacerbated the negative macroeconomic effects triggered by the level financial shock. Moreover, this constellation of disturbances pushed the firms to their borrowing limit, and, ultimately, generated a broad-based collapse in economic activity. We showed that in this state of the world, macroeconomic stabilization requires the monetary and macroprudential instruments complementing each other.

Finally, through the lenses of our model, we assessed how the economic trade-offs revealed by each uncertainty shock interact with the adopted policy framework. We showcased how the effects of uncertainty shocks vary across different policy frameworks, as embedded in the interest rate reactiveness to inflation and in the macroprudential instrument sensitivity to credit. Our results imply that each shock is unique and there is no single universal strictly preferred policy strategy. Therefore, a "one-size-fits-all" type of policy framework appears not adequate in dealing with uncertainty shocks. In particular, in the case of financial uncertainty shocks, we found that even if strong macroprudential policy provides a powerful stabilization mechanism, deploying such a tool would not necessary be optimal in terms of private consumption and, implicitly, societal welfare. This underscores the importance of timely identifying the nature of the uncertainty shocks and carefully designing and calibrating the proper policy mix, conditional on the authorities' formally assigned mandates in terms of price and financial stability.

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Appendix A.

Intermediate goods producers

Here we provide the complete maximization problem of intermediate goods producers. Each firm maximizes discounted pay-offs using the household's stochastic discount factor:

$$\max_{N_t(i),I_t(i),K_{t+1}(i),u_t(i),P_t(i)} \quad \mathbb{E}_t \sum_{s=0}^{\infty} \Delta_{t+s} \frac{\Pi_{t+s}(i)}{P_{t+s}}, \tag{1}$$

where

$$\frac{\Pi_t(i)}{P_t} = \left(\frac{P_t(i)}{P_t}\right)^{1-\epsilon} Y_t - R_t \left(\frac{W_t}{P_t} N_t(i) + I_t(i)\right) - \frac{\psi_p}{2}\left[\frac{P_t(i)}{\pi P_{t-1}(i)} - 1\right]^2 Y_t(i) \tag{2}$$

where the terms on the right-hand side of the expression represent firm's income, expenses related to the repayment of the working capital loan (principal and interest), and price adjustment costs. The maximization is subject to the following constraints:

1. the production function

$$Y_t(i) = \left(\frac{P_t(i)}{P_t}\right)^{-\epsilon} Y_t \leq A_t \left[K_t(i)u_t(i)\right]^{\alpha} N_t(i)^{1-\alpha} - FC \tag{3}$$

2. the capital accumulation equation

$$K_{t+1}(i) = (1-\delta_t(i))K_t(i) + I_t(i)\left[1 - \frac{\psi_i}{2}\left(\frac{I_t(i)}{I_{t-1}(i)} - 1\right)^2\right], \tag{4}$$

   where ψ_i captures the investment adjustment cost parameter. Note that in steady state $\frac{I_t}{I_{t-1}} = 1$, and this collapses to the standard capital accumulation equation.

3. the depreciation rate of capital (which depends on its utilization rate)

$$\delta_t(i) = \delta_0 + \delta_1\left(u_t(i) - 1\right) + \frac{\delta_2}{2}\left(u_t(i) - 1\right)^2 \tag{5}$$

4. the working capital assumption coupled with a borrowing limit (i.e. collateral constraint)

$$\frac{W_t}{P_t} N_t(i) + I_t(i) \leq \left(\zeta_t - \upsilon_t\right) Q_t K_t(i) \tag{6}$$

   where υ_t represents the macroprudential policy instrument (see Subsection 2.4) and Q_t is the price of a marginal unit of installed capital (Tobin's Q, which varies over time).

The firm problem reads as follows:

