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DP13450

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**FINANCIAL ECONOMICS AND
MONETARY ECONOMICS AND
FLUCTUATIONS**

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Discussion Paper DP13450
Published 14 January 2019
Submitted 14 December 2018

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JEL Classification: E32, C11, C32, G12

Keywords: Uncertainty shocks, Business Cycles, Term Structure of Interest Rates, time-varying risk premia

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The Origins and Effects of Macroeconomic Uncertainty

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November 2018 §

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§We thank Nick Bloom, Jesus Fernandez-Villaverde, Francisco Gomes, Francois Gourio, Giorgio Primiceri, Hikaru Saijo, and all seminar participants at 2017 SITE Summer workshop on uncertainty, NBER, Duke University, ESOBE conference, IAAE conference, and London Business School for helpful comments and suggestions. An earlier version of this paper circulated with the title “Pricing Macroeconomic Uncertainty.”

1 Introduction

It is well-established that broad measures of macroeconomic and financial market uncertainty vary significantly over time.¹ There is also an emerging literature interested in studying how these changes in uncertainty affect business cycle fluctuations in micro-founded general equilibrium models. With a few exceptions, this literature tends to find that uncertainty is not among the main sources of macroeconomic fluctuations. However, these papers typically only use macroeconomic data to pin down the effects of uncertainty, consider only one source of uncertainty, and rely on calibration exercises in which the process for uncertainty is separately estimated.² In this paper, we use both macroeconomic and term structure data, distinguish between demand-side and supply-side uncertainty, and conduct a structural estimation of a micro-founded model in which the process for uncertainty and its effects are jointly estimated. Our results demonstrate that uncertainty matters. In particular, we uncover sizable effects of uncertainty shocks on business cycle and term premia dynamics. The specific effects of demand-side and supply-side uncertainty are examined through multiple endogenous risk propagation channels.

Asset prices contain valuable information about uncertainty, given that changes in macroeconomic uncertainty generate fluctuations in risk premia. We find that changes in nominal term premia contain key identifying information disciplining the effects of uncertainty and its propagation through various risk channels. At the same time, there is empirical and anecdotal evidence suggesting that changes in measures of uncertainty are related to heterogeneous sources (e.g., Bloom (2014)) and are also imperfectly correlated. Figure 1 plots various uncertainty measures whose pairwise correlations range between -0.30 to 0.85. We find it important to distinguish between different sources of uncertainty, and we explicitly model fluctuating demand and supply uncertainty. We identify demand uncertainty as originating from shocks to the time discount factor while supply uncertainty as emanating from shocks to TFP growth. In particular, we show that these two types of uncertainty act through distinct channels. Finally, jointly estimating the process for uncertainty and its effects on the economy has the important implication that uncertainty is not only identified via changes in stochastic volatility, but also through its first-order effects on the economy.

Our quantitative analysis is based on a dynamic stochastic general equilibrium (DSGE) model along the lines of Christiano, Eichenbaum, and Evans (2005), but with the following departures. First, we assume that the representative household has Epstein and Zin (1989) recursive preferences to capture sensitivity towards low-frequency consumption growth and discount rate risks. Second, we allow for stochastic volatility changes

¹See, for example, Baker, Bloom, and Davis (2016) and Jurado, Ludvigson, and Ng (2015)

²Some examples include Bloom (2009), Bloom, Floetotto, Jaimovich, Saporta-Eksten, and Terry (2012), and Basu and Bundick (2017).

in TFP and preference shocks, both modeled as distinct Markov chains, estimated jointly within our DSGE model. Changes in stochastic volatility *and* the endogenous response of the economy to these changes both contribute to fluctuations in uncertainty. Third, we use an iterative solution method to endogenously capture sizable and time-varying risk premia. By modelling stochastic volatility as regime changes, we obtain a conditionally log-linear solution that facilitates an estimation using a modification of the standard Kalman filter. Lastly, we use data on nominal bond yields across different maturities in our estimation.

Our solution method captures the first- and second-order effects of uncertainty on agents' decision policies, as well as effects on conditional risk premia. We show that this feature of our solution method sharpens the identification of uncertainty dynamics. In addition, our solution method provides an approximate analytical risk decomposition that uncovers distinct risk propagation channels for which uncertainty affects macroeconomic fluctuations. We use the risk decomposition to illustrate how uncertainty shocks produce different effects depending on the origin (e.g., demand or supply). Our analysis therefore provides an economic interpretation for why there is not a consensus on the macroeconomic effects of uncertainty shocks. More broadly, our risk decomposition can be utilized in a wide range of dynamic stochastic models, and is therefore of independent interest.

Figure 2 illustrates the strong relation between real activity, measured as detrended GDP, the slope of the nominal yield curve, and macroeconomic volatility.³ As the economy enters a recession, the slope of the yield curve and macroeconomic volatility both tend to rise. In our model, movements from low to high volatility regimes endogenously trigger a decline in real activity and a steepening of the yield curve, consistent with the data. We find that the effects of uncertainty are quantitatively significant. The two uncertainty shocks together explain over 14% of the variation in investment growth, around 10% for consumption growth, and 28% for the slope of the nominal yield curve. These shocks also produce significant countercyclical variation in the nominal term premium. The effects of uncertainty are even more sizable when focusing on fluctuations at business cycle frequencies. An economy that is exclusively affected by uncertainty shocks would generate business cycle fluctuations for consumption and investment as large as 24.5% and 31%, respectively, of an analogue economy with both uncertainty and traditional level shocks.

Both demand-side and supply-side uncertainty generate positive comovement between consumption and investment, which is often a challenge for standard macroeconomic models. Thus, uncertainty shocks emerge as an important source of business cycle fluctuations. However, the origin of uncertainty plays an important role, as the two types of uncertainty impact the economy in very distinct ways. Compared to demand-

³Detrended GDP is obtained by applying a bandpass filter. Similar results hold if GDP is detrended using an HP filter. The slope of the term structure is computed as the difference between the five-year yields and the one-year yield. Macroeconomic volatility is measured as a five-year moving average of the standard deviation of GDP growth.

side uncertainty, supply-side uncertainty has larger effects on inflation and is relatively more important for explaining fluctuations in investment. Furthermore, while in the first half of our sample, demand- and supply-side uncertainty tend to move together, they decouple in the second half of the sample.

Nominal term premia in our model is driven by time-varying demand and supply uncertainty. As such, using the term structure of interest rates as observables in our estimation is important for disciplining the effects of uncertainty. While both supply and demand uncertainty are important for the unconditional nominal term premia, we find that the conditional dynamics of nominal term premia are mostly attributed to variation in demand-side uncertainty through the inflation risk premia component. Therefore, the observed term structure dynamics help to sharpen the identification of the two different sources of uncertainty. Without using term structure data in our estimation, the timing of the uncertainty shocks is quite different, the volatility regimes are less persistent, and the effects of the uncertainty shocks on the macroeconomy are smaller.

To understand how uncertainty shocks affect the real economy and account for these differences, we use an approximate model solution method that allows us to identify and quantify five distinct *risk propagation channels* for uncertainty shocks that are labeled as precautionary savings, investment risk premium, inflation risk premium, nominal pricing bias, and investment adjustment channel. The *precautionary savings* term reflects the prudence of the representative household towards uncertainty about future income. This prudence term arises through the households' consumption-savings Euler equation. The *investment risk premium* term emerges through the investment Euler equation, which depends on the covariance between the pricing kernel and the return on investment. The *inflation risk premium* term shows up through the Fisherian equation, and the nominal term premium imposes strong restrictions on this channel. The *nominal pricing bias* arises in the Phillips curve due to the presence of nominal rigidities that makes firms more prudent when setting nominal goods prices. Finally, the *investment adjustment channel* arises because of rigidities in the household's ability to immediately adjust investment to the desired level.

Our decomposition of the risk propagation channels show that different forces contribute to generating empirically realistic macroeconomic and asset pricing dynamics. The precautionary savings, investment risk premium, and the nominal pricing bias terms are the most quantitatively important risk propagation channels for business cycles. The parameters governing price stickiness, capital adjustment costs, and elasticity of labor supply are critical for determining the effects from these risk propagation channels. Price stickiness and labor supply elasticity are important for determining the sign and magnitude of the precautionary savings channel, while capital adjustment costs are important for determining the sign and magnitude of the investment risk premium channel. The degree of price stickiness and labor supply elasticity determines the

sensitivity of labor demand shifts to uncertainty changes. The degree of capital adjustment costs affects the covariance of the return on investment and the stochastic discount factor, which determines the effect of the investment risk premium channel. The degree of price stickiness is important for determining the effects of the nominal pricing bias.

The *investment risk premium* channel plays a key role in amplifying the response of investment to changes in supply-driven uncertainty. The investment risk premium channel has opposite effects on investment for supply- and demand-side uncertainty. The underlying reason is that physical capital is a poor hedge against negative TFP shocks, but a good hedge for adverse preference shocks. In particular, demand and supply-side shocks produce different signs in the covariance between the pricing kernel and the return on investment. In response to a negative TFP shock, marginal utility increases but the value of physical capital decreases. Therefore, investment in physical capital commands a positive risk premium with respect to TFP shocks. In contrast, preference shocks produce the opposite pattern. A negative preference shock increases marginal utility and the value of capital. Therefore, investment commands a negative risk premium with respect to preference shocks. Consequently, when supply-side uncertainty increases, households have an incentive to lower investment so as to reduce exposure to TFP shocks. Instead, when demand-side uncertainty increases, households have an incentive to increase investment to hedge against preference shocks. Overall, this channel plays a key role in explaining why the cumulative decline in investment to an increase supply-side (demand-side) uncertainty is amplified (dampened).

We then use our decomposition to understand the small response of inflation to demand-driven uncertainty shocks, but a large response to supply-driven uncertainty. These inflation responses can be accounted for by differences in how the precautionary savings and nominal pricing bias channels operate under the two uncertainty shocks. Both demand- and supply-side uncertainty shocks trigger a strong precautionary savings channel effect, which generates downward pressure on inflation. However, for demand-driven uncertainty, another quantitatively important propagation channel is the nominal pricing bias, which is natural given that level preference shocks are one of the main drivers of inflation dynamics. For demand-side uncertainty shocks, the precautionary savings and nominal pricing bias channels have opposite effects on inflation that cancel each other out, and consequently, the cumulative effect on inflation is close to zero. In contrast, for supply-side uncertainty, the nominal pricing bias is not quantitatively important, since TFP growth shocks are not important for explaining inflation dynamics. Therefore, the cumulative effect of an increase in supply-side uncertainty is driven by the precautionary savings propagation channel, leading to a large decline in inflation.

Our paper relates to Basu and Bundick (2017) in that we also consider the role of the precautionary

savings channel, in conjunction with sticky prices, for the propagation of demand-side uncertainty shocks. In our estimation, we find that this channel is quantitatively important. Thus, we complement the findings of Basu and Bundick (2017), but differ along the following dimensions. First, we develop a novel analytical decomposition that unveils four additional risk propagation channels. In our estimation, we find that two of these four channels, the investment risk premium and nominal pricing bias, are as quantitatively important as the precautionary savings channel. Second, we conduct a structural estimation of our model using macroeconomic and bond yield data instead of calibration. In our structural estimation the process for uncertainty is not exogenously given, but jointly estimated with the rest of the model. We find that uncertainty plays a key role for both macro and term structure dynamics. Finally, we allow for both demand- and supply-side uncertainty changes, while Basu and Bundick (2017) only consider demand-side uncertainty shocks. While both types of uncertainty shocks are important for explaining business cycles, we find that the macroeconomic responses to these shocks to be quite different. For example, supply-side uncertainty changes generate more severe recessions, with significantly larger effects on inflation and investment. Our analytical decomposition allows us to carefully disentangle the economic margins that account for these different responses.

Our paper connects to the broader literature studying the impact of uncertainty shocks in macroeconomic models (e.g., Bloom (2009), Bloom, Floetotto, Jaimovich, Saporta-Eksten, and Terry (2012), Bachmann and Bayer (2014), Fernández-Villaverde, Guerrón-Quintana, Rubio-Ramírez, and Uribe (2011), Fernández-Villaverde, Guerrón-Quintana, Kuester, and Rubio-Ramírez (2015), Justiniano and Primiceri (2008), Bianchi, Ilut, and Schneider (2014), Schaal (2017), Fajgelbaum, Schaal, and Taschereau-Dumouchel (2017), and Saijo (2017), etc.). We differ from these papers in that we (i) allow for multiple sources of uncertainty, (ii) conduct a structural estimation, (iii) use asset pricing data, in the form of nominal bond yields in the estimation and a prior on the investment risk premium, to discipline the effects of uncertainty, and (iv) do not deviate from the assumption of rational expectations.

The pricing of consumption and volatility risks builds on the endowment economy models of Bansal and Yaron (2004), Piazzesi and Schneider (2007), and Bansal and Shaliastovich (2013). However, we differ by considering a general equilibrium framework with production, where the dynamics of stochastic consumption volatility risks are linked to the time-varying second moments of structural macroeconomic shocks and to the endogenous response of the macroeconomy to changes in the volatility of these shocks. Furthermore, our production-based setting allows us to consider the endogenous feedback between risk premia and business cycle fluctuations via uncertainty shocks. The role of preference shocks for generating a positive real term premia relates to the endowment economy model of Albuquerque, Eichenbaum, Luo, and Rebelo (2016). We

build on this work, and show that time discount factor shocks also provide a novel endogenous source of inflation risk premia in a New Keynesian framework.

More broadly, our paper relates to an emerging literature studying asset prices in New Keynesian models (e.g., Bekaert, Cho, and Moreno (2010), Bikbov and Chernov (2010), Hsu, Li, and Palomino (2014), Rudebusch and Swanson (2012), Dew-Becker (2014), Bretscher, Hsu, and Tamoni (2017), Weber (2015), Kung (2015), and Campbell, Pflueger, and Viceira (2014)). With respect to these papers, we conduct a structural estimation of a micro-founded model assuming continuity between how assets are priced by the representative agent in the model and by the econometrician.

This paper is organized as follows. Section 2 presents a simplified model to introduce the decomposition of the effects of uncertainty into five distinct risk channels. In this section, we also explain our solution approach. Section 3 describes the full model. Section 4 contains the main results. Section 5 concludes.

2 Risk Propagation Channels

To illustrate the key model mechanisms and our solution method, we consider a simplified version of the benchmark model used for structural estimation. We find that in a New-Keynesian model, uncertainty shocks can be contractionary – even when the precautionary savings channel places upward pressure on investment – due to the presence of four other risk propagation channels, unveiled in our analytical decomposition characterized below. Thus, the overall effect of uncertainty is determined by how uncertainty propagates through the different channels. Analyzing uncertainty changes through the lens of these risk propagation channels helps us to understand (i) the heterogeneous effects of different uncertainty shocks on the macroeconomy, (ii) the role of risk premia for imposing restrictions on the propagation channels, and (iii) how various model frictions pin down the effect of the propagation channels. This approach can be applied to other models and it is therefore of independent interest.

2.1 Simplified Model

Household The representative household has a recursive utility over streams of consumption, C_t , and hours worked, L_t :

$$V_t = \left((1 - \beta_t) u(C_t, L_t)^{1-1/\psi} + \beta_t \left(E_t \left[V_{t+1}^{1-\gamma} \right] \right)^{\frac{1-1/\psi}{1-\gamma}} \right)^{\frac{1}{1-1/\psi}} \quad (1)$$

$$u(C_t, L_t) = C_t e^{-\tau_0 \frac{L_t^{1+\tau}}{1+\tau}}, \quad (2)$$

where γ is the coefficient of risk aversion, ψ is the elasticity of intertemporal substitution. The household also supplies labor services, L_t , to a competitive labor market at a real wage W_t . In the limit, when $\psi \rightarrow 1$, the preferences specified above become

$$V_t = u(C_t, L_t)^{(1-\beta_t)} \left(E_t \left[V_{t+1}^{1-\gamma} \right] \right)^{\frac{\beta_t}{1-\gamma}} \quad (3)$$

This is the case that we consider below.

We define a preference shock, \tilde{b}_t , such that, $\beta_t = \frac{1}{1+\tilde{b}_t e^{\beta_t}}$. The preference shock, \tilde{b}_t , follows an AR(1) process, with volatility of innovations depending on the aggregate volatility regime, ξ_t :

$$\tilde{b}_{t+1} = \rho_\beta \tilde{b}_t + \sigma_{\beta, \xi_{t+1}} \varepsilon_{\beta, t+1}. \quad (4)$$

The volatility regime, ξ_t , follows a Markov-switching process with a transition matrix H .

The representative household owns capital, \bar{K}_{t-1} , pre-determined at time $t-1$, which it supplies to competitive capital markets at a real rental rate r_t^k . The household accumulates capital according to the following law of motion:

$$\bar{K}_t = \bar{K}_{t-1} (1 - \delta_0) + [1 - S(I_t/I_{t-1})] I_t \quad (5)$$

$$S(I_t/I_{t-1}) = (\varphi_I/2) (I_t/I_{t-1} - e^\mu)^2, \quad (6)$$

where I_t is time t investment and the function $S(I_t/I_{t-1})$ reflects capital adjustment costs.

The time t budget constraint of the household is

$$P_t C_t + P_t I_t + B_{t+1}/R_t = P_t D_t + P_t W_t L_t + B_t + P_t \bar{K}_{t-1} r_t^k \quad (7)$$

where P_t is the nominal price of the consumption good, B_{t+1} is the amount of nominal one-period bonds held by household at time t with maturity at time $t+1$, R_t is the gross nominal interest rate set at time t by the monetary authority, D_t is the real dividend income received from the intermediate firms

The optimization problem of the household results in the following intertemporal first order condition:

$$1 = E_t [M_{t+1} P_t / P_{t+1}] R_t, \quad (8)$$

where

$$M_{t+1} = \frac{1 - \beta_{t+1}}{1 - \beta_t} \beta_t \left(\frac{V_{t+1}^{1-\gamma}}{E_t [V_{t+1}^{1-\gamma}]} \right) \left(\frac{C_{t+1}}{C_t} \right)^{-1} \quad (9)$$

is the Stochastic Discount Factor (SDF). The intratemporal condition is:

$$W_t = \tau_0 L_t^\tau C_t. \quad (10)$$

The first order condition with respect to the investment decision is:

$$q_t \left[1 - \frac{\varphi_I}{2} \left(\frac{I_t}{I_{t-1}} - e^\mu \right)^2 - \varphi_I \left(\frac{I_t}{I_{t-1}} - e^\mu \right) \frac{I_t}{I_{t-1}} \right] + E_t \left[M_{t+1} q_{t+1} \varphi_I \left(\frac{I_{t+1}}{I_t} - e^\mu \right) \frac{I_{t+1}^2}{I_t^2} \right] = 1 \quad (11)$$

$$1 = E_t \left[M_{t+1} R_{t+1}^i \right], \quad (12)$$

where the return on investment, R_{t+1}^i , is defined as:

$$R_{t+1}^i \equiv \frac{r_{t+1}^k + q_{t+1} (1 - \delta_0)}{q_t}. \quad (13)$$

Final Goods A representative firm produces the final (consumption) good in a perfectly competitive market. The firm uses a continuum of differentiated intermediate goods, $X_{i,t}$, as input in the following constant elasticity of substitution (CES) production technology:

$$Y_t = \left(\int_0^1 X_{i,t}^{\frac{\nu-1}{\nu}} di \right)^{\frac{\nu}{\nu-1}}, \quad (14)$$

where ν is elasticity of substitution between intermediate goods. The profit maximization problem of the firm yields the following isoelastic demand schedule with price elasticity ν :

$$X_{i,t} = Y_t (P_{i,t}/P_t)^{-\nu}, \quad (15)$$

where P_t is the nominal price of the final good and $P_{i,t}$ is the nominal price of the intermediate good i .

