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Jesús Fernández-Villaverde
Pablo Guerrón-Quintana
Juan F. Rubio-Ramírez

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Jesús Fernández-Villaverde[1], Pablo Guerrón-Quintana[2] & Juan F. Rubio-Ramírez[3]

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Abstract

This paper develops a particle ..ltering algorithm to estimate dynamic equilibrium models with stochastic volatility using a likelihood-based approach. The algorithm, which exploits the structure and profusion of shocks in stochastic volatility models, is versatile and computationally tractable even in large-scale models. As an application, we use our algorithm and Bayesian methods to estimate a business cycle model of the U.S. economy with both stochastic volatility and parameter drifting in monetary policy. Our application shows the importance of stochastic volatility in accounting for the dynamics of the data.

Keywords: Dynamic equilibrium models, Stochastic volatility, Parameter drifting, Bayesian methods.

JEL: E10, E30, C11.

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1: University of Pennsylvania, NBER, and CEPR, <jesusfv@econ.upenn.edu>.
2: Federal Reserve Bank of Philadelphia, <pablo.guerron@phil.frb.org>.
3: Duke University, Federal Reserve Bank of Atlanta, BBVA Research and FEDEA, <juan.rubio-ramirez@duke.edu>

1. Introduction

This paper develops a particle filtering algorithm to estimate dynamic equilibrium models with stochastic volatility using a likelihood-based approach. The novelty of our algorithm is that it does not require the presence of linear measurement errors to evaluate the likelihood function of the model. In order to do that, we characterize the properties of the solution of these models when approximated with the second-order expansion. As an application of our procedure, we estimate a medium-size business cycle economy.

Our results are useful because, motivated by the findings of Stock and Watson (2002) and Sims and Zha (2006), many recent papers have built dynamic equilibrium models with volatility shocks (also known as uncertainty shocks). Among them, we can highlight Fernández-Villaverde and Rubio-Ramírez (2007), Justiniano and Primiceri (2008), Bloom (2009), and Fernández-Villaverde *et al.* (2010c). In these models, and in the tradition of stochastic volatility (Shephard, 2008), there are two types of shocks: structural shocks (shock to productivity, to preferences, etc.) and volatility shocks (shocks to the standard deviation of the innovations to the structural shocks).

To fulfill the promise in this literature, we need tools to estimate this class of models. However, the task is complicated by the inherent non-linearity that stochastic volatility generates. Linearization is ill-equipped to handle time-varying volatility because it yields certainty-equivalent policy functions. That is, volatility influences neither the agents' decision rules nor the laws of motion of the aggregate variables. Hence, to consider how stochastic volatility affects those factors, it is imperative to employ at least the second-order approximation to the equilibrium dynamics of the economy and to use simulation-based estimators of the likelihood.

To accomplish that last task, one could, in principle, rely on the baseline particle filter presented in Fernández-Villaverde and Rubio-Ramírez (2007). Unfortunately, that version of the particle filter requires, when estimating models with stochastic volatility, the presence of linear measurement errors in observables. Otherwise, we would be forced to solve a large quadratic system of equations with multiple solutions, an endeavor for which there are no suitable algorithms. Although measurement errors are plausible, they complicate identification in small samples and entangle the interpretation of the results.

To get around this problem, we show how to write an alternative particle filter that exploits the structure of the second-order approximation to the equilibrium dynamics of an economy with stochastic volatility without the need of linear measurement errors. Second-order approximations accurately capture important implications of stochastic volatility and are convenient because they are not computationally expensive.

We proceed in two steps. First, we characterize the second-order approximation to the decision rules of a dynamic equilibrium model with stochastic volatility. Second, we demonstrate how to use this characterization to write the alternative particle filter. The key is to show how the quadratic problem associated with the evaluation of the approximated measurement density is reduced to a much simpler linear problem that only involves a matrix inversion. After we have evaluated the likelihood, we can combine it with a prior and a Markov chain Monte Carlo (McMc) algorithm to draw from the posterior distribution.

Our characterization of the second-order approximation to the decision rules is also of interest in itself. Among other things, it is useful to analyze the equilibrium of the model, to explore the shape of its impulse response functions, or to calibrate it. More concretely, we prove that:

1. The first-order approximation to the decision rules of the agents (or any other equilibrium object of interest) does not depend on volatility shocks and they are certainty equivalent.

2. The second-order approximation to the decision rules of the agents only depends on volatility

shocks on terms where volatility is multiplied by the innovation to its own structural shock. For instance, if we have a productivity shock and a volatility shock to it, the only non-zero term where the volatility shock to productivity appears is the one where the volatility shock multiplies the innovation to the productivity shock. Thus, only a few of the terms in the second-order approximation are non-zero.

3. The perturbation parameter will only appear in a non-zero term where it is raised to a square. This term is a constant that corrects for precautionary behavior induced by risk.

As an application, we estimate a business cycle model of the U.S. economy. The model incorporates stochastic volatility in the shocks that drive its dynamics and parameter drifting in the parameters that control monetary policy. In that way, we include two of the main mechanisms that researchers have highlighted to account for the time-varying volatility of U.S. time series - heteroscedastic shocks and parameter drifting- and let the likelihood decide which of them better accounts for the data. Last, we have a model that is as rich as many of the models employed in modern quantitative macroeconomics. While estimating such a large model is a computational challenge, we wanted to demonstrate that our procedure is of practical use and to make our application a blueprint for the estimation of other dynamic equilibrium models.

Our main empirical findings are as follows. First, the posterior distribution of the parameters puts most of its mass in areas that denote a fair amount of stochastic volatility. Second, a model comparison exercise indicates that, even after controlling for stochastic volatility, the data prefer a specification where monetary policy changes over time. This finding should not be interpreted, though, as implying that volatility shocks did not play a role. It means, instead, that a successful model of the U.S. economy requires the presence of both stochastic volatility and parameter drifting, a result that challenges the results of Sims and Zha (2006). Finally, we document the evolution of the structural shocks, of stochastic volatility, and the parameters of monetary policy. We emphasize the confluence, during the 1970s, of times of high volatility and weak responses to inflation, and, during the 1990s, of positive structural shocks and low volatility even if monetary policy was weaker than often argued. In the appendix, we construct counterfactual histories of the U.S. data by varying some aspect of the model such as shutting down time-varying volatility or imposing alternative monetary policies.

An alternative to our stochastic volatility framework would be to work with Markov regime-switching models such as those of Bianchi (2009) or Farmer *et al.* (2009). These models provide a promising extra degree of flexibility in modelling aggregate dynamics. In fact, some of the fast changes in policy parameters that we document in our empirical section suggest that discrete jumps could be a good representation of the data. We hope to undertake in the future a more careful assessment of the advantages and disadvantages of stochastic volatility versus Markov regime-switching models.

Finally, even if the motivation for our approach and the application belong to macroeconomics, the tools we present are not specific to that field. One can think about the importance of estimating dynamic equilibrium models with stochastic volatility in many other fields such as finance (Bansal and Yaron, 2004) or international economics (Fernández-Villaverde *et al.*, 2010c).

The rest of the paper is organized as follows. Section