$$\begin{aligned}
\mathcal{L} =& \mathbb{E}_t \sum_{s=0}^{\infty} \Delta_{t+s} \left\{ \left(\frac{P_{t+s}(i)}{P_{t+s}}\right)^{1-\epsilon} Y_{t+s} - R_{t+s}\left(\frac{W_{t+s}}{P_{t+s}} N_{t+s}(i) + I_{t+s}(i)\right) - \ldots \right.\\
& - \frac{\psi_p}{2}\left[\frac{P_{t+s}(i)}{\pi P_{t+s-1}(i)} - 1\right]^2 \left(\frac{P_{t+s}(i)}{P_{t+s}}\right)^{-\epsilon} Y_{t+s} - \ldots\\
& - \mathcal{MC}_{t+s}\left(\left(\frac{P_{t+s}(i)}{P_{t+s}}\right)^{-\epsilon} Y_{t+s} - A_t\left[K_t(i)u_t(i)\right]^{\alpha} N_t(i)^{1-\alpha} + FC\right) + \ldots\\
& + Q_{t+s}\left[I_{t+s}(i) - \frac{\psi_i}{2}\left(\frac{I_{t+s}(i)}{I_{t+s-1}(i)} - 1\right)^2 I_{t+s}(i) + (1-\delta_{t+s}(i))K_{t+s}(i) - K_{t+s+1}(i)\right] + \ldots\\
& \left. + \mu_{t+s}\left((\zeta_{t+s} - \upsilon_{t+s})Q_{t+s}K_{t+s}(i) - \frac{W_{t+s}}{P_{t+s}} N_{t+s}(i) - I_{t+s}(i)\right)\right\}
\end{aligned}$$

where $\mathcal{MC}_t$ represents the real marginal cost of producing one additional unit of intermediate good i, and μ_t denotes the Lagrange multiplier corresponding to the collateral constraint.

Solving the maximization problem leads to the following optimality conditions, which govern the behavior of each firm i:

$$\frac{W_t}{P_t}(R_t + \mu_t) = (1-\alpha)\mathcal{MC}_t A_t \left[K_t(i)u_t(i)\right]^{\alpha} N_t(i)^{-\alpha} \tag{7}$$

$$\frac{R_t^K}{P_t} = \alpha\mathcal{MC}_t A_t \left[K_t(i)u_t(i)\right]^{\alpha-1} N_t(i)^{1-\alpha} \tag{8}$$

$$Q_t\delta'\left(u_t(i)\right) = \alpha\mathcal{MC}_t A_t \left[K_t(i)u_t(i)\right]^{\alpha-1} N_t(i)^{1-\alpha}, \text{ where } \delta'\left(u_t(i)\right) \equiv \delta_1 + \delta_2\left(u_t(i)-1\right) \tag{9}$$

$$\begin{aligned}\psi_p\left(\frac{P_t(i)}{P_t}\right)^{-\epsilon}\left(\frac{P_t(i)}{\pi P_{t-1}(i)}-1\right)\frac{P_t}{\pi P_{t-1}(i)} &= (1-\epsilon)\left(\frac{P_t(i)}{P_t}\right)^{-\epsilon} + \epsilon\mathcal{MC}_t\left(\frac{P_t(i)}{P_t}\right)^{-\epsilon-1} + \dots \\ +\,\epsilon\left(\frac{P_t(i)}{P_t}\right)^{-\epsilon}\frac{P_t}{P_t(i)}\frac{\psi_p}{2}\left(\frac{P_t(i)}{\pi P_{t-1}(i)}-1\right)^2 &+ \psi_p\mathbb{E}_t\Delta_{t+1}\left(\frac{Y_{t+1}}{Y_t}\left(\frac{P_{t+1}(i)}{P_{t+1}}\right)^{-\epsilon}\left(\frac{P_{t+1}(i)}{\pi P_t(i)}-1\right)\frac{P_{t+1}(i)}{\pi P_t(i)}\frac{P_t}{P_t(i)}\right)\end{aligned} \tag{10}$$

$$Q_t = \mathbb{E}_t\left\{\Delta_{t+1}\left[u_{t+1}(i)\frac{R_{t+1}^K}{P_{t+1}} + Q_{t+1}\left(1-\delta\left(u_{t+1}(i)\right) + \mu_{t+1}(\zeta_{t+1}-\upsilon_{t+1})\right)\right]\right\} \tag{11}$$

$$R_t + \mu_t = Q_t\left[1-\frac{\psi_i}{2}\left(\frac{I_t(i)}{I_{t-1}(i)}-1\right)^2 - \psi_i\left(\frac{I_t(i)}{I_{t-1}(i)}-1\right)\frac{I_t(i)}{I_{t-1}(i)}\right] + \psi_i\mathbb{E}_t\left[\Delta_{t+1}Q_{t+1}\left(\frac{I_{t+1}(i)}{I_t(i)}-1\right)\left(\frac{I_{t+1}(i)}{I_t(i)}\right)^2\right] \tag{12}$$

$$\frac{W_t}{P_t}N_t(i) + I_t(i) = \left(\zeta_t - \upsilon_t\right)Q_t K_t(i), \text{ if } \mu_t > 0 \tag{13}$$

where $\frac{R_t^K}{P_t}$ represents the marginal revenue product per unit of capital services ($K_t u_t$). Note that in the borrowing limit we allow for macroprudential policy intervention, captured by υ_t, which we discuss in Subsection 2.4.