Intermediate Goods The intermediate goods sector is characterized by a continuum of monopolistic competitive firms. Each intermediate goods firm hires labor, $L_{i,t}$, and rents capital, $K_{i,t}$, on competitive markets and produces output, $X_{i,t}$, using a constant returns to scale technology:

$$X_{i,t} = K_{i,t}^\alpha (e^{n_i} L_{i,t})^{1-\alpha}, \quad (16)$$

where n_t is a stochastic productivity trend with the following law of motion:

$$\Delta n_t = \mu + x_t, \quad (17)$$

$$x_t = \rho_x x_{t-1} + \sigma_{x,\xi_t} \varepsilon_{x,t}, \quad \varepsilon_{x,t} \sim N(0,1), \quad (18)$$

where μ is the unconditional mean of productivity growth and x_t is a TFP growth shock. Note that the standard deviation σ_{x,ξ_t} depends on the volatility regime ξ_t .

The intermediate firms face a cost of adjusting the nominal price a la Rotemberg (1982), measured in terms of the final goods as

$$G(P_{i,t}, P_{i,t-1}, Y_t) = \frac{\phi_R}{2} \left(\frac{P_{i,t}}{\Pi_{ss} P_{i,t-1}} - 1 \right)^2 Y_t, \quad (19)$$

where $\Pi_{ss} \geq 1$ is the steady-state inflation rate and ϕ_R is the magnitude of the price adjustment costs. The source of funds constraint is :

$$P_t D_{i,t} = P_{i,t} X_{i,t} - P_t W_t L_{i,t} - P_t r_t^k K_{i,t} - P_t G(P_{i,t}, P_{i,t-1}, Y_t), \quad (20)$$

where $D_{i,t}$ is the real dividend paid by the firm. The objective of the firm is to maximize shareholder's value, $V_t^{(i)} = V^{(i)}(\cdot)$, taking the pricing kernel, M_t , the competitive real wage, W_t , the real rental rate of capital, r_t^k , and the vector of aggregate state variables $\Psi_t = (P_t, Z_t, Y_t)$ as given:

$$V^{(i)}(P_{i,t-1}; \Psi_t) = \max_{P_{i,t}, L_{i,t}, K_{i,t}} \left\{ D_{i,t} + E_t \left[M_{t+1} V^{(i)}(P_{i,t}; \Psi_{t+1}) \right] \right\}, \quad (21)$$

subject to

$$D_{i,t} = \frac{P_{i,t}}{P_t} X_{i,t} - W_t L_{i,t} - r_t^k K_{i,t} - G(P_{i,t}, P_{i,t-1}, Y_t), \quad (22)$$

$$X_{i,t} = Y_t \left(\frac{P_{i,t}}{P_t} \right)^{-\nu}, \quad (23)$$

$$X_{i,t} = K_{i,t}^\alpha (Z_t L_{i,t})^{1-\alpha}. \quad (24)$$

The optimization problem results in the first-order condition corresponding to the price setting decision:

$$(1 - \nu) \left(\frac{P_{i,t}}{P_t} \right)^{-\nu} \frac{Y_t}{P_t} + \nu W_t \frac{L_{i,t}}{1-\alpha} \left(\frac{P_{i,t}}{P_t} \right)^{-1} \frac{1}{P_t} - \phi_R \left(\frac{P_{i,t}}{\Pi_{ss} P_{i,t-1}} - 1 \right) \frac{Y_t}{\Pi_{ss} P_{i,t-1}} + E_t \left[M_{t+1} \phi_R \left(\frac{P_{i,t+1}}{\Pi_{ss} P_{i,t}} - 1 \right) \frac{Y_{t+1} P_{i,t+1}}{\Pi_{ss} P_{i,t}^2} \right] = 0, \quad (25)$$

and the first-order condition for the amount of capital:

$$r_t^k = \frac{\alpha}{1-\alpha} W_t \frac{L_{i,t}}{K_{i,t}}. \quad (26)$$

Central Bank The central bank follows a Taylor rule that depends on output and inflation deviations from steady-state:

$$\ln\left(\frac{R_t}{R_{ss}}\right) = \rho_r \ln\left(\frac{R_{t-1}}{R_{ss}}\right) + (1 - \rho_r)\left(\rho_\pi \ln\left(\frac{\Pi_t}{\Pi_{ss}}\right) + \rho_y \ln\left(\frac{\hat{Y}_t}{\hat{Y}_{ss}}\right)\right) + \sigma_{R,\xi_t} \varepsilon_{R,t}, \quad (27)$$

where R_t is the gross nominal short rate, $\Pi_t \equiv P_t/P_{t-1}$ is the gross inflation rate, $\hat{Y}_t \equiv Y_t/Z_t$ is detrended output, and $\varepsilon_{R,t} \sim N(0, 1)$ is a monetary policy shock. Variables with a *ss* subscript denote steady-state values.

Symmetric Equilibrium In the symmetric equilibrium, all intermediate firms make identical decisions: $P_{i,t} = P_t$, $X_{i,t} = X_t = Y_t$, $K_{i,t} = K_t$, $L_{i,t} = L_t$, $D_{i,t} = D_t$. Also, nominal bonds are in zero net supply $B_t = 0$. Clearing of capital market implies $K_{i,t} = \bar{K}_{t-1}$. The aggregate resource constraint is

$$Y_t = C_t + I_t + .5\phi_R (\Pi_t/\Pi_{ss} - 1)^2 Y_t. \quad (28)$$

2.2 Log-linearization with risk-adjustment

Our goal is to study the effects of uncertainty on both asset prices and the macroeconomy. If standard log-linearization techniques were applied, all of the effects of uncertainty would be lost. Instead, we implement a risk-adjusted log-linearization of the model (e.g., Jermann (1998), Lettau (2003), Backus, Routledge, and Zin (2010), Uhlig (2010), Dew-Becker (2012), Malkhozov (2014), and Bianchi, Ilut, and Schneider (2014)). The idea behind this approximation method is that all expectational equations are approximated assuming that the variables are conditionally log-normal. The approximate solution indeed satisfies this condition, because it is linear in the state variables. Then we solve a resulting system of linear expectational difference equations augmented with an iterative procedure designed to capture a risk-adjustment component. This procedure allows us to solve rational expectation models in which uncertainty is controlled by a Markov-switching process by using solution methods that have been developed for log-linear approximations. It is important to emphasize that we allow risk to affect not only asset prices, but also the policy functions controlling the macroeconomic variables. This is crucial to study the effects of uncertainty on the macroeconomy.

We apply the risk adjusted log-linearization to the first-order conditions and market clearing conditions presented above. Define the risk-free rate, $R_{f,t}$ as the return on a theoretical risk-free asset, which pays one

unit of consumption good in every state of the world next period. The risk-free rate satisfies the following asset pricing equation:

$$1 = E_t \left[M_{t+1} R_{f,t} \right], \quad (29)$$

or

$$\frac{1}{R_{f,t}} = E_t \left[M_{t+1} \right] \quad (30)$$

As described above, the log-linearization approach that we are using approximates all expectational equations assuming that the variables are conditionally log-normal. So, log-linearizing (30), we get

$$-\tilde{r}_{f,t} = E_t \left[\tilde{m}_{t+1} \right] + \frac{1}{2} \text{Var}_t \left[\tilde{m}_{t+1} \right] \quad (31)$$

Here, and below, variables with a tilde denote log-deviations from the deterministic steady state of the corresponding variables.⁴ We can then log-linearize the expression for the stochastic discount factor (9) using our risk adjustment approach:⁵

$$\tilde{m}_{t+1} = \left[\begin{array}{c} \bar{\beta} \tilde{b}_{t+1} - \tilde{b}_t + (1 - \gamma)(\tilde{v}_{t+1} - E_t[\tilde{v}_{t+1} + \tilde{x}_{t+1}]) - (\tilde{c}_{t+1} - \tilde{c}_t) \\ -\gamma \tilde{x}_{t+1} - \frac{1}{2}(1 - \gamma)^2 \text{Var}_t[\tilde{v}_{t+1} + \tilde{x}_{t+1}] \end{array} \right], \quad (32)$$

and then substitute it out in (31) to get:

$$\tilde{c}_t = E_t \left[\tilde{c}_{t+1} \right] - \tilde{r}_{f,t} + (1 - \bar{\beta} \rho_\beta) \tilde{b}_t + \rho_x \tilde{x}_t - \underbrace{\frac{1}{2} \text{Var}_t \left[\tilde{m}_{t+1} \right] + \frac{1}{2} (1 - \gamma)^2 \text{Var}_t \left[\tilde{v}_{t+1} + \tilde{x}_{t+1} \right]}_{\text{Precautionary savings motive}}, \quad (33)$$

which is an Euler equation with respect to the risk-free rate. The risk adjustment component, $-\frac{1}{2} \text{Var}_t \left[\tilde{m}_{t+1} \right] + \frac{1}{2} (1 - \gamma)^2 \text{Var}_t \left[\tilde{v}_{t+1} + \tilde{x}_{t+1} \right]$, captures the precautionary savings motive. This term reflects the prudence of the household towards uncertainty about future income. Formally, the precautionary savings term relates to the convexity of marginal utility (e.g., Kimball (1990)).

Log-linearizing and risk-adjusting the intertemporal first-order condition of the household (Eq. (8)) and combining it with the expression for the log risk-free rate (Eq. (31)), we get:

$$\tilde{r}_t = \tilde{r}_{f,t} + E_t \left[\tilde{\pi}_{t+1} \right] + \underbrace{\text{Cov}_t \left[\tilde{m}_{t+1}; \tilde{\pi}_{t+1} \right] - \frac{1}{2} \text{Var}_t \left[\tilde{\pi}_{t+1} \right]}_{\text{Inflation Risk Premium}}, \quad (34)$$

where \tilde{r}_t is the nominal short-term interest rate. The risk adjustment term, $\text{Cov}_t \left[\tilde{m}_{t+1}; \tilde{\pi}_{t+1} \right] - \frac{1}{2} \text{Var}_t \left[\tilde{\pi}_{t+1} \right]$, corresponds to an inflation risk premium, and it reflects the fact that the payoff of a nominal short term

⁴For capital, $\tilde{k}_t = \log K_t - \log K_{ss}$

⁵ $E_t \left[e^{(\tilde{v}_{t+1} + \tilde{x}_{t+1})(1-\gamma)} \right]$ is approximated as $\exp \left((1 - \gamma) E_t [\tilde{v}_{t+1} + \tilde{x}_{t+1}] + \frac{(1-\gamma)^2}{2} \text{Var}_t [\tilde{v}_{t+1} + \tilde{x}_{t+1}] \right)$

bond in real terms is uncertain. Indeed, the rate of return on this bond in consumption units depends on the realization of inflation next period. Therefore, the covariance of inflation with the pricing kernel determines the inflation risk premium on the short-term nominal bond. If inflation tends to be high when the marginal utility of wealth is high, then nominal short-term bonds are risky and investors demand a risk premium for holding them.

We log-linearize and risk-adjust the equation characterizing the investment decision of the household, Eq. (12), and use Eq. (31) to obtain:

$$E_t[\tilde{r}_{i,t+1} - \tilde{r}_{f,t}] = \underbrace{-Cov_t[\tilde{m}_{t+1}; \tilde{r}_{i,t+1}] - \frac{1}{2}Var_t[\tilde{r}_{i,t+1}]}_{\text{Investment Risk Premium}}. \quad (35)$$

The risk adjustment component in brackets embodies an investment risk premium. If the return on investment is low when the marginal utility of wealth is high, then the return on investment in physical capital is risky and will command a risk premium. Therefore, in equilibrium, households will choose a level of investment such that the expected investment return will be higher than the risk-free rate by an amount sufficient to compensate them for the risk that they are exposed to.

The expression for \tilde{q}_t is obtained by log-linearizing Eq. (11):

$$\tilde{q}_t - \varphi_I e^{2\mu} \Delta i_t + \varphi_I e^{2\mu} \bar{\beta} \left(E_t[\Delta i_{t+1}] + \underbrace{Cov_t[\tilde{m}_{t+1} + \tilde{q}_{t+1}; \Delta i_{t+1}] + \frac{5}{2}Var_t[\Delta i_{t+1}]}_{\text{Investment adjustment}} \right) = 0, \quad (36)$$

where $\Delta i_{t+1} = \tilde{i}_{t+1} - \tilde{i}_t + x_{t+1}$ is log investment growth. The risk adjustment term in this equation captures the fact that when making an investment decision at time t , households consider its impact on the capital adjustment costs at time $t+1$, which depends on investment growth Δi_{t+1} . Therefore, the household takes into account uncertainty about future investment growth and how it co-varies with the shadow value of capital and the pricing kernel.

Next, consider the price-setting decision of the intermediate firms. We apply the same risk-adjustment technique to log-linearize the equation characterizing the price-setting decision of the intermediate firms (Eq. (25)) to obtain the risk-adjusted Phillips Curve:

$$\tilde{\pi}_t = \bar{\beta} E_t[\tilde{\pi}_{t+1}] + \kappa_R (\tilde{w}_t + \tilde{l}_t - \tilde{y}_t) + \underbrace{\frac{1}{2} \bar{\beta}^* \left(2Cov_t[\tilde{m}_{t+1} + \tilde{y}_{t+1} + \tilde{x}_{t+1}; \tilde{\pi}_{t+1}] + 3Var_t[\tilde{\pi}_{t+1}] \right)}_{\text{Nominal Pricing Bias}}, \quad (37)$$

where the risk-adjustment component represents the nominal pricing bias and $\kappa_R = \frac{\nu-1}{\phi_R}$. The variance term captures a precautionary price-setting motive due to the presence of the price-adjustment costs. The covariance term between inflation and the pricing kernel relates to the inflation risk premium. In addition,

the nominal pricing bias also depends on covariance terms between output and TFP with inflation.

The rest of the equations, which are needed to close the system, do not have terms which depend on expectations of the endogenous variables. As a result, a simple log-linearization suffices and no additional risk-adjustment terms are needed:

Capital accumulation equation (Eq. (5)):

$$\tilde{k}_{t+1} = (1 - \delta_0)e^{-\mu}(\tilde{k}_t - \tilde{x}_t) + (1 - (1 - \delta_0)e^{-\mu})\tilde{i}_t. \quad (38)$$

Production function (Eq. (16)) (in the symmetric equilibrium $Y_t = X_{i,t}$):

$$\tilde{y}_t = \alpha\tilde{k}_t + (1 - \alpha)\tilde{l}_t. \quad (39)$$

Resource constraint (Eq. (28)):

$$\tilde{y}_t = (C_{ss}/Y_{ss})\tilde{c}_t + (I_{ss}/Y_{ss})\tilde{i}_t. \quad (40)$$

Taylor rule (Eq. (27)):

$$\tilde{r}_t = \rho_r\tilde{r}_{t-1} + (1 - \rho_r)\left(\rho_\pi\tilde{\pi}_t + \rho_y\tilde{y}_t\right) + \sigma_{R,\xi_t}\varepsilon_{R,t}. \quad (41)$$

Rental rate of capital (Eq. (26)):

$$\tilde{r}_t^k = \tilde{w}_t + \tilde{l}_t - \tilde{k}_t. \quad (42)$$

Household intratemporal first-order condition (Eq. (10)):

$$\tilde{w}_t = \tilde{c}_t + \tau\tilde{l}_t. \quad (43)$$

Finally, an extra equation describing the dynamics of the log of the value function, v_t , is obtained by a log-linearization and risk-adjustment of Eq. (1):

$$\tilde{v}_t = (1 - \bar{\beta})(\tilde{c}_t - \tau_0\tilde{l}_t) + \bar{\beta}\left(-\mu\tilde{b}_t + E_t\left[\tilde{v}_{t+1} + \tilde{x}_{t+1}\right] + .5(1 - \gamma)Var_t\left[\tilde{v}_{t+1} + \tilde{x}_{t+1}\right]\right) \quad (44)$$

Note that this equation is only required to compute the risk-adjustment terms.

To summarize, based on the risk-adjusted log-linearization of the model above, we identify five risk propagation channels through which uncertainty affects the economy: a *precautionary savings motive channel* represented by the risk adjustment terms in the Eq. (33); an *inflation risk premium channel* represented by the risk-adjustment terms in the equation for short-term nominal interest rate (Eq. (34)); an *investment risk premium channel* captured by the risk adjustment terms in the intertemporal investment decision (Eq. (35)); a *nominal pricing bias channel* represented by the risk-adjustment terms in the Phillips Curve (Eq. (37)); a *investment adjustment channel* captured by the risk adjustment terms in Eq. (36).

2.3 Solution Method

The key step for implementing our solution method is realizing that in a model in which stochastic volatility is modeled as a Markov-switching process, uncertainty at time t only depends on the regime in place at time t , denoted by ξ_t . Thus, the system of equations presented above can be written by using matrix notation as in a standard log-linearization:

$$\Gamma_0 S_t = \Gamma_1 S_{t-1} + \Gamma_\sigma Q_{\xi_t} \varepsilon_t + \Gamma_\eta \eta_t + \Gamma_{c,\xi_t}, \quad (45)$$

where the DSGE state vector S_t contains all variables of the model known at time t , Q_{ξ_t} is a regime-dependent diagonal matrix with all standard deviation of the shocks on the main diagonal, ε_t is a vector with all structural shocks, η_t is a vector containing the expectation errors, and the Markov-switching constant Γ_{ξ_t} captures the effects of uncertainty:

$$\Gamma_{c,\xi_t} = \begin{pmatrix} a_1 Cov_t [c'_1 S_{t+1}; d'_1 S_{t+1}] \\ a_2 Cov_t [c'_2 S_{t+1}; d'_2 S_{t+1}] \\ \vdots \end{pmatrix}, \quad (46)$$

where we have used the fact that uncertainty at time t only depends on the regime in place at time t , denoted by ξ_t . Elements of Γ_{c,ξ_t} represent risk adjustment terms. c_i , d_i are vectors of coefficients and a_i are constants, implied by our risk adjustment technique.