Final goods producers

Since the problem of final goods producers in our setting follows the standard approach in the NK literature, we choose to defer it to the appendix. The final good Y_t with price P_t is assembled by a perfectly competitive final goods sector from the individual intermediate goods $Y_t(i)$ through the following constant returns to scale technology (i.e. a CES aggregator):

$$\left[\int_0^1 Y_t(i)^{\frac{\epsilon-1}{\epsilon}}di\right]^{\frac{\epsilon}{\epsilon-1}} \geq Y_t$$

where ϵ represents the elasticity of substitution between any two input goods in the production of the final good.

Each intermediate input good $Y_t(i)$ is produced by one firm and sold for a price $P_t(i)$. Taking as given prices P_t and $P_t(i)$, the final goods producing-firms maximize profits by choosing quantities $Y_t(i)$

$$\Psi_t = P_t Y_t - \int_0^1 P_t(i)Y_t(i)di$$

subject to the constant returns to scale production function. This optimization problem yields the following first order condition for each variety i, implying that the demand for the individual good $Y_t(i)$ depends negatively on the relative price and positively on aggregate output:

$$Y_t(i) = \left(\frac{P_t(i)}{P_t}\right)^{-\epsilon}Y_t \tag{14}$$

Perfect competition results in zero profits, $\Psi_t = 0$, which implies the following expression for the aggregate price index:

$$P_t = \left[\int_0^1 P_t(i)^{1-\epsilon}di\right]^{\frac{1}{1-\epsilon}} \tag{15}$$

Appendix B.

The full set of equilibrium conditions characterizing the economic environment reads as follows:

$$\Delta_{t+1} = \beta \frac{\xi^C_{t+1}}{\xi^C_t} \left(\frac{C_{t+1} - \gamma \frac{N_{t+1}^{1+\eta}}{1+\eta}}{C_t - \gamma \frac{N_t^{1+\eta}}{1+\eta}} \right)^{-\nu} \tag{1}$$

$$\gamma N_t^{\eta} = w_t \tag{2}$$

$$1 = \mathbb{E}_t \left[\Delta_{t+1} R_t / \pi_{t+1} \right] \tag{3}$$

$$Q_t = \mathbb{E}_t \left\{ \Delta_{t+1} \left[r^K_{t+1} u_{t+1} + Q_{t+1} \left(1 - \delta(u_{t+1}) + \mu_{t+1}(\zeta_{t+1} - \upsilon_t) \right) \right] \right\} \tag{4}$$

$$R_t + \mu_t = Q_t \left[1 - \frac{\psi_i}{2} \left(\frac{I_t}{I_{t-1}} - 1 \right)^2 - \psi_i \left(\frac{I_t}{I_{t-1}} - 1 \right) \frac{I_t}{I_{t-1}} \right] + \psi_i \mathbb{E}_t \left\{ \Delta_{t+1} Q_{t+1} \left(\frac{I_{t+1}}{I_t} - 1 \right) \left(\frac{I_{t+1}}{I_t} \right)^2 \right\} \tag{5}$$

$$w_t N_t + I_t \leq \left(\zeta_t - \upsilon_t \right) Q_t K_t \tag{6}$$

$$r^K_t = Q_t \left(\delta_1 + \delta_2 (u_t - 1) \right) \tag{7}$$

$$Y_t = A_t \left(u_t K_t \right)^{\alpha} N_t^{1-\alpha} - FC \tag{8}$$

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

$$\delta(u_t) = \delta_0 + \delta_1 (u_t - 1) + \frac{\delta_2}{2} (u_t - 1)^2 \tag{10}$$

$$\epsilon - 1 = \epsilon \mathcal{MC}_t - \psi_p \left(\frac{\pi_t}{\bar{\pi}} - 1 \right) \frac{\pi_t}{\bar{\pi}} + \epsilon \frac{\psi_p}{2} \left(\frac{\pi_t}{\bar{\pi}} - 1 \right)^2 + \psi_p \beta \mathbb{E}_t \frac{\lambda_{t+1}}{\lambda_t} \left(\frac{\pi_{t+1}}{\bar{\pi}} - 1 \right) \frac{\pi_{t+1}}{\bar{\pi}} \frac{Y_{t+1}}{Y_t} \tag{11}$$

$$w_t \left(R_t + \mu_t \right) = (1-\alpha) \mathcal{MC}_t A_t \left(u_t K_t \right)^{\alpha} N_t^{-\alpha} \tag{12}$$