However, we cannot compute the volatility terms in Γ_{c,ξ_t} without knowing the solution for S_t . This is because to compute the one-step-ahead variance and covariance terms, we need to know how the economy reacts to the exogenous shocks, ε_t , and the regime changes themselves. Therefore, we employ the following iterative procedure. First, given some $\Gamma_{c,\xi_t} = \tilde{\Gamma}_{c,\xi_t}$, the solution to Eq. (45) can be characterized as a Markov Switching Vector Autoregression (Hamilton (1989), Sims and Zha (2006)):

$$S_t = T S_{t-1} + R Q_{\xi_t} \varepsilon_t + C_{\xi_t}. \quad (47)$$

Taking (47) as given, we can now compute the implied level of uncertainty (i.e., the implied $\tilde{\Gamma}_{c,\xi_t}$). In particular,

$$\begin{aligned} Cov_t [c'_1 S_{t+1}; d'_1 S_{t+1}] &= E_t \{ Cov_t [c'_1 S_{t+1}; d'_1 S_{t+1} | \xi_{t+1}] \} + Cov_t \{ E_t [c'_1 S_{t+1} | \xi_{t+1}]; E_t [d'_1 S_{t+1} | \xi_{t+1}] \} \\ &= c'_1 E_t [R Q_{\xi_{t+1}} (R Q_{\xi_{t+1}})'] d_1 + c'_1 Var_t [C_{\xi_{t+1}}] d_1, \end{aligned} \quad (48)$$

where we used the law of total covariance: $Cov(X, Y) = E(Cov(X, Y | Z)) + Cov(E(X | Z), E(Y | Z))$. Note that the changes in the Markov-switching constant, induced by the risk adjustment, are themselves a source

of uncertainty. Given the new value for $\tilde{\Gamma}_{c,\xi_t}$, we repeat the iteration: first, compute a new solution to (45), and then update $\tilde{\Gamma}_{c,\xi_t}$. This iterative procedure continues until the desired level of accuracy is reached. It is worth emphasizing that only C_{ξ_t} depends on Γ_{c,ξ_t} , while the matrices, T and R , do not depend on it, so we only need to iterate on C_{ξ_t} . Furthermore, standard conditions for the existence and uniqueness of a stationary solution apply, given that regime changes enter the model additively. Thus, we know that a finite level of uncertainty exists, as long as a solution exists and the shocks are stationary.

In the solution (Eq. 47), the matrices, T and R , are equivalent to a standard log-linear solution. Therefore, conditional on the volatility regime, the dynamics of the model are the same as in a standard log-linear solution. Volatility matters in two ways. First, like in log-linearized models, volatility affects the size of the innovations, captured by Q_{ξ_t} . Second, volatility affects the level of uncertainty in endogenous variables. Changes in uncertainty, in turn, impact the risk adjustment term, C_{ξ_t} , which is not present in a standard log-linear approximation. This term reflects the endogenous response of the economy to uncertainty and it is a source of uncertainty itself. Thus, the overall level of uncertainty is larger than in a model with no risk-adjustment. Thus, the risk adjustment term adjusts the levels of the variables, determines model dynamics in response to a volatility regime change, and produces additional uncertainty.

Rewrite Eq. (47) in the following form to emphasize dependence of the solution on structural parameters, θ^p , the stochastic volatility processes, θ^v , and transition probability matrix, H :

$$S_t = T(\theta^p)S_{t-1} + R(\theta^p)Q(\xi_t, \theta^v)\varepsilon_t + C(\xi_t, \theta^v, \theta^p, H). \quad (49)$$

Importantly, the Markov-switching constant, $C_{\xi_t} = C(\xi_t, \theta^v, \theta^p, H)$ depends on the structural parameters because for a given volatility of the exogenous disturbances, different structural parameters determine the various levels of uncertainty. In a standard log-linearization, this term would always be zero. As shown below, this approach allows us to capture salient asset pricing features despite having approximated a model with a conditionally linear solution. Furthermore, given that agents are aware of the possibility of regime changes, uncertainty also depends on the transition matrix, H . Finally, given that regime changes enter the system of equations additively, the conditions for the existence and uniqueness of a solution are not affected by the presence of regime changes. The model can then be solved by using solution algorithms developed for fixed coefficient general equilibrium models (Blanchard and Kahn (1980) and Sims (2002)). The model can also be solved by using the solution algorithms explicitly developed for MS-DSGE models (Farmer, Waggoner, and Zha (2009), Farmer, Waggoner, and Zha (2011), Cho (2016), and Foerster, Rubio-Ramírez, Waggoner, and Zha (2016)), but these methods are more computationally expensive. The appendix shows that the risk-adjusted log-linearization provides a good approximation of the model solution.

2.4 Nominal Bond Yields

Before illustrating the key mechanisms in our model, we characterize how bond yields are determined. Let $P_t^{(n)}$ be the n -period nominal bond price at time t . This bond price satisfies the following asset pricing Euler equation:

$$P_t^{(n)} = E_t \left[M_{t+1} P_{t+1}^{(n-1)} / \Pi_{t+1} \right]. \quad (50)$$

Applying the same log-linearization and risk-adjustment technique from above, we get

$$\tilde{p}_t^{(n)} = E_t \left[\tilde{m}_{t+1} - \tilde{\pi}_{t+1} + \tilde{p}_{t+1}^{(n-1)} \right] + .5 Var_t \left[\tilde{m}_{t+1} - \tilde{\pi}_{t+1} + \tilde{p}_{t+1}^{(n-1)} \right], \quad (51)$$

where the variables with a tilde denote log deviations of the corresponding variables from the deterministic steady state. Using this equation, we solve for nominal bond prices iteratively, starting from $n = 2$ (Note that the gross short-term nominal interest rate is an inverse of the price of a one-period nominal bond, $R_t = 1/P_t^{(1)}$, and therefore, $\tilde{p}_t^{(1)} = -\tilde{r}_t$). Given Eq. (47), the solution to Eq. (51) is given by:

$$\tilde{p}_t^{(n)} = T_p S_{t-1} + R_p Q_{\xi_t} \varepsilon_t + C_{p, \xi_t}. \quad (52)$$

Having solved for $\tilde{p}_t^{(n-1)}$ and knowing the solution of the model (47), we can compute $Var_t \left[\tilde{m}_{t+1} - \tilde{\pi}_{t+1} + \tilde{p}_{t+1}^{(n-1)} \right]$ in a way similar to Eq. (48) to get the solution for $\tilde{p}_t^{(n)}$. Given a price of the n -period nominal bond $P_t^{(n)} = P_{ss}^{(n)} e^{\tilde{p}_t^{(n)}}$, the yield on this bond is given by:

$$y_t^{(n)} = -\frac{1}{n} \log P_t^{(n)},$$

where $P_{ss}^{(n)}$ is the price of the n -period nominal bond in the deterministic steady state. Importantly, the pricing of bonds is internally consistent, in the sense that the econometrician and the agent in the model price bonds in the same way.

2.5 Uncertainty Decomposition

To understand the role of each of the five risk propagation channels described above, we consider a calibration of the simplified model. The ensuing analysis shows that the overall effects of the different sources of uncertainty on the macroeconomy are pinned down by how uncertainty propagates through these different channels. We find that in a New-Keynesian model, uncertainty shocks can be contractionary and generate positive comovement between investment and consumption – even when the precautionary savings motive works in the opposite direction – due to the presence of the four other channels.

Figure 3 displays impulse response functions for an increase in the volatility of the preference shock

(panel a) and of the TFP growth shock (panel b). An increase in demand uncertainty generates positive comovement between consumption, investment, and output (solid red line). The other lines illustrate the contribution to the overall effect of heightened uncertainty from the following propagation channels: precautionary savings (dashed line), investment risk premium (line with circles), the nominal pricing bias (dotted line) and investment adjustment channel (dotted line with diamond markers). The inflation risk premium is not quantitatively important in this calibration and have small overall effects on the economy. Therefore we plot it separately on a different scale (see Figure 4). The effects of the individual propagation channels on each variable differ depending on the origin of uncertainty. Importantly, the degree of price adjustment and capital adjustment costs are important for determining the sign and magnitude of these channels.

With higher supply or demand uncertainty, the precautionary savings channel increases the desire for saving, reflected in the drop in consumption and a rise in investment. This effect is reflected in the variance of marginal utility growth, given by Eq. (33). In this calibration, we only have a moderate degree of price adjustment costs, however with a sufficiently high degree of price stickiness, higher uncertainty will generate a large enough downward shift in labor demand that translates to a fall in investment, labor hours, and output, which is the mechanism that Basu and Bundick (2017) uses to produce positive comovement between macroeconomic aggregates. Importantly, our decomposition in this example illustrates how other risk propagation channels – namely, the investment risk premium, nominal pricing bias, and investment adjustment – can also help to offset the positive investment response from the precautionary savings channel to deliver a negative overall investment response to an increase in uncertainty.

The sign of the investment risk premium channel depends mainly on the covariance between the return on investment and the pricing kernel (see Eq. 35). This covariance is determined by the response to the level shocks, and the impulse responses are depicted in Figure 5. The level preference and TFP shocks give rise to negative comovement between the return on investment and the real stochastic discount factor, which translates into a positive investment risk premium, on average. Therefore, when uncertainty increases, either with demand or supply, the investment risk premium rises, as investing in capital becomes riskier; and in equilibrium, investment declines. The fall in investment generates a subsequent decline in output. The fall in investment also leads to an increase in consumption through the resource constraint.

The effect of the investment risk premium channel is not quantitatively large for demand-side uncertainty, because the response of the return on investment to a level preference shock is quantitatively small (see the left panel in figure 5). Therefore, the preference shock contributes relatively little to the riskiness of investing in capital. In contrast, for supply-side uncertainty changes, the investment risk premium channel is the most important for determining the investment response. It is also worth noting that the investment risk

premium channel is most important for determining the dynamics of investment relative to its effect on other macroeconomic quantities. The equity premium is closely tied to the investment risk premium in the model, and consequently, in our structural estimation, we require this term to be positive on average, and we verify that it increases with an increase in investment risk.

The investment adjustment channel depends on the volatility of future investment growth, and how it comoves with the real stochastic discount factor and marginal q (see Eq. 36). Both level supply- and demand-side shocks produce similar comovement between these variables, and therefore, both types of uncertainty propagates through this channel in a similar way. They lead to a decline in investment and output, while also having a small positive effect on consumption. Qualitatively, the effect is similar to how an uncertainty shock propagates through the investment risk premium channel.

The nominal pricing bias channel depends on (i) the variance of inflation and (ii) the covariance between inflation and the real stochastic discount factor, output, and TFP growth (see Eq. 37). The variance term relates to a precautionary price-setting effect highlighted in Fernández-Villaverde, Guerrón-Quintana, Kuester, and Rubio-Ramírez (2015) that creates a desire for firms to increase prices more when uncertainty is higher in the presence of sticky prices. However, the sign of the overall effect of the nominal pricing bias also depends on the comovement between inflation and the pricing kernel, output, and TFP, which are determined by the responses to the level shocks depicted in Figure 5. A demand shock generates positive comovement between inflation and the real stochastic discount factor, while a TFP shock generates negative comovement. Consequently, the response of the macroeconomy to an increase in TFP growth volatility has the opposite sign with respect to the response to an increase in the volatility of preference shocks. Therefore, the source of the uncertainty shock plays an important role in determining its effects through this channel.

As mentioned earlier the inflation risk premium channel has small quantitative effects in this calibration, however for completeness, we provide economic intuition for how the effects of this channel are determined. The inflation risk premium channel depends on the covariance between the stochastic discount factor and inflation (see Eq. 34). In Figure 5, we can see that in this calibrated example, a preference shock generates positive comovement between inflation and the real stochastic discount factor (therefore, positive nominal term premium), while the technology shock generates negative comovement (therefore, negative nominal term premium). Given the different signs in the covariances, supply-side and demand-side uncertainty generate opposite responses (Figure 4).

Both the nominal pricing bias and the inflation risk premium channels depend on the covariance between the real pricing kernel and inflation, and are therefore tightly linked to nominal term premia. Hence, we can discipline these channels using asset pricing data, namely, nominal bond yields across different maturities. As

we show below, in the estimated model, both supply-side and demand-side uncertainty contribute positively to term premia, albeit through two very different mechanisms.

3 Quantitative Model for Estimation

In this section, we describe the full model used for the structural estimation. We enrich the simplified model from the section above with a series of ingredients that have been proven important to match macroeconomic dynamics. We also allow for a rich set of shocks to show that even when additional disturbances are introduced, uncertainty plays a key role in explaining the bulk of business cycle and term structure fluctuations. Overall the estimated model has seven exogenous shocks: preference, TFP growth, monetary policy shock, markup, relative price of investment, government spending, and liquidity. We also allow for two stochastic volatility processes to distinguish between supply-side (TFP) and demand-side (preferences) uncertainty. The volatility processes are modeled as two independent Markov-chains, ξ_t^S and ξ_t^D , with transition matrices H^S and H^D , where the letters, S and D , are used to label the supply- and demand-side shocks, respectively. We then obtain a combined chain, $\xi_t \equiv \{\xi_t^D, \xi_t^S\}$, with the corresponding transition matrix, $H \equiv H^D \otimes H^S$. A detailed description of the model follows below.

Household Assume that the representative household has recursive utility over streams of consumption, C_t , and labor, L_t :

$$V_t = u(C_t, L_t, B_{t+1})^{(1-\beta_t)} \left(E_t \left[V_{t+1}^{1-\gamma} \right] \right)^{\frac{\beta_t}{1-\gamma}} \quad (53)$$

We introduce habit formation in consumption and preference for liquidity, by specifying the utility kernel in the following form:

$$u(C_t, L_t, B_{t+1}) = (C_t - h\bar{C}_{t-1})e^{-\tau_0 \frac{L_t^{1+\tau}}{1+\tau}} e^{\zeta_{B,t} \frac{B_{t+1}}{R_t P_t Z_t^*}}, \quad (54)$$

where the variable, $\zeta_{B,t}$, shock captures time-variation in the liquidity premium on short-term government bonds. The average liquidity premium is determined by the steady-state value of this variable, ζ_B . As shown below, the liquidity premium turns out to explain only a small fraction of the observed term premia. As before, γ is the coefficient of risk aversion, the elasticity of intertemporal substitution is set equal to 1, $Z_t^* = e^{n_t} \Upsilon^{\frac{\alpha}{1-\alpha} t}$ is the stochastic trend of the economy, B_{t+1} is the amount of nominal one-period bonds held by household at time t , P_t is the nominal price of consumption good. The discount factor, β_t , is defined as $\beta_t = \left(1 + \hat{\beta} e^{\tilde{b}_t} \right)^{-1}$, where \tilde{b}_t is a preference shock

$$\tilde{b}_{t+1} = \rho_\beta \tilde{b}_t + \sigma_{\beta, \xi_{t+1}^D} \varepsilon_{\beta, t+1}, \quad \varepsilon_{\beta, t+1} \sim N(0, 1) \quad (55)$$

and ξ_t^D is a Markov-switching process with transition matrix, H^D , which determines the volatility regime for the preference shock. The liquidity shock $\tilde{\zeta}_{B,t} \equiv \log(\zeta_{B,t}/\zeta_B)$ follows an AR(1) process:

$$\tilde{\zeta}_{B,t+1} = \rho_{\zeta_B} \tilde{\zeta}_{B,t} + \sigma_{\zeta_B} \varepsilon_{\zeta_B,t+1}, \quad \varepsilon_{\zeta_B,t+1} \sim N(0, 1). \quad (56)$$

The household supplies labor service, L_t , to a competitive labor market at the real wage rate, W_t . They also own the capital stock, \bar{K}_{t-1} , predetermined at time $t-1$, and rent out capital services, $K_t = U_t \bar{K}_{t-1}$, to a competitive capital market at the real rental rate, r_t^k , where U_t is capital utilization. They accumulate capital according to the following law of motion:

$$\bar{K}_t = \bar{K}_{t-1} (1 - \delta(U_t)) + [1 - S(I_t/I_{t-1})] I_t, \quad (57)$$

$$S(I_t/I_{t-1}) = .5\varphi_I \left(I_t/I_{t-1} - e^{\mu^*} \Upsilon \right)^2, \quad (58)$$

$$\delta(U_t) = \delta_0 + \delta_1(U_t - U_{ss}) + .5\delta_2(U_t - U_{ss})^2, \quad (59)$$

where the capital depreciation rate, $\delta(U_t)$, depends on the utilization rate of capital, U_t .

The time t budget constraint of the household is

$$P_t C_t + P_t (e^{\zeta_{\Upsilon,t}} \Upsilon^t)^{-1} I_t + B_{t+1}/R_t = D_t + P_t W_t L_t + B_t + P_t \bar{K}_{t-1} r_t^k U_t - P_t T_t, \quad (60)$$

where P_t is the nominal price of the consumption good, B_{t+1} is the amount of nominal one-period bonds held by household at time t that mature at $t+1$, R_t is the gross nominal interest rate set at time t by the monetary authority, D_t is the real dividend income received from the intermediate firms, and T_t denotes lump-sum taxes. The parameter, Υ , controls the average rate of decline in the price of the investment good relative to the consumption good, while $\zeta_{\Upsilon,t}$ is a shock to this relative price:

$$\zeta_{\Upsilon,t+1} = \rho_{\Upsilon} \zeta_{\Upsilon,t} + \sigma_{\zeta_{\Upsilon}} \varepsilon_{\zeta_{\Upsilon},t+1}, \quad \varepsilon_{\zeta_{\Upsilon},t+1} \sim N(0, 1). \quad (61)$$

Final Goods A representative firm produces the final (consumption) good in a perfectly competitive market. The firm uses a continuum of differentiated intermediate goods, $X_{i,t}$, as input in the following CES production technology

$$Y_t = \left(\int_0^1 X_{i,t}^{\frac{1}{1+\lambda_{p,t}}} di \right)^{1+\lambda_{p,t}}, \quad (62)$$

where $\lambda_{p,t}$ determines elasticity of substitution between intermediate goods. $\lambda_{p,t}$ follows AR(1) process in logs:

$$\log \lambda_{p,t} - \log \bar{\lambda}_p = \rho_{\lambda} (\log \lambda_{p,t-1} - \log \bar{\lambda}_p) + \sigma_{\lambda} \varepsilon_{\lambda,t}, \quad \varepsilon_{\lambda,t} \sim N(0, 1). \quad (63)$$

The profit maximization problem of the firm yields the following isoelastic demand schedule with price elasticity, $\nu_t = \frac{1+\lambda_{p,t}}{\lambda_{p,t}}$:

$$X_{i,t} = Y_t (P_{i,t}/P_t)^{-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}}$$

where P_t is the nominal price of the final good and $P_{i,t}$ is the nominal price of the intermediate good i .

Intermediate Goods The intermediate goods sector is characterized by a continuum of monopolistic competitive firms. Each intermediate goods firm produces intermediate goods, $X_{i,t}$, using labor, $L_{i,t}$, and capital, $K_{i,t}$, with the following constant returns to scale technology:

$$X_{i,t} = K_{i,t}^\alpha (Z_t L_{i,t})^{1-\alpha}.$$

The variable, Z_t , is an aggregate technology shock defined as:

$$\begin{aligned} Z_t &= e^{n_t}, \\ \Delta n_t &= \mu + x_t, \\ x_t &= \rho_x x_{t-1} + \sigma_{x,\xi_t^S} \varepsilon_{x,t}, \quad \varepsilon_{x,t} \sim N(0,1), \end{aligned}$$

where μ is the unconditional mean of productivity growth, ρ_x is the persistence parameter of the autoregressive process x_t , and the Markov-switching process, ξ_t^S , controls the volatility of shocks to TFP growth. As explained above, this Markov-switching process is controlled by the transition matrix H^S , where we use the letter S to emphasize the supply-side nature of this shock.

The intermediate firms face a cost of adjusting the nominal price à la Rotemberg (1982), measured in terms of the final good as

$$G(P_{i,t}, P_{i,t-1}, Y_t) = \frac{\phi_R}{2} \left(\frac{P_{i,t}}{\Pi_{ss}^{\kappa_\pi} \Pi_{t-1}^{(1-\kappa_\pi)}} P_{i,t-1} - 1 \right)^2 Y_t,$$

where $\Pi_{ss} \geq 1$ is the steady-state inflation rate, ϕ_R is the magnitude of the price adjustment costs, and the parameter κ_π controls price indexation to past inflation relative to steady-state inflation. The source of funds constraint is:

$$P_t D_{i,t} = P_{i,t} X_{i,t} - P_t W_t L_{i,t} - P_t r_t^k K_{i,t} - P_t G(P_{i,t}, P_{i,t-1}, Y_t),$$

where $D_{i,t}$ is the real dividend paid by the firm. The objective of the firm is to maximize shareholder value, $V_t^{(i)} = V^{(i)}(\cdot)$, taking the pricing kernel, M_t , competitive real wage, W_t , competitive real rental rate of

capital, r_t^k , and vector of aggregate state variables, $\Psi_t = (P_t, Z_t, Y_t)$, as given:

$$V^{(i)}(P_{i,t-1}; \Psi_t) = \max_{P_{i,t}, L_{i,t}, K_{i,t}} \left\{ D_{i,t} + E_t \left[M_{t+1} V^{(i)}(P_{i,t}; \Psi_{t+1}) \right] \right\}.$$

Central Bank The central bank follows a modified Taylor rule that depends on output and inflation deviations:

$$\ln \left(\frac{R_t}{R_t^*} \right) = \rho_r \ln \left(\frac{R_{t-1}}{R_t^*} \right) + (1 - \rho_r) \left(\rho_\pi \ln \left(\frac{\Pi_t}{\Pi_{ss} e^{\bar{\pi}^*}} \right) + \rho_y \ln \left(\frac{\hat{Y}_t}{\hat{Y}_{ss}} \right) \right) + \sigma_R \varepsilon_{R,t},$$

where R_t is the gross nominal short rate, $\hat{Y}_t \equiv Y_t/Z_t^*$ is detrended output, and $\Pi_t \equiv P_t/P_{t-1}$ is the gross inflation rate. Variables with an *ss* subscript denote deterministic steady-state values. We allow the inflation target to differ from the deterministic steady-state inflation to take into account that average inflation does not necessarily coincide with the deterministic steady-state when risk is taken into account in the solution method. The correction is controlled by the parameter, $\bar{\pi}^*$.

Symmetric Equilibrium In equilibrium all intermediate firms make identical decisions $P_{i,t} = P_t$, $X_{i,t} = X_t = Y_t$, $K_{i,t} = K_t$, $L_{i,t} = L_t$, $D_{i,t} = D_t$, and nominal bonds are in zero net supply $B_t = 0$. The aggregate resource constraint is:

$$Y_t = C_t + (e^{\zeta_{r,t}} \Upsilon^t)^{-1} I_t + .5 \phi_R \left(\Pi_t / (\Pi_{ss}^{\kappa_\pi} \Pi_{t-1}^{1-\kappa_\pi}) - 1 \right)^2 Y_t + G_t,$$

where G_t are government spending, which follows exogenously specified AR(1) process in logs:

$$\log G_{t+1} - \log G_{ss} = \rho_g (\log G_t - \log G_{ss}) + \sigma_g \varepsilon_{g,t+1}.$$

Government spending is financed by lump-sum taxes on households: $G_t = T_t$.

4 Empirical Analysis

We estimate the model by using Bayesian methods. The sample 1984:Q2-2015:Q4 is considered. The model solution retains the key non-linearity represented by regime changes, but it is linear conditional on a regime sequence. Thus, Bayesian inference can be conducted using Kim's modification of the basic Kalman filter to compute the likelihood (i.e., Kim and Nelson (1999)). In addition to the priors on the single model parameters, we also have priors on the unconditional means of inflation, the real interest rate, the slope

of the nominal yield curve, and the investment risk premium. Unlike in a linear model, the unconditional means of these variables are not pinned down by a single parameter. Thus, these priors induce a joint prior on the parameters of the model, in a way similar to Del Negro and Schorfheide (2008). The priors for the model parameters are combined with the likelihood to obtain the posterior distribution.

Eleven observables are used: GDP per-capita growth, inflation, FFR, consumption growth, investment growth, price of investment growth, one-year yield, two-year yield, three-year yield, four-year yield, and five-year yield. Given that there are more observables than shocks (i.e., eleven variables compared to seven shocks), we allow for observation errors on all variables, except for the FFR. We also repeated our estimation excluding the zero-lower-bound period, with no significant changes in the results. Finally, alternative versions of the model are estimated, such as, a specification in which both volatility processes are perfectly correlated or another specification where all shocks exhibit stochastic volatility that are perfectly correlated, but these versions did not lead to a better fit of the data. As it will become clear below, the data seems to favor a separation between supply- and demand- side uncertainty shocks.

4.1 Parameter Estimates and Model Fit

Table 1 reports the posterior mean for the structural parameters together with the 90% error bands and the priors. A few comments are in order. First, we fix the elasticity of intertemporal substitution to 1. Second, the parameters controlling the magnitude of the price adjustment cost, ϕ_R , and the average markup, ν , cannot be separately identified. Thus, when solving the model, we define and estimate the parameter, $\kappa_R = \frac{\nu-1}{\phi_R}$, while we fix the parameter, ν .⁶ The resulting estimated value for κ_R implies an elevated level of price stickiness, in line with the existing New Keynesian literature. Third, in accordance with previous results in the literature, we find a more than one-to-one response of the FFR to inflation, despite the long time spent at the zero lower bound. The fact that the response is well above 1 guarantees that the Taylor principle is satisfied.

Table 1 reports estimates for the volatilities of the shocks and the persistence of the two regimes. Figure 6 reports the probability of the High volatility regimes (Regime 2 for each chain) for the preference shock (top panel) and the TFP shock (bottom panel). The high volatility regime for the preference shock is less persistent than the low volatility regime, while the opposite is true for the high TFP-volatility regime.

Figure 7 compares the variables as implied by our model with the observed variables. Recall that we have observation error on all variables except for the FFR. The figure shows that the model does a very good

⁶The average markup (ν) affects the steady state of the model. For the purpose of computing the steady state we fix this parameter to 6, a value that implies an average net markup of 20% and that is considered in the ballpark (see Galí (1999)).

job in matching the behavior of both the macro variables and the term structure. We observe some visible deviations between model-implied and observed variables only for the growth rate of the price of investment. Thus, observation errors do not play a key role in matching the observed path for yields and macro variables. The last panel of the figure also shows that the model tracks very well the behavior of the slope of the yield curve, defined as the difference between the one-year and five-year yields. As we will see below, variations of the term premium over the business cycle play a key role in generating such a close fit.

4.2 The Effects of Uncertainty

Given that the model allows for two TFP volatility regimes and two preferences volatility regimes, there are a total of four regimes labeled as follows: (i) Low Preference-Low TFP volatility; (ii) Low Preference-High TFP volatility; (iii) High Preference-Low TFP volatility; and (iv) High Preference-High TFP volatility. We are interested in characterizing the level of uncertainty across the four regimes. Uncertainty is computed taking into account the possibility of regime changes, following the methods developed in Bianchi (2016). For each variable, z_t , we measure uncertainty by computing the conditional standard deviation, $sd_t(z_{t+s}) = \sqrt{\mathbb{V}_t(z_{t+s})} = \sqrt{\mathbb{E}_t[z_{t+s} - \mathbb{E}_t(z_{t+s})]^2}$, where $\mathbb{E}_t(\cdot) \equiv \mathbb{E}(\cdot|\mathbb{I}_t)$ and \mathbb{I}_t denotes the information available at time t . We assume that \mathbb{I}_t includes knowledge of the regime in place at time t , the data up to time t , and the model parameters for each regime, while future regime realizations are unknown. These assumptions are consistent with the information set available to agents in our model, and so our measure of uncertainty reflects uncertainty supposedly faced by the agent in the model across the four regimes. Note that there are two sources of uncertainty. The first one is straightforward: As the size of the Gaussian shocks hitting the economy increases, uncertainty goes up. The second one is more subtle: The endogenous response of the macroeconomy to uncertainty is in itself a source of uncertainty. Thus, the magnitude of the response to uncertainty and the frequency of regime changes matter for the overall level of uncertainty. The relative contribution of these two sources of uncertainty are described in detail below.

Figure 8 reports the levels of uncertainty across the different regimes. The time horizon s appears on the x-axis. Solid and dashed lines are used to denote Low and High preference shock volatility regimes, respectively. Conditional on these line styles, we use lines with dots and without dots to denote Low and High TFP shock volatility, respectively. Not surprisingly, when both demand-side and supply-side volatilities are high (dashed-line with dots), uncertainty is high for all variables at all horizons. When only one of the shocks is in the high volatility regime, the effects differ across the variables. For inflation, the FFR, and the slope of the yield curve, the main driver of uncertainty is the volatility of the preference shock. Instead, uncertainty about the growth rate of the real variables is higher when TFP is in the high volatility regime.

It is also interesting to notice that uncertainty for consumption and GDP is slightly hump-shaped when the High TFP volatility regime prevails. In other words, when TFP volatility is high, uncertainty is not monotonically increasing with the time horizon, as agents are more uncertain about the short-run than the long-run. This is because two competing forces are at play. On the one hand, events that are further into the future are naturally harder to predict, as the possibility of shocks and regime changes increase. On the other hand, in the long run, the probability of still being in the high volatility regime declines.

Figure 9 presents a simulation to understand the impact of these changes in uncertainty on business cycle fluctuations and the term structure. We take the most likely regime sequence, as presented in Figure 6, and simulate the economy based on the parameters at the posterior mode, setting all Gaussian shocks to zero. The top left panel reports the cyclical behavior of GDP and the slope of the yield curve implied by the model. An increase in uncertainty produces a drop in real activity and an increase in the slope of the yield curve, which consequently generates negative comovement between the slope of the yield curve and real activity, as in the data (e.g., Ang, Piazzesi, and Wei (2006)). The four panels in the second and third row of the figure compare the movements in the slope, GDP, consumption, and investment, induced by the increase in uncertainty, with the business cycle fluctuations of the actual series. The estimated sequence of the volatility regimes produces business cycle fluctuations and changes in the slope of the yield curve in a way that closely tracks the observed fluctuations in the data.

The fluctuations in uncertainty also lead to significant breaks in the term premium. Term premium is defined as the difference between the yield on a 5-year bond and the expected average short-term yield (1 quarter) over the same five years (following Rudebusch, Sack, and Swanson (2006)). The expected value is computed taking into account the possibility of regime changes using the methods developed in Bianchi (2016). The top-right panel of Figure 9 shows that both supply-side and demand-side uncertainty lead to an increase in the term premium. Specifically, Table 4 shows that the nominal (real) term premia associated with the different regimes are: (1) Low Preference - Low TFP volatility: 0.58% (0.33%); (2) Low Preference - High TFP volatility: 0.84% (0.60%); (3) High Preference - Low TFP volatility: 1.03% (0.51%); and (4) High Preference - High TFP volatility: 1.29% (0.78%). In Subsection 4.4, the mechanisms that lead to these sizeable premia are explored in detail. For now, we are highlighting that term premia are large and vary considerably in response to changes in uncertainty.

Our estimated model allows for a rich set of shocks to avoid forcing the estimation to artificially attribute a large role to the uncertainty shocks. The results presented above suggest that uncertainty shocks can in fact lead to sizeable fluctuations for both the macroeconomy and bond risk premia. In order to formally quantify the importance of uncertainty shocks with respect to the other disturbances, we proceed in two

steps. First, we compute a variance decomposition by comparing the unconditional variance, as implied by the model when only one shock is active, to the overall variance. Second, we explore how much variation in endogenous variables at business cycle frequencies can be generated by uncertainty shocks. We do this by computing the volatility of business cycle fluctuations in an economy where only uncertainty shocks are present and comparing it to the volatility of business cycle fluctuations in an economy where both uncertainty and level shocks are active.⁷

The decomposition of the unconditional variance for the observables is reported in the left panel of Table 2. The results confirm that uncertainty shocks play an important role in explaining fluctuations in the slope of the yield curve (28% of the unconditional variance), but they also account for a large fraction of the variability of consumption and investment growth (14.26% and 9.67%, respectively). The right panel of Table 2 highlights that uncertainty shocks appear even more important if we focus on their ability to generate sizable business cycle fluctuations. Uncertainty shocks explain a substantial part of the variation in consumption, investment, and output over the business cycle. In particular 24.52% of the variation in consumption and around 31% of the variation in investment at business cycle frequencies can be explained by uncertainty shocks. Finally, uncertainty shocks also explain 38.44% of business cycle variation in the slope of the yield curve, confirming the evidence presented in Figure 9.

Finally, the variance decomposition in the left panel of Table 2 shows that the combination of TFP shocks, preference shocks, and their corresponding volatility shocks accounts for a very large fraction of the volatility of the macroeconomy and bond yields. Specifically, these shocks combined account for more than 80% of the variance of GDP growth, for more than 90% of the variance of consumption growth, for more than 85% of the variance of investment growth, and for almost 60% of the variance of inflation and the slope of the term structure of interest rates. The only other shock that plays a significant role is the markup shock. However, this shock only appears to account for high-frequency movements in the volatility of inflation, as it is often the case in estimated New-Keynesian models. Thus, the combination of first and second moments shocks to TFP and preferences account for the bulk of the volatility of the observed variables, despite the fact that we allow for a series of other shocks, like the liquidity shock, that generally play a significant role in the estimation of New-Keynesian DSGE models without the risk-adjustment. This suggests that extending standard estimation technique to include the first-order effects of uncertainty shocks can significantly change the importance of the other shocks, possibly allowing for more parsimonious models to explain the observed fluctuations.

⁷From a technical point of view the contribution of uncertainty shocks is given by the amount of volatility generated by the Markov-switching constant.

4.3 Inspecting the Mechanism

To better understand the mechanisms at work, we decompose the effects of the uncertainty shocks into the five risk propagation channels that were discussed in the context of the simplified model of Section 2: Precautionary savings, investment risk premium, inflation risk premium, nominal pricing bias, and investment adjustment. The results show that the origins of uncertainty are important to understand its effects.

Figure 10 presents the median and 90% error bands for the impulse responses to a demand-side (dashed line) and a supply-side (solid line) uncertainty shock, while Figure 11 presents the median and 90% error bands for the *difference* between these impulse responses. Impulse responses are computed as the change in the expected path of the endogenous variables following an initial impulse, in line with the way impulse responses are computed for shocks to levels. Specifically, these impulse responses assume a shift from low to high uncertainty in the first period, but from that point on they are computed integrating out future regime changes. Thus, the impulse responses are conceptually different from the simulations reported in Figure 9 where the posterior mode regime sequence was imposed.

Despite these technical differences that take into account uncertainty about the future regime path, uncertainty shocks still emerge as a driving force of the business cycle. Both demand- and supply-side uncertainty shocks generate positive comovement between consumption, investment, output, as there is an economic contraction following heightened macroeconomic uncertainty. Also, higher uncertainty increases the nominal and real slope and term premia, consistent with the observed dynamics in the data. However, a supply-side uncertainty shock leads to a much larger decline in inflation. Furthermore, the recession generated by a supply-side uncertainty shock is visibly larger, as confirmed by the first row of Figure 10. The effects on term premia are also quantitatively different, with the supply-side uncertainty shock generating a smaller increase in the nominal term premium and a larger increase in the real term premium.

Figure 12 decomposes the effect of uncertainty increases for preferences (Panel a) and in TFP (Panel b). Note that, in contrast to the calibrated simplified model presented above, the precautionary savings channel generates positive comovement between consumption, investment, and output. In our estimated model, the magnitude of price adjustment costs is sufficiently high that it flips the sign of investment (due to a larger downward shift in labor demand). However, while this channel plays a key role in driving consumption down following an uncertainty shock, other channels play an equally important role to understand the effects of uncertainty on the other macroeconomic variables.

When the economy experiences a supply-side uncertainty shock, the investment risk channel is equally (and at certain horizons more) important than the precautionary savings channel in determining a decline

in investment. On the other hand, when the economy experiences a demand-side uncertainty shock, the risk propagation channel works in the opposite direction and mitigates the decline in investment. Thus, demand and supply uncertainty propagate differently through the investment risk premium channel. The difference is determined by how the shadow value of capital responds to adverse demand and supply shocks (figure 13). For the household, capital works as a hedge against adverse preference shocks, because the return on investment is positive in a state of the world with high marginal utility of wealth (high SDF). The opposite is true for a negative TFP shock, as the return on investment is negative in the high SDF state. So, when supply side uncertainty increases, the effect of the investment risk premium channel is driven by investment becoming riskier and households, *keeping all else equal*, optimally choosing to cut investment. In contrast, when demand uncertainty increases, investment becomes less risky and the effect of this channel is determined by the household choosing a relatively higher level of investment than it would choose if investment risk premium remained constant.

Importantly, the net effect of demand-side uncertainty on investment is still negative because of the combined effect of the precautionary savings and nominal pricing bias channels. Indeed, when the economy experiences a demand-side uncertainty shock, the nominal pricing bias channel contributes to the decline in consumption and investment. In response to an increase in demand-side uncertainty the nominal price bias determines effects similar to a markup shock, given that it enters the New-Keynesian Phillips curve in an isomorphic way. Inflation goes up, consumption and investment go down. This contributes to exacerbating the recession while mitigating the effects on inflation.

The decomposition also helps in understanding why the response of inflation is so muted in the two cases. In both cases, the precautionary savings channel determines deflationary pressure. However, following a demand-side uncertainty shock the pricing bias channel essentially nullifies the effects on inflation, while in the case of the supply-side uncertainty shock this channel plays a very little role. To understand why, it is useful to revisit the impulse responses presented in Figure 13. Inflation experiences a persistent increase in response to a demand shock, while a supply shock has very little quantitative impact on inflation dynamics. As a result, the nominal pricing bias channel is not quantitatively important for supply side uncertainty: Firms do not adjust their price-setting decision, as supply side uncertainty has limited impact on uncertainty about future inflation. In contrast, the preference shock is an important driver of inflation dynamics, and demand-side uncertainty directly translates into uncertainty about future inflation. Hence, the nominal pricing bias is an important determinant of the economy's response to demand-side uncertainty.

Finally the other two channels, inflation risk premium and investment adjustment, have small quantitative effects.

4.4 Yield Curve

In this section, we provide more details about the fit of the model and the mechanisms at play by inspecting the ability of the model of matching movements in the term structure. We already conducted a first check on the fit of the model in Figure 7 showing that the yields across various maturities, as implied by our model, track very closely observed yields despite allowing for observation errors on all variables, except for the FFR. In what follows, we analyze how the model is able to match the dynamics of yields and the slope so closely.

Table 3 reports the nominal and real yield curve as implied by our estimated model. Our model generates an upward-sloping real and nominal yield curve with sizable average term spreads. Both preference and TFP shocks are important for generating the unconditional real term premium, while the preference shock is important for generating the unconditional inflation risk premium. It is worth emphasizing that in our estimated model, the endogenous risk premium is significantly more important than the liquidity premium in generating nominal premia and the only determinant of *real* premia. The liquidity premium is the premium arising from a linear term that captures the preference of the household for short-term bonds, and it is controlled by the parameter, ζ_B . Thus, liquidity shocks seem to play only a small role for explaining business cycle fluctuations, and moreover, the liquidity premium seems less important in determining term premia compared to the risk-based channels.

The right side of Table 3 shows that the overall nominal term premium is 0.96%, generating an unconditional slope of the term structure very much in line with the data (1.05%). The risk premium accounts for the bulk of the term premium: 0.90% Vs. 0.06%. The real term premium is 0.56% and it is all due to the risk premium arising from the preference and TFP shocks. To understand the relative importance of demand-side versus supply-side uncertainty in generating the premia, we consider a counterfactual simulation in which the standard deviations of all shocks are set to zero, except for preference (TFP) shocks. When only preference (TFP) shocks are allowed, the nominal term premium is 0.77% (0.29%), while with only preference (TFP) shocks, the real term premium is 0.26% (0.34%). These results show that demand-side uncertainty is relatively more important in determining the nominal term premium, while the two sources of uncertainty contribute to the real term premia of a similar magnitude. Next, we study how the two sources of uncertainty lead to sizable risk premia.

Persistent shocks to time discount rates coupled with recursive preferences contributes significantly to both the real term premia and inflation risk premia. To understand the mechanism behind this finding, Figure 14 presents the impulse responses to such a shock for some key variables. A negative preference shock (less patience) induces household to consume more and save less, which decreases the wealth-to-consumption

ratio. A drop in the wealth-to-consumption ratio implies a decline in the return on a claim to aggregate consumption. When agents prefer an early resolution of uncertainty ($\psi > 1/\gamma$), a decrease in the return on the consumption claim increases marginal utility. When the shock is persistent, this leads to a sharp increase in marginal utility. A persistent negative time preference shock also increases the real rate persistently, which erodes the payoffs of long real bonds more than short ones. Given that a negative time preference shock is associated with high marginal utility, long real bonds provide less insurance against bad states of the world relative to short real bonds. In equilibrium, this helps to generate an upward-sloping real yield curve and a positive real term premia, in a way similar to Albuquerque, Eichenbaum, Luo, and Rebelo (2016).

The time preference shock endogenously generates a negative relation between marginal utility and inflation, which translates into positive inflation risk premia increasing with maturity. A persistent negative time preference shock increases aggregate demand, which raises inflation persistently. The negative time preference shock is also associated with high marginal utility as discussed above. Persistently higher inflation erodes the value of long nominal bonds more than short nominal bonds during high marginal utility states. Consequently, the nominal yield curve is upward-sloping.

The persistent TFP growth shocks in conjunction with habits contributes positively to real term premia. A negative TFP growth shock decreases consumption today relative to habit (proportional to lagged consumption), decreasing surplus consumption (i.e., the difference between consumption and habits), and raising marginal utility. However, next period, the habit catches up and increases expected surplus consumption growth. This induces a borrowing motive to smooth surplus consumption, which therefore increases the real rate akin to Wachter (2006). A persistent increase in the real rate erodes the value of long-term real bonds more than short-term ones. Therefore long-term real bonds provide less insurance against high marginal utility states induced by negative TFP shocks, which contributes to the upward-sloping real yield curve and positive real term premia. However, the TFP shocks do not generate significant inflation risk premia as TFP shocks have a very small effect on inflation (see Figure 13). Therefore, the impact of TFP shocks on the nominal term premia are primarily through the real term premia component.

Table 4 illustrates how the dynamics of real and nominal term premia are driven by the preference and TFP uncertainty shocks. As preference uncertainty shocks contribute significantly to the unconditional real term premia and inflation risk premia, changes in demand-side uncertainty generates sizable variation in the conditional real term premia and the conditional inflation risk premia. In contrast, TFP uncertainty shocks mainly contribute to real term premia and not towards inflation risk premia since the level TFP shocks mainly contribute to the unconditional real term premia. Quantitatively, changes in demand-side uncertainty produce large fluctuations in term premia through the effects on inflation risk premia.

4.5 Informational Content of the Term Structure

Given the importance of demand- and supply-side uncertainty for term premia movements, the use of term structure data in our estimation is crucial for identifying the overall effects of uncertainty and distinguishing between the two types of uncertainty. Figures 15 and 16 plot the impulse response functions for demand and supply uncertainty shocks from our benchmark estimation using term structure data (solid line) and an estimation without using term structure data (dashed line). Interestingly, the estimated effects of demand-side uncertainty are significantly amplified using term structure data than without, while the effects are muted for supply-side uncertainty. As demand-side uncertainty is more important for nominal term premia compared to supply-side uncertainty, including term structure data in the estimation therefore increases the relative importance of demand-side uncertainty.

Figure 17 illustrates that the inclusion of term structure data in the estimation affects the timing, duration, and importance of uncertainty shocks. In particular, comparing this figure with Figure 9, it is evident that using term structure data provides valuable information for the role of uncertainty in explaining business cycle fluctuations. When the term structure is not included, periods of high uncertainty have a shorter duration and produce smaller effects. Furthermore, in the 1991 recession there is no visible effect from the increase in demand-side uncertainty, consistent with the impulse responses from Figure 15. Overall, when the term structure is not included, liquidity shocks become more important for explaining business cycle fluctuations as they account for around 77% and 29% of investment and consumption volatility, respectively, compared to 2.31% and 0.94% in the benchmark estimation. On the other hand, the estimation excluding the term structure also implies a counterfactual yield curve, as the unconditional nominal slope is only 0.27%, with most of the nominal spread coming from the real curve (see Table 5). This is due to the fact that demand shocks are a key source of inflation risk premia, but when term structure data is excluded, the role of demand shocks are significantly reduced as illustrated in Figure 15. Thus, the term structure encodes important information about uncertainty and macroeconomic fluctuations, and also disciplines the relative importance of liquidity shocks. The joint estimation exploits the strong relation between the slope of the yield curve, business cycle fluctuations, and uncertainty.

5 Conclusion

This paper quantitatively explores the effects of different macroeconomic uncertainty shocks on business cycle and asset pricing fluctuations. We build and estimate a DSGE model that features realistic bond risk premia. We estimate the model using macroeconomic data, the term structure of interest rates, and

imposing restrictions on the average investment risk premium. Our model allows for stochastic changes in the volatility of demand-side (preferences) and supply-side (TFP) shocks, while at the same time controlling for other disturbances often included in the estimation of New-Keynesian DSGE models. Uncertainty shocks are triggered by changes in stochastic volatility, but the endogenous response of the macroeconomy to these changes is in itself a source of uncertainty.

We study the effects of uncertainty through the lens of a novel decomposition that identifies five endogenous risk propagation mechanisms: precautionary savings, investment risk premium, inflation risk premium, nominal pricing bias, and investment adjustment channels. The effects arising from the investment and inflation risk premia channels are disciplined by the investment risk and nominal term premia, respectively.

We find sizable effects of changes in uncertainty. Both demand-side and supply-side generate a positive comovement in consumption, investment, and output. The responses of inflation and term premia differ depending on the source of uncertainty. Supply-side uncertainty leads to larger contractions in both investment and consumption. These differences are explained in light of the way uncertainty propagates through the real economy. In response to an increase in supply-side uncertainty, an increase in the risk of investing in physical capital contributes to determine a larger recession. Instead, when demand-side uncertainty is high, investment in capital becomes more attractive, reducing the fall in investment. In response to an increase in demand-side uncertainty, the negative effects on inflation from the precautionary savings channel are nullified by a nominal bias in pricing. The joint estimation of macro and yield curve variables put additional discipline on the relative importance of these channels, as the model is also asked to account for the negative comovement between term premia and the macroeconomy. Overall, our results highlight the importance of accounting for the origins of macroeconomic uncertainty and for using asset prices to discipline the various risk propagation channels for uncertainty.

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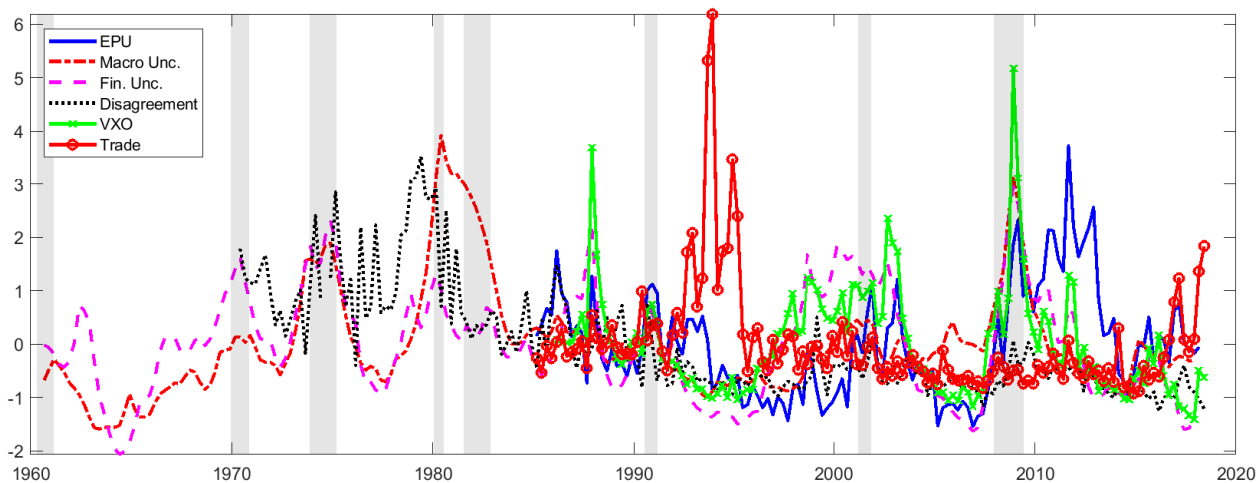


Figure 1: This figure plots various uncertainty measures. All measures are demeaned and normalized to have standard deviation equal to 1. ‘EPU’ - Economic Policy Uncertainty Index (Baker, Bloom, and Davis (2016)), ‘Macro Unc.’ - Macroeconomic uncertainty index for 12 month horizon (Jurado, Ludvigson, and Ng (2015)). ‘Fin Unc.’ - Financial uncertainty index for 12 month horizon (Jurado, Ludvigson, and Ng (2015), Ludvigson, Ma, and Ng (2018)). ‘Disagreement’ - Forecast disagreement about real GDP growth. 75th percentile minus 25th percentile of the forecast for growth rate at 4 quarters horizon. ‘VXO’ - CBOE S&P 100 Volatility Index. ‘Trade’ - Trade policy uncertainty (a component of Economic Policy Uncertainty Index). The pairwise correlations range from -0.30 to 0.85.

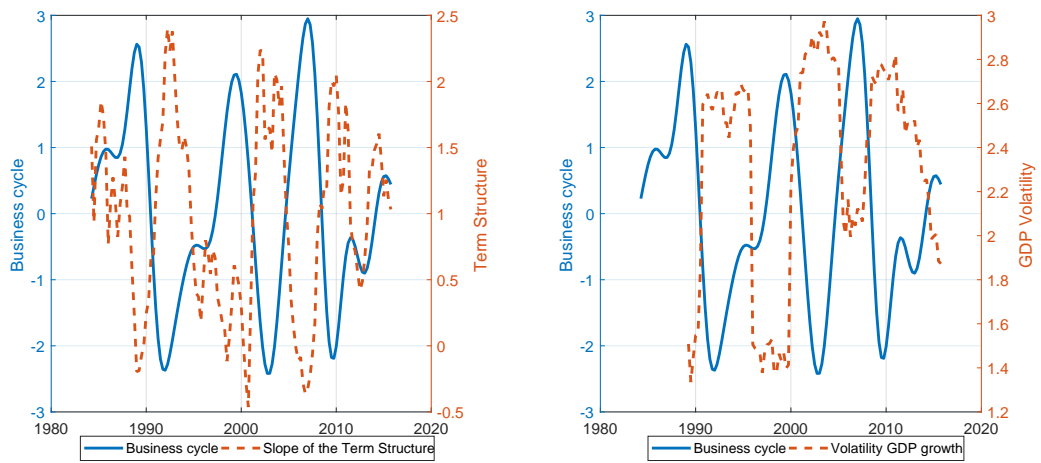


Figure 2: Slope and volatility over the business cycle. Panel A plots the comovement between the slope of the yield curve (dashed line) and the cyclical component of GDP (solid line) and Panel B plots the comovement between the volatility of GDP growth (dashed line) and the cyclical component of GDP growth (solid line) from the data.

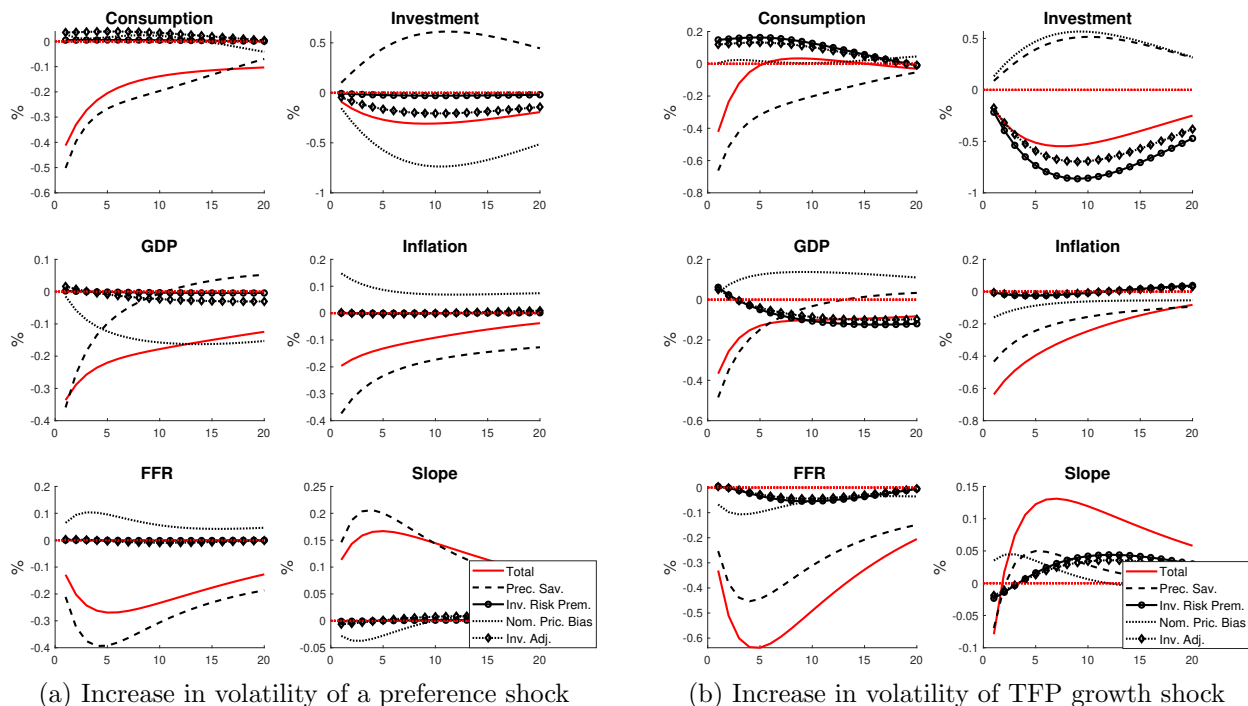


Figure 3: Calibrated model. The impulse responses represent a change in the expected path of the corresponding variable in response to a volatility regime changes. The units of the y-axis are percentage deviations from a steady state (values for inflation, FFR and Slope are annualized). Units on the x axis are quarters. The red solid line depicts the total effect of the volatility regime change. The black dashed line shows the contribution of the precautionary savings motive. The black line with circles shows the contribution of the channel operating through change in risk premium on investment return. The black dotted line shows the contribution of a channel operating through the nominal pricing bias. The dotted line with diamond markers shows the contribution of the investment adjustment channel. We use the following parameter values: $\bar{\beta} = 0.996$, $\rho_{\beta} = 0.98$, $\alpha = 0.33$, $\psi = 1$, $\gamma = 10$, $\mu = 0.005$, $\rho_x = 0.1$, $\kappa_R = 0.004$, $\pi_{ss} = 0.007$, $\rho_r = 0.7$, $\rho_{\pi} = 1.5$, $\rho_y = 0.1$, $\delta_0 = 0.02$, $\varphi_I = 15$, $\tau = 5$, $\sigma_b(\xi^D = 1) = 0.0125$, $\sigma_b(\xi^D = 2) = 0.0250$, $\sigma_x(\xi^S = 1) = 0.0075$, $\sigma_x(\xi^S = 2) = 0.0150$.

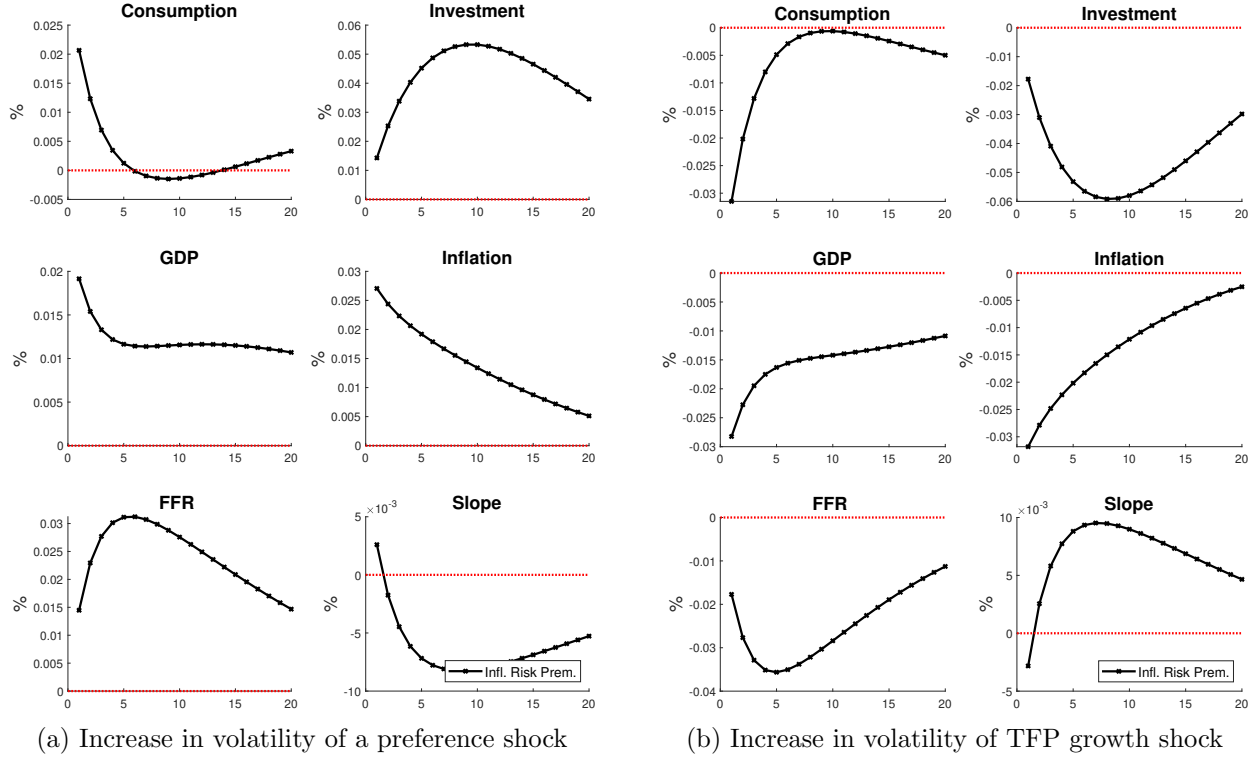


Figure 4: Calibrated model: Inflation risk premium channel of uncertainty. The impulse responses represent a change in the expected path of the corresponding variables when volatility regime changes. The units of the y-axis are percentage deviations from a steady state (values for inflation, FFR and Slope are annualized). Units on the x axis are quarters. We use the following parameter values: $\bar{\beta} = 0.996$, $\rho_{\beta} = 0.98$, $\alpha = 0.33$, $\psi = 1$, $\gamma = 10$, $\mu = 0.005$, $\rho_x = 0.1$, $\kappa_R = 0.004$, $\pi_{ss} = 0.007$, $\rho_r = 0.7$, $\rho_{\pi} = 1.5$, $\rho_y = 0.1$, $\delta_0 = 0.02$, $\varphi_I = 15$, $\tau = 5$, $\sigma_b(\xi^D = 1) = 0.0125$, $\sigma_b(\xi^D = 2) = 0.0250$, $\sigma_x(\xi^S = 1) = 0.0075$, $\sigma_x(\xi^S = 2) = 0.0150$.

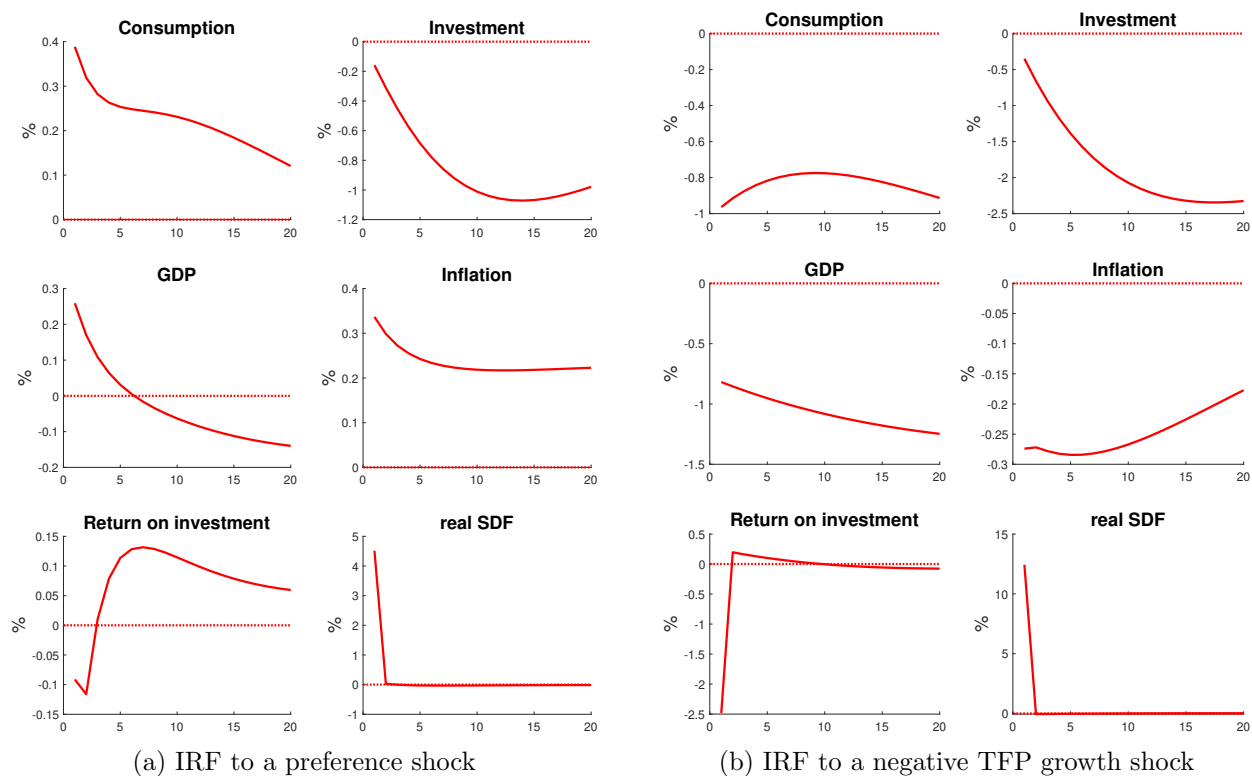


Figure 5: Calibrated model. The units of the y-axis are percentage deviations from a steady state (values for inflation and return on investment are annualized). Units on the x axis are quarters. We use the following parameter values: $\bar{\beta} = 0.996$, $\rho_{\beta} = 0.98$, $\alpha = 0.33$, $\psi = 1$, $\gamma = 10$, $\mu = 0.005$, $\rho_x = 0.1$, $\kappa_R = 0.004$, $\pi_{ss} = 0.007$, $\rho_r = 0.7$, $\rho_{\pi} = 1.5$, $\rho_y = 0.1$, $\delta_0 = 0.02$, $\varphi_I = 15$, $\tau = 5$, $\sigma_b(\xi^D = 1) = 0.0125$, $\sigma_b(\xi^D = 2) = 0.0250$, $\sigma_x(\xi^S = 1) = 0.0075$, $\sigma_x(\xi^S = 2) = 0.0150$.

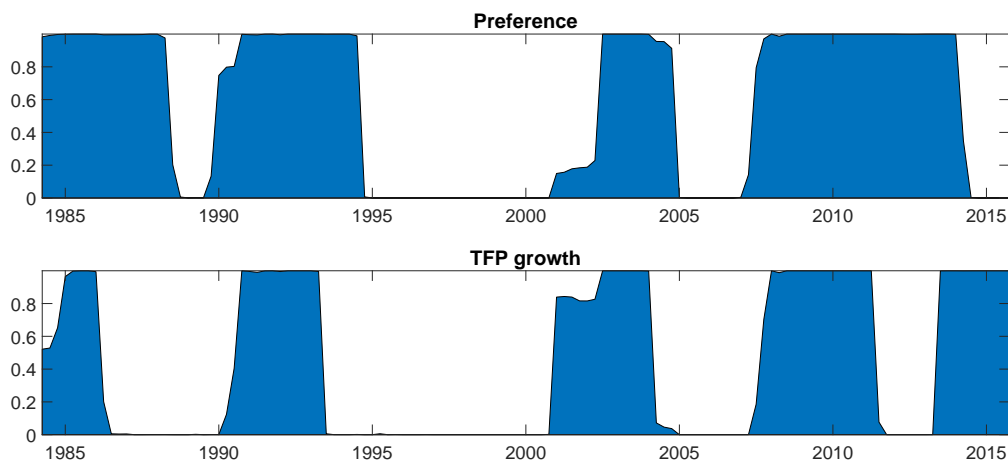


Figure 6: Regime probabilities. The figure plots the probability of the high uncertainty regime for the preference shock (top panel) and the TFP growth shock (bottom panel).

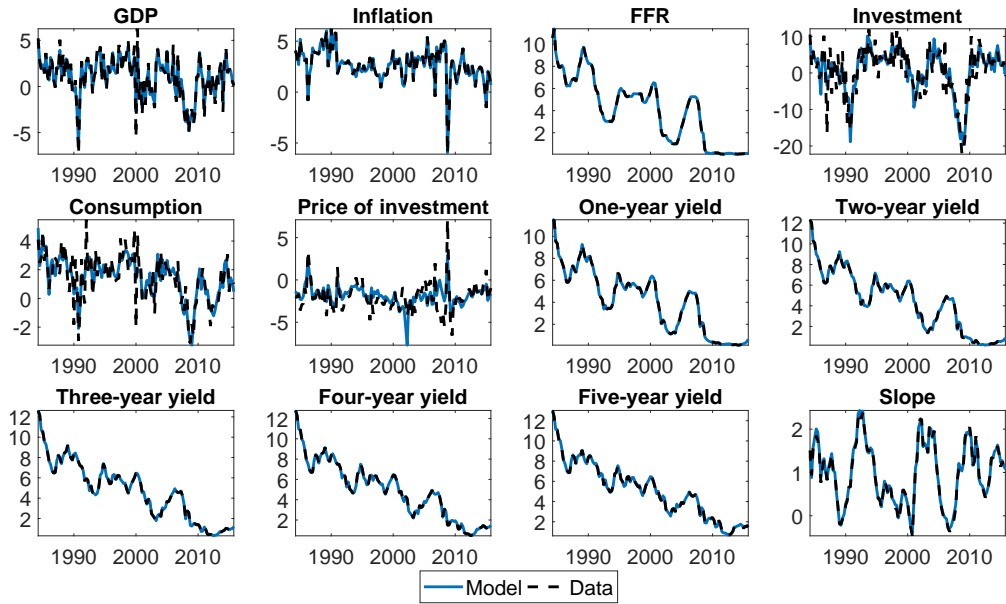


Figure 7: Actual and fitted series. The figure compares the fluctuations of the macroeconomy and the term structure of interest rates implied by our model (blue solid line) with the fluctuations observed in the data (black dashed line).

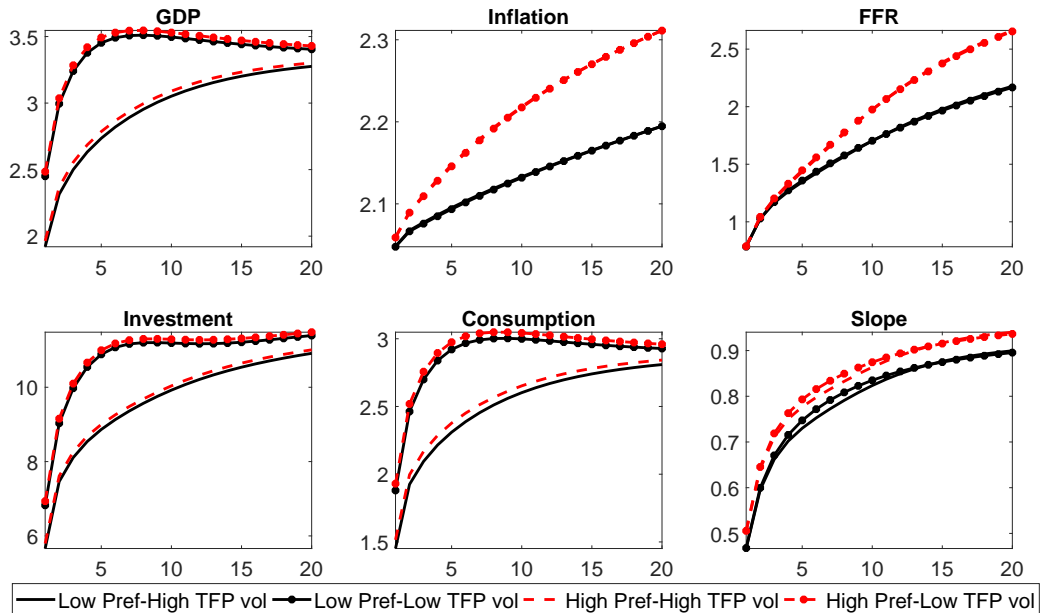


Figure 8: Uncertainty. The figure reports the level of uncertainty at different horizons. Uncertainty is computed taking into account the possibility of regime changes.

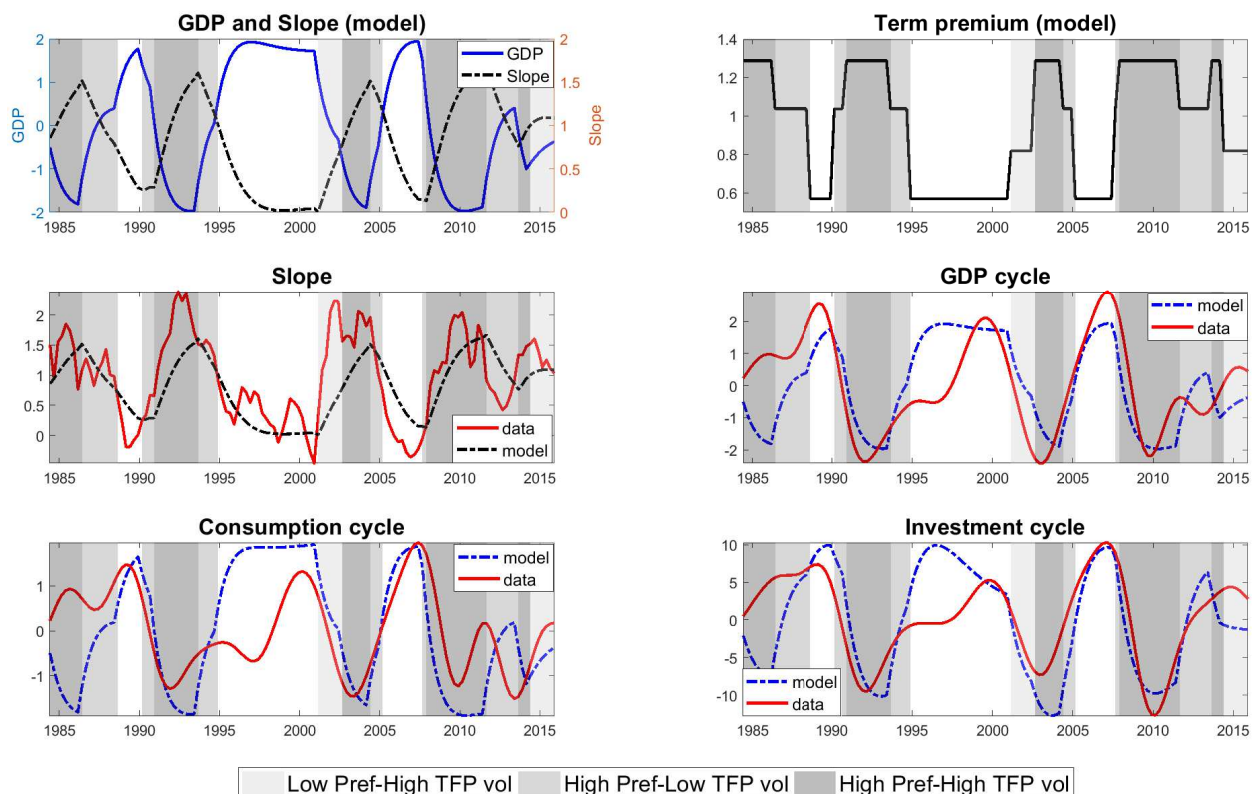


Figure 9: Uncertainty-driven fluctuations. The figure plots selected variables from the simulation of the model with estimated volatility regime sequence (all Gaussian shocks are set to zero in this simulation). Top left panel: simulated path of GDP, expressed in log-deviations from steady state, and slope of the yield curve, expressed as a difference between 5-year yield and 1-year yield. Top right panel: simulated dynamic of nominal term premium in the model, expressed as a difference between 5-year nominal yield and an expected average yield on 1-quarter nominal bond over the next 20 quarters. Middle left panel: simulated slope of the yield curve and slope of the yield curve observed in the data. The subsequent panels plot the model-implied path of GDP, consumption, and investment in response to changes in uncertainty and the cyclical components of the corresponding series in the data (obtained using bandpass filter). Units on the y-axis for macro variables are percentage points (model and data). Units on the y-axis for Term premium and Slope are annualized percent (data and model).

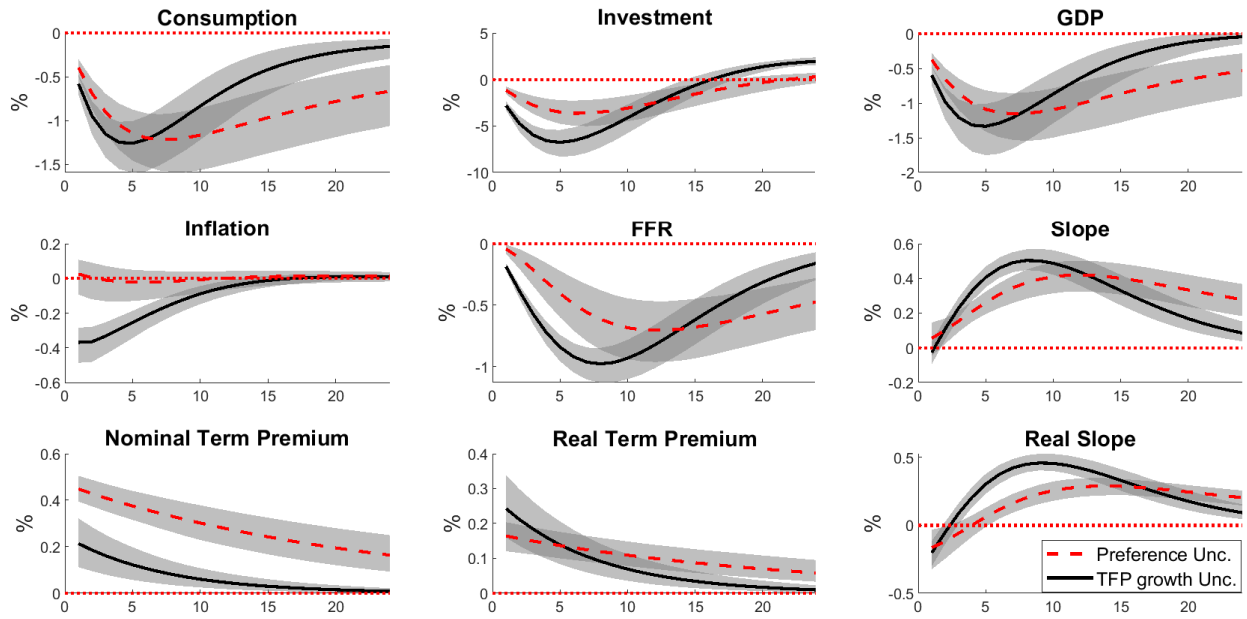


Figure 10: Responses to uncertainty shocks. This figure plots impulse responses to a change from low uncertainty regime to high uncertainty regime for preference and TFP growth shocks. The gray areas represent 90% credible sets. The impulse responses are computed as the change in the expected path of the corresponding variables when the volatility regime changes. The figure plots impulse responses of consumption, investment, GDP, inflation, Fed Funds Rate (1-quarter nominal interest rate), the slope of the yield curve expressed as the difference between 5-year and 1-year nominal yields, nominal term premium defined as the difference between 5-year nominal yield and an expected average yield on 1-quarter nominal bond over the next 20 quarters, the real term premium defined as the difference between 5-year real yield and an expected average yield on 1-quarter real bond over the next 20 quarters, the real slope expressed as the difference between 5-year and 1-year real yields. The units of the y-axis are percentage deviations from a steady state (values for inflation, interest rates and term premia are annualized). Units on the x axis are quarters.

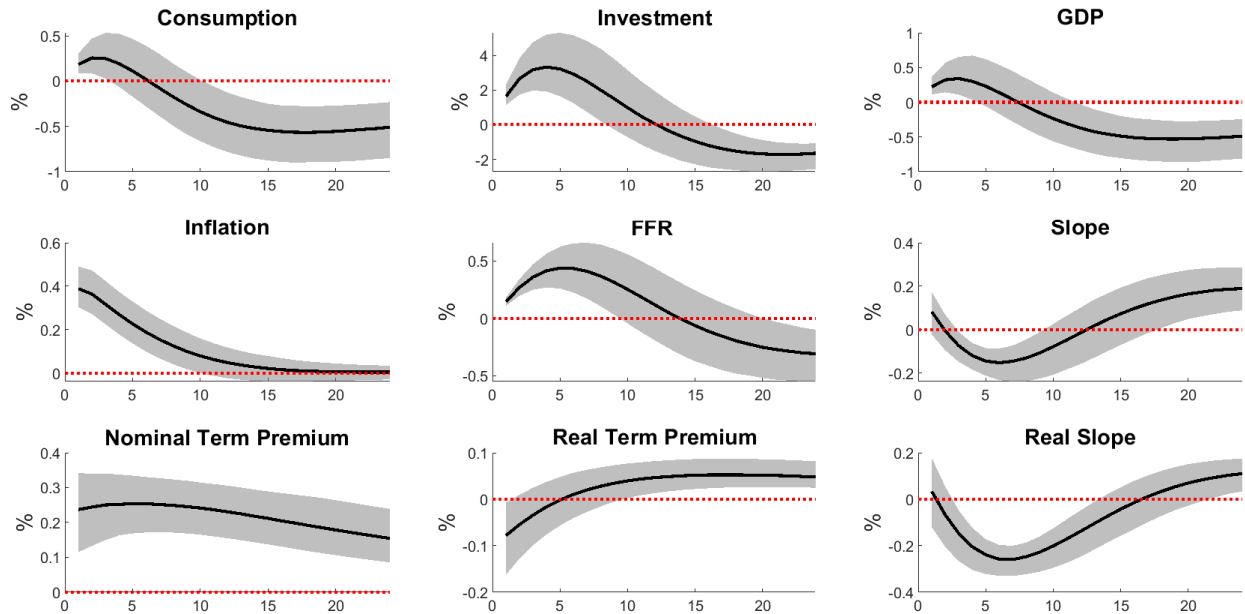


Figure 11: Heterogeneous effects of uncertainty. This figure plots the difference between the impulse responses to demand and supply uncertainty. The gray areas represent 90% credible sets. The impulse responses are computed as the change in the expected path of the corresponding variables when the volatility regime changes. The figure plots impulse responses of consumption, investment, GDP, inflation, Fed Funds Rate (1-quarter nominal interest rate), the slope of the yield curve expressed as the difference between 5-year and 1-year nominal yields, nominal term premium defined as the difference between 5-year nominal yield and an expected average yield on 1-quarter nominal bond over the next 20 quarters, the real term premium defined as the difference between 5-year real yield and an expected average yield on 1-quarter real bond over the next 20 quarters, the real slope expressed as the difference between 5-year and 1-year real yields. The units of the y-axis are percentage deviations from a steady state (values for inflation, interest rates and term premia are annualized). Units on the x axis are quarters.

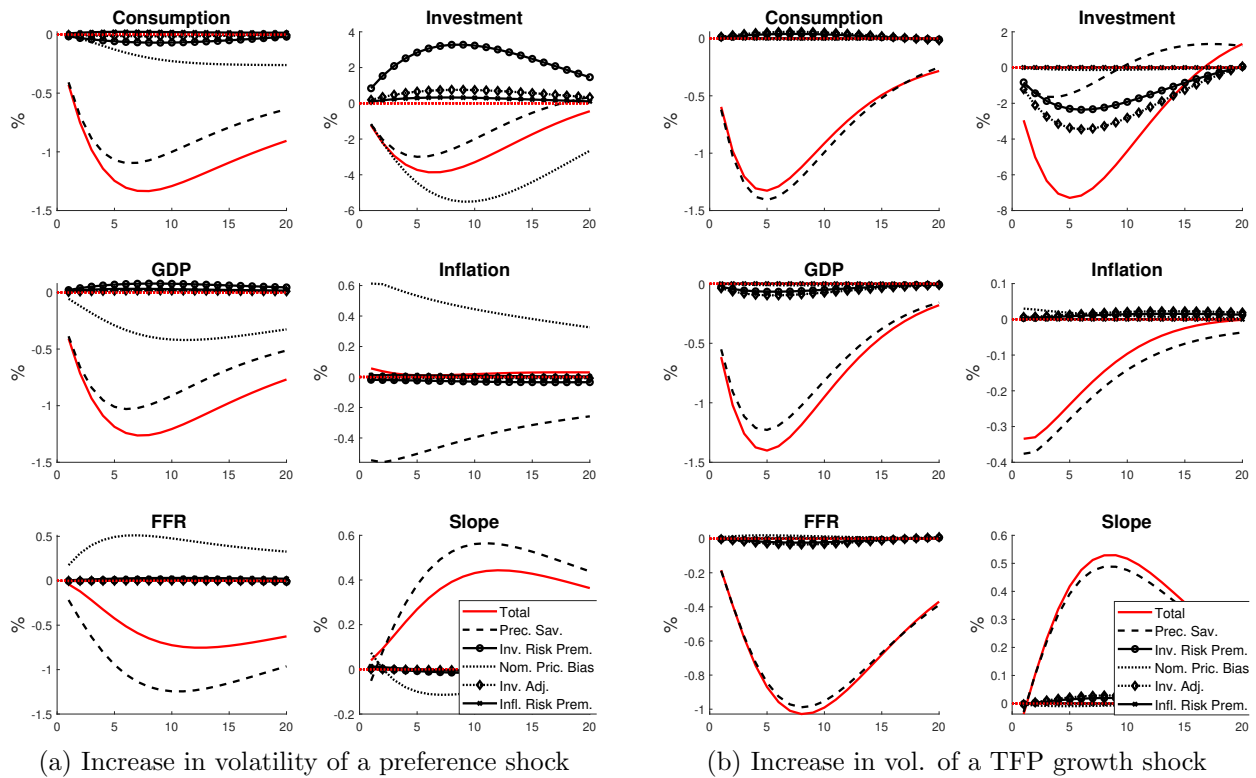


Figure 12: Inspecting the mechanism. The impulse responses represent a change in the expected path of corresponding variables when volatility regime changes. The units of the y-axis are percentage deviations from a steady state (values for inflation and FFR are annualized). Units on the x axis are quarters. The red solid line depicts an IRF to volatility regime change in a benchmark model. The black dashed line shows the contribution of a precautionary savings motive. The black line with circles shows the contribution of the channel operating through change in the risk premium on investment return. The black line with crosses shows the contribution of inflation risk premium channel. The black dotted line shows the contribution of the nominal pricing bias channel. The line with diamond markers shows the contribution of the investment adjustment channel

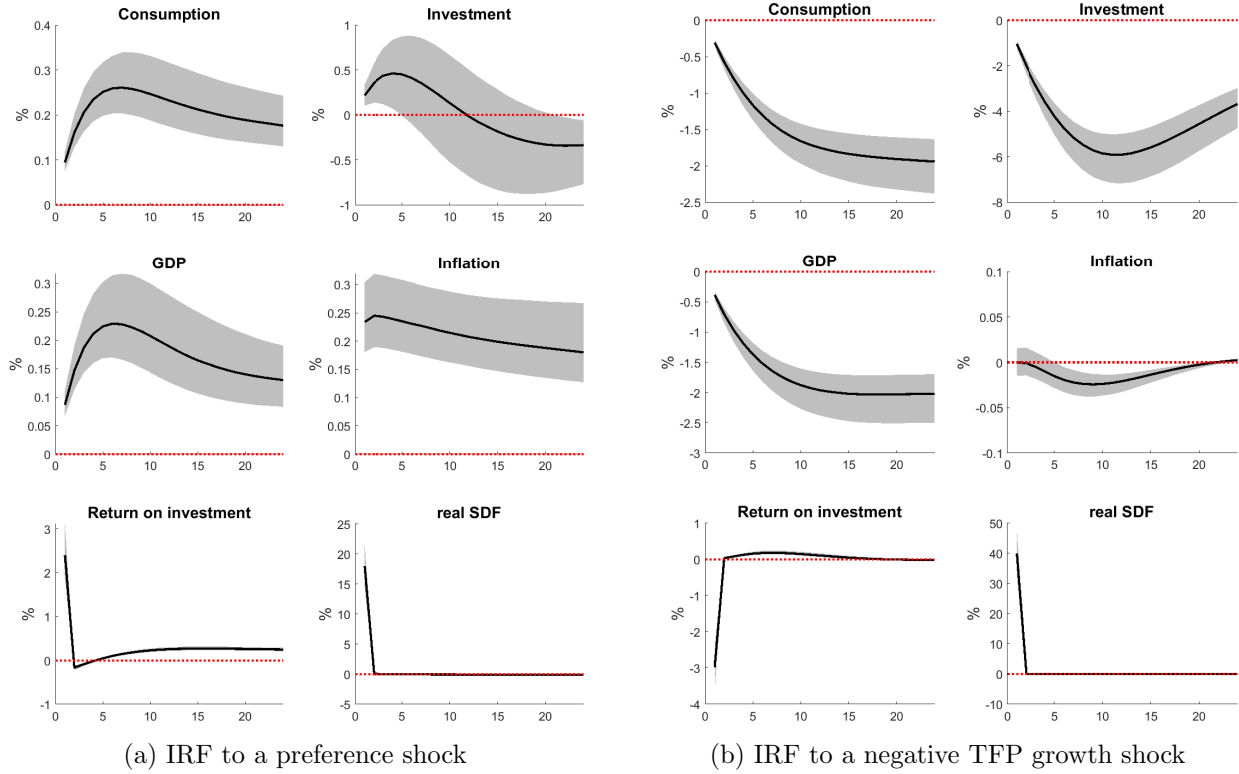


Figure 13: Impulse responses to level preference and TFP shocks. The units of the y-axis are percentage deviations from a steady state (values for inflation and return on investment are annualized). Units on the x axis are quarters.

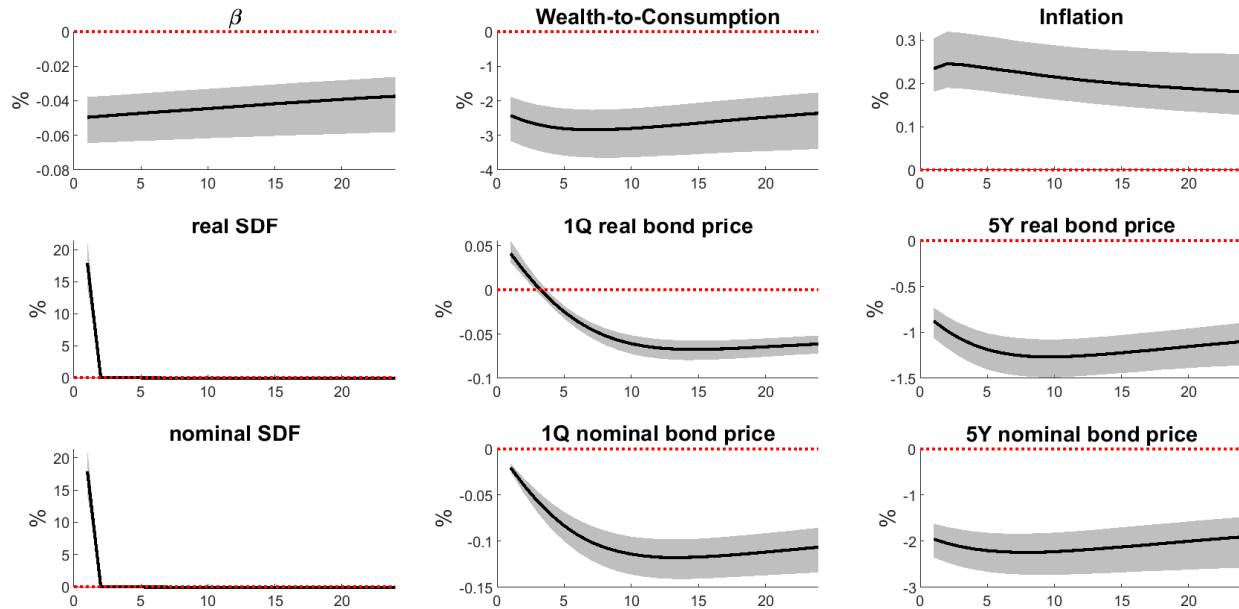


Figure 14: IRF to a preference shock and term premium. The units of the y-axis are percentage deviations from a steady state (values for inflation are annualized). Units on the x axis are quarters. The top left panel plots β_t - loading on continuation utility in Epstein - Zin value function.

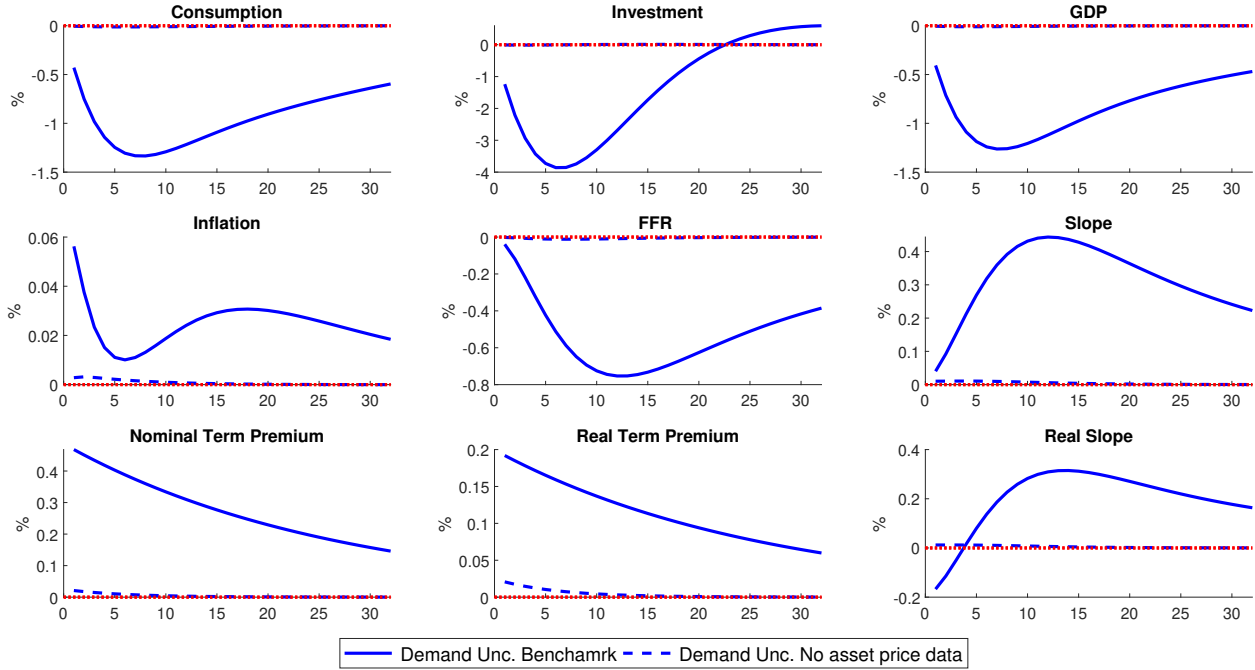


Figure 15: Effects of demand-side uncertainty when removing the term structure. This figure plots the impulse responses to a demand-side uncertainty shock based on the benchmark estimation (solid line) and in an alternative estimation without the term structure (dashed line).

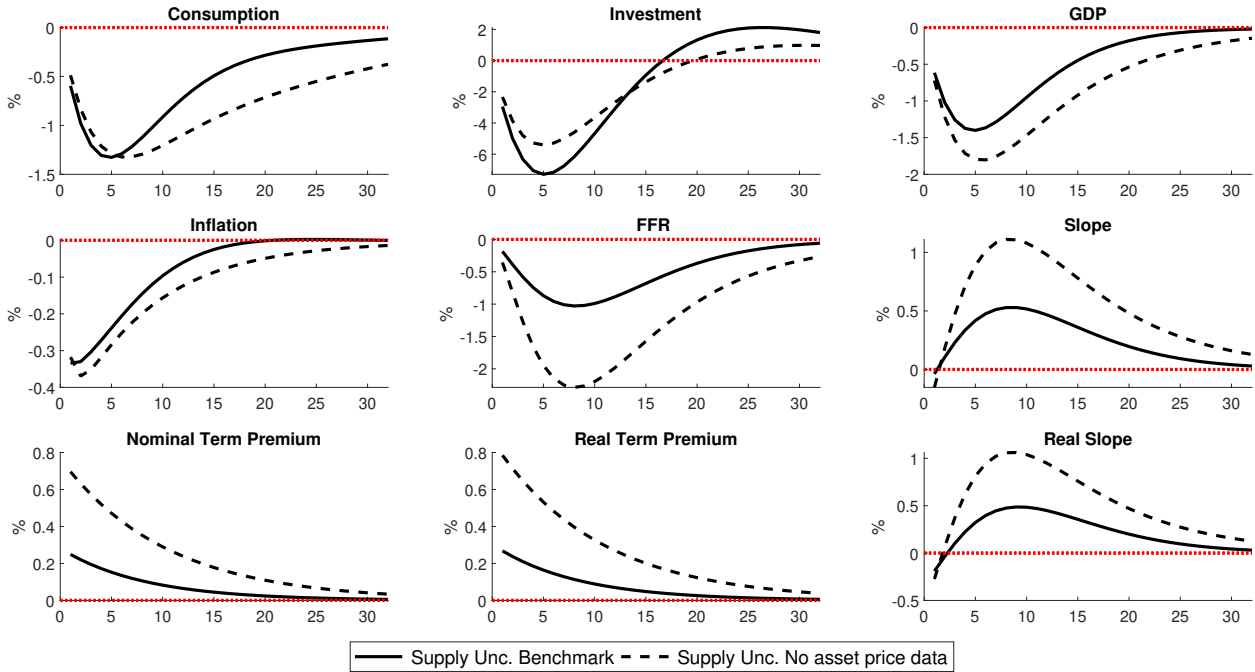


Figure 16: Effects of supply-side uncertainty when removing the term structure. This figure plots the impulse responses to a supply-side uncertainty shock based on the benchmark estimation (solid line) and in an alternative estimation without the term structure (dashed line).

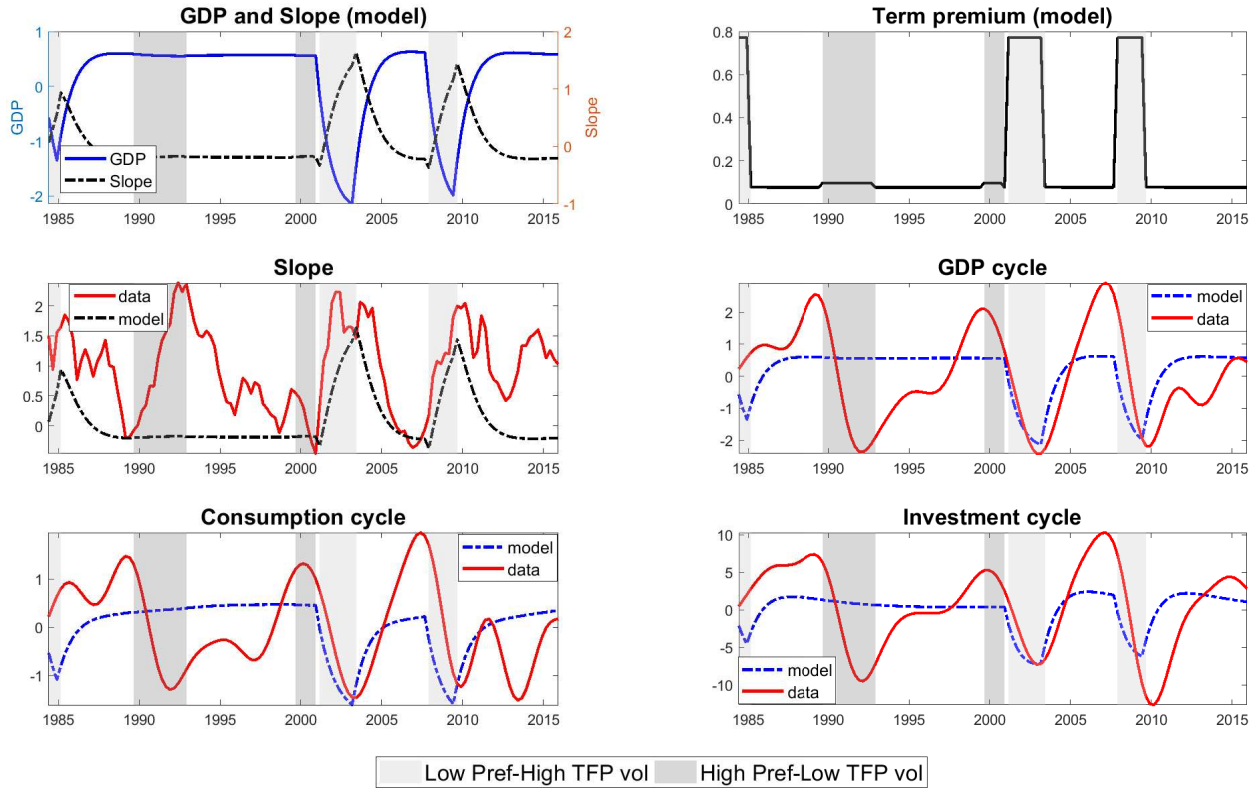


Figure 17: Uncertainty-driven fluctuations in an estimated model without the term structure. The figure plots selected variables from the simulation of the model estimated without asset pricing data. The simulation only considers the effects of uncertainty based on the estimated regime sequence (all Gaussian shocks are set to zero in this simulation). Top left panel: simulated path of GDP, expressed in log-deviations from steady state, and slope of the yield curve, expressed as a difference between 5-year yield and 1-year yield. Top right panel: simulated dynamic of nominal term premium in the model, expressed as a difference between 5-year nominal yield and an expected average yield on 1-quarter nominal bond over the next 20 quarters. Middle left panel: simulated slope of the yield curve and slope of the yield curve observed in the data. The subsequent panels plot the model-implied path of GDP, consumption, and investment in response to changes in uncertainty and the cyclical components of the corresponding series in the data (obtained using bandpass filter). Units on the y-axis for macro variables are percentage points (model and data). Units on the y-axis for Term premium and Slope are annualized percent (data and model).

		Posterior			Prior		
		Mean	5%	95%	Type	Param. 1	Param. 2
<i>Model parameters:</i>							
Subjective discount factor	β	0.9843	0.9818	0.9867	B	0.9800	0.0100
Persist. of preference shock	ρ_β	0.9893	0.9816	0.9965	B	0.5000	0.2000
Degree of habit formation	h	0.8735	0.8508	0.8990	B	0.5000	0.2000
Risk aversion	γ	18.4716	12.6640	24.2366	G	10.0000	5.0000
Elasticity of labor supply	τ	8.2173	5.8233	11.1089	G	5.0000	4.0000
Liquidity preference param.	$100\zeta_B$	0.1557	0.0804	0.2548	G	0.1500	0.0500
Persistence of liquidity shock	ρ_{ζ_B}	0.8580	0.8253	0.8872	B	0.5000	0.2000
Average economic growth	$100\mu^*$	0.1334	0.0268	0.2543	N	0.4000	0.1250
Persist. of TFP growth shock	ρ_x	0.6693	0.5825	0.7373	B	0.1500	0.1000
Capital share in production	α	0.0881	0.0605	0.1160	B	0.3500	0.1000
Average capital depreciation	δ_0	0.0163	0.0139	0.0188	B	0.0350	0.0050
Capital depreciation param.	δ_2	7.4286	3.6509	12.1433	G	10.0000	5.0000
Capital adj. cost parameter	φ_I	7.1240	5.8048	8.7090	G	5.0000	3.0000
Persist. price of invest. shock	ρ_Υ	0.9556	0.9334	0.9762	B	0.5000	0.2000
Slope of phillips curve	$100\kappa_R$	0.0809	0.0599	0.1090	G	5.0000	4.0000
Persistence of markup shock	ρ_χ	0.0406	0.0164	0.0718	B	0.2500	0.1000
Indexation to past inflation	κ_π	0.9439	0.8901	0.9821	B	0.5000	0.2000
Monetary policy inertia	ρ_r	0.8246	0.8004	0.8473	B	0.5000	0.2000
Taylor rule param., inflation	ρ_π	1.6850	1.5089	1.8967	N	2.0000	0.5000
Taylor rule param., output	ρ_y	0.1841	0.1258	0.2457	G	0.5000	0.2000
Inflation in steady state	π_{ss}	0.0091	0.0072	0.0110	N	0.0070	0.0013
Risk adj. of inflation target	$\bar{\pi}^*$	0.0214	0.0161	0.0268	N	0.0050	0.0050
Share of gov.spending	η_g	0.1355	0.0834	0.1999	B	0.1500	0.0500
<i>Standard deviations of shocks:</i>							
Preference, low unc.	$100\sigma_\beta(\xi^D = 1)$	2.4172	1.9365	2.9388	IG	0.0016	3.2652
Preference, high unc.	$100\sigma_\beta(\xi^D = 2)$	4.0592	3.4989	4.7359	IG	0.0016	3.2652
TFP growth, low unc.	$100\sigma_x(\xi^S = 1)$	0.4106	0.3096	0.5349	IG	0.0001	2.5891
TFP growth, high unc.	$100\sigma_x(\xi^S = 2)$	0.8695	0.6599	1.1849	IG	0.0001	2.5891
Monetary policy	$100\sigma_R$	0.1312	0.1162	0.1477	IG	0.0000	2.5891
Markup	$100\sigma_\chi$	0.5077	0.4581	0.5622	IG	0.0016	3.2652
Price of invest.	$100\sigma_{\zeta_\Upsilon}$	0.3456	0.2899	0.4053	IG	0.0000	2.5891
Gov. spending	$100\sigma_g$	2.8867	1.8351	4.3727	IG	0.0016	3.2652
Liquidity	$100\sigma_{\zeta_B}$	0.0899	0.0796	0.1010	IG	0.0000	2.5891
<i>Regime persistence:</i>							
Low demand uncertainty	$H_{1,1}^D$	0.9804	0.9668	0.9913	D	0.8889	0.0721
High demand uncertainty	$H_{2,2}^D$	0.9759	0.9605	0.9878	D	0.8889	0.0721
Low supply uncertainty	$H_{1,1}^S$	0.9270	0.9083	0.9432	D	0.8889	0.0721
High supply uncertainty	$H_{2,2}^S$	0.9413	0.9062	0.9691	D	0.8889	0.0721
<i>Standard deviations of observation errors:</i>							
GDP	σ_y	0.1534	0.0660	0.2323	IG	0.0000	2.0000
Inflation	σ_π	0.0475	0.0260	0.0806	IG	0.0000	2.0000
Investment	σ_i	0.7410	0.6286	0.8738	IG	0.0000	2.0000
Consumption	σ_c	0.2063	0.1709	0.2484	IG	0.0000	2.0000
Price of investment	σ_{π_I}	0.3476	0.2885	0.4115	IG	0.0000	2.0000
1-year yield	σ_{y_1}	0.0103	0.0061	0.0148	IG	0.0000	2.0000
2-year yield	σ_{y_2}	0.0090	0.0069	0.0111	IG	0.0000	2.0000
3-year yield	σ_{y_3}	0.0063	0.0048	0.0079	IG	0.0000	2.0000
4-year yield	σ_{y_4}	0.0090	0.0068	0.0110	IG	0.0000	2.0000
5-year yield	σ_{y_5}	0.0154	0.0127	0.0180	IG	0.0000	2.0000
<i>Priors and posteriors on endogenous variables:</i>							
Inflation	π	2.2564	1.6634	2.8103	N	2	0.5
Equity premium	$E(r^i - r_f)$	0.8761	0.7113	1.0423	N	1	0.1
Real interest rate	$r - \pi$	0.4962	-0.0984	1.0811	N	2	0.5
Slope	$y_5 - y_1$	0.8403	0.7644	0.9172	N	0.9	0.05

Table 1: Mean, 90% error bands and prior distributions of the DSGE model parameters. Column 6 reports type of the prior distribution: B - beta, G - gamma, N - normal, IG - inverse gamma, D - dirichlet. For all distribution types, except inverse gamma, columns 7 and 8 report mean (Param. 1) and standard deviation (Param. 2) of the corresponding distribution. For inverse gamma distribution columns 7 and 8 report shape and scale parameters.

	Unconditional variance decomposition					Uncertainty and business cycle	
	Preference	TFP growth	Monetary	Markup	Uncertainty	Median	Conf. Inter.
GDP	2.60	71.67	1.10	1.78	6.69	23.19	(16.49; 31.15)
Inflation	31.62	0.06	0.04	67.72	0.49	14.47	(11.60; 17.88)
FFR	79.13	1.65	4.46	7.22	6.42	38.26	(29.58; 48.10)
Investment	2.56	70.27	2.56	4.40	16.05	33.76	(24.15; 45.88)
Consumption	4.27	78.64	1.48	2.36	9.05	23.86	(17.35; 32.50)
Slope	16.41	9.43	16.29	27.70	24.75	38.73	(30.43; 47.61)

Table 2: The left panel presents the contribution of the different shocks to the unconditional variance of the macroeconomic variables and the slope of the yield curve. The right panel analyzes the importance of uncertainty shocks in generating business cycle fluctuations with respect to the traditional level shocks. Specifically, we use the posterior mode parameter values to simulate two economies 1,000 times. In the first economy, only uncertainty shocks occur. In the second economy, we have level shocks on top of the same uncertainty shocks. For each simulation and for each variable we extract business cycle fluctuations using a bandpass filter. Finally, for each simulation we compute the ratio between the volatilities of the business cycle fluctuations for the two economies.

	Yields						Slope				
	1Q	1Y	2Y	3Y	4Y	5Y	Total	Risk	Liquidity	Only Pref.	Only TFP
Nominal	2.77	2.88	3.08	3.31	3.53	3.72	0.95	0.89	0.06	0.63	0.41
Real	0.57	0.58	0.71	0.89	1.06	1.21	0.63	0.63	-	0.22	0.43

Table 3: The left panel reports unconditional means of nominal and real yields in the estimated model for the following maturities: 1-quarter and 1,2,3,4,5 years. The right panel reports the slopes of the corresponding term structures, defined as the difference between yields on 5-year and 1-quarter bonds. The first column in the right panel reports the total value, while the next two columns decompose the difference between 5-year and 1-quarter yield into risk premium and liquidity premium. The last two columns report the slope of the term structure in a model with only preference shocks and only TFP growth shocks. Values are annualized percent. The 1-quarter real yield corresponds to the risk free rate $r_{f,t}$ in the model. Real bond prices are computed as $P_{r,t}^{(n)} = E_t[M_{t+1}P_{r,t+1}^{(n-1)}]$, where M_{t+1} is a real SDF.

Uncertainty regime				
Preference uncertainty	Low	Low	High	High
TFP growth uncertainty	Low	High	Low	High
Nominal Term Premium	0.57	0.82	1.04	1.29
Real Term Premium	0.40	0.67	0.59	0.86
Inflation Risk Premium	0.17	0.15	0.44	0.42

Table 4: This table reports nominal and real term premia conditional on the uncertainty regime. The term premium in the model is computed as the difference between 5-year yield and the expected average yield on 1-quarter bond over the next 20 quarters. The inflation risk premium refers to the difference between nominal and real term premia

	Term Premia				Average Slope
	Low	Low	High	High	
Preference Unc.					
TFP growth Unc.	Low	High	Low	High	
Nominal	0.08	0.77	0.10	0.79	0.27
Real	-0.07	0.72	-0.05	0.74	0.10

Table 5: This table reports results from the model estimated without using asset price data. The left panel reports nominal and real term premia conditional on the uncertainty regime. The term premium in the model is computed as the difference between 5-year yield and the expected average yield on the 1-quarter bond over the next 20 quarters. The right panel reports the unconditional slopes of the corresponding term structures, defined as the difference between yields on 5-year and 1-quarter bonds.

A Appendix. First order conditions from the estimated model

The household's intertemporal condition is

$$1 = E_t \left[M_{t+1} \frac{P_t}{P_{t+1}} \right] R_t + \frac{1}{Z_t^*} \bar{\zeta}_B e^{\tilde{\zeta}_{B,t}} (C_t - h\bar{C}_{t-1}) \quad (64)$$

where

$$M_{t+1} = \frac{1 - \beta_{t+1}}{1 - \beta_t} \beta_t \left(\frac{V_{t+1}}{(E_t V_{t+1})^{\frac{1}{1-\gamma}}} \right)^{1-\gamma} \left(\frac{u(C_{t+1}, L_{t+1}, B_{t+2})}{u(C_t, L_t, B_{t+1})} \right)^{-1} \left(\frac{u'_1(C_{t+1}, L_{t+1}, B_{t+2})}{u'_1(C_t, L_t, B_{t+1})} \right) \quad (65)$$

is the stochastic discount factor. The intratemporal condition is

$$W_t = \tau_0 L_t^r (C_t - h\bar{C}_{t-1})$$

First order conditions of the household with respect to a capital utilization choice and investment decision result in the following two equations:

$$\begin{aligned} & \frac{r_t^k}{\delta'(U_t)} \left[1 - \frac{\varphi_I}{2} \left(\frac{I_t}{I_{t-1}} - e^{\mu^*} \Upsilon \right)^2 - \varphi_I \left(\frac{I_t}{I_{t-1}} - e^{\mu^*} \Upsilon \right) \frac{I_t}{I_{t-1}} \right] + \\ & + E_t \left[M_{t+1} \frac{r_{t+1}^k}{\delta'(U_{t+1})} \varphi_I \left(\frac{I_{t+1}}{I_t} - e^{\mu^*} \Upsilon \right) \frac{I_{t+1}^2}{I_t^2} \right] = (e^{\zeta_{r,t}} \Upsilon^t)^{-1} \end{aligned}$$

$$\frac{r_t^k}{\delta'(U_t)} = E_t \left[M_{t+1} \left(r_{t+1}^k U_{t+1} + \frac{r_{t+1}^k}{\delta'(U_{t+1})} (1 - \delta(U_{t+1})) \right) \right]$$

FOC of the intermediate firm i with respect to the price setting decision:

$$\begin{aligned} & \left(1 - \frac{1+\lambda_{p,t}}{\lambda_{p,t}} \right) \left(\frac{P_{i,t}}{P_t} \right)^{-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} \frac{Y_t}{P_t} + W_t \frac{L_{i,t}}{1-\alpha} \left(\frac{1+\lambda_{p,t}}{\lambda_{p,t}} \right) \left(\frac{P_{i,t}}{P_t} \right)^{-1} \frac{1}{P_t} \\ & - \phi_R \left(\frac{P_{i,t}}{\Pi_{ss}^{\kappa\pi} \Pi_{t-1}^{(1-\kappa\pi)} P_{i,t-1}} - 1 \right) \frac{Y_t}{\Pi_{ss}^{\kappa\pi} \Pi_{t-1}^{(1-\kappa\pi)} P_{i,t-1}} + E_t \left[M_{t+1} \phi_R \left(\frac{P_{i,t+1}}{\Pi_{ss}^{\kappa\pi} \Pi_t^{(1-\kappa\pi)} P_{i,t}} - 1 \right) \frac{Y_{t+1} P_{i,t+1}}{\Pi_{ss}^{\kappa\pi} \Pi_t^{(1-\kappa\pi)} P_{i,t}^2} \right] = 0 \end{aligned}$$

FOC of the intermediate firm i with respect to the capital choice:

$$r_t^k = \frac{\alpha}{1-\alpha} W_t \frac{L_{i,t}}{K_{i,t}}$$

B Appendix. Accuracy test

To assess the accuracy of the log-linear solution with risk adjustment employed in this paper, we conduct a Den Haan and Marcet (1994) test for the estimated model. We simulate 5000 economies for 3500 periods and drop first 500 observations using the posterior mode for the parameter values. We use the conditionally linear policy functions for consumption, value function, and nominal interest rate to compute the time path of the corresponding variables. We then use the original non-linear Euler equation (64) to compute realized Euler equation errors:

$$err_{t+1} = M_{t+1} \frac{P_t}{P_{t+1}} R_t + \bar{\zeta}_B e^{\tilde{\zeta}_{B,t}} \left(\hat{C}_t - \frac{1}{\Delta Z_t^*} h \hat{C}_{t-1} \right) - 1 \quad (66)$$

where the stochastic discount factor M_{t+1} is given by (65) and $\hat{C}_t = C_t/Z_t^*$. Under the null hypothesis that the approximation is exact the Euler equation (64) implies $E_t(err_{t+1}) = 0$

We then compute the Den Haan-Marcet statistic (Den Haan and Marcet (1994)):

$$DM = \left[T \left(\sum_{s=1}^T (err_s)/T \right)^2 \right] / \left[\sum_{s=1}^T (err_s^2)/T \right].$$

Under the null hypothesis this statistic has a chi-squared distribution. We obtain 5,000 statistics, one for each simulated economy and we check how many of them are above the 95% and below the 5% chi-squared critical values. Table 6 shows that the percentages of realized test statistics below 5% and above 95% critical values of a χ^2 distribution are very close to the theoretical ones. This result shows that our log-linearization approach with risk adjustment terms provides a good approximation of the model solution.

	Below 5%	Above 95%
Approximate solution	5.40%	5.92%

Table 6: This table reports the proportion of realized Den Haan, Marcet (1994) test statistics below 5% and above 95% critical values of χ^2 distribution. We simulate 5000 economies for 3500 periods and discard the first 500 observations.