$$\mathcal{MC}_t = \frac{1}{A_t} \left(\frac{r^K_t}{\alpha} \right)^{\alpha} \left(\frac{w_t \left(R_t + \mu_t \right)}{1-\alpha} \right)^{1-\alpha} \tag{13}$$

$$L_t = w_t N_t + I_t \tag{14}$$

$$R_t = R_{t-1}^{\rho_r} \left[R \left(\frac{\pi_t}{\pi} \right)^{\kappa_\pi} \left(\frac{Y_t - Y_{t-1}}{Y_{t-1}} \right)^{\kappa_y} \right]^{1-\rho_r} e^{\varepsilon_t} \tag{15}$$

$$\upsilon_t = \upsilon_{t-1}^{\rho_\upsilon} \left[\left(\frac{L_t}{L} \right)^{\kappa_{cr}} \right]^{1-\rho_\upsilon} e^{\nu_t} \tag{16}$$

$$Y_t = C_t + I_t + \frac{\psi_p}{2} \left(\frac{\pi_t}{\bar{\pi}} - 1 \right)^2 Y_t \tag{17}$$

$$GDP_t = C_t + I_t \tag{18}$$

$$A_t = (1 - \rho_a) + \rho_a A_{t-1} + \sigma^A_t \epsilon^A_t \tag{19}$$

$$\xi^C_t = (1 - \rho_{\xi^C}) + \rho_{\xi^C} \xi^C_{t-1} + \sigma^{\xi^C}_t \epsilon^{\xi^C}_t \tag{20}$$

$$\zeta_t = (1 - \rho_\zeta)\zeta + \rho_\zeta \zeta_{t-1} + \sigma^\zeta_t \epsilon^\zeta_t, \tag{21}$$

$$\ln \sigma^A_t = (1 - \rho_{\sigma_a}) \ln \sigma_a + \rho_{\sigma_a} \ln \sigma^A_{t-1} + \epsilon^{\sigma^A}_t \tag{22}$$

$$\ln \sigma^{\xi^C}_t = (1 - \rho_{\sigma_{\xi^C}}) \ln \sigma_{\xi^C} + \rho_{\sigma_{\xi^C}} \ln \sigma^{\xi^C}_{t-1} + \epsilon^{\sigma^{\xi^C}}_t \tag{23}$$

$$\ln \sigma^\zeta_t = (1 - \rho_{\sigma_\zeta}) \ln \sigma_\zeta + \rho_{\sigma_\zeta} \ln \sigma^\zeta_{t-1} + \epsilon^{\sigma^\zeta}_t \tag{24}$$

Appendix C.

Figure 9 displays the high correlation of about 90% between financial conditions and their corresponding model-based volatility (posterior mean), based on our TVP-BVAR model with stochastic volatility, estimated using US data covering the period 1975Q1-2019Q4.

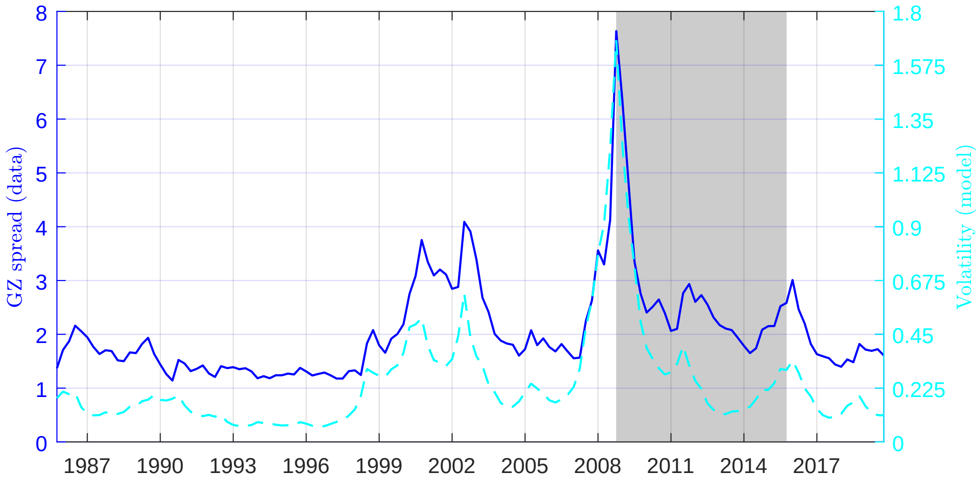

Figure 9: Credit spreads *versus* their corresponding model-based volatility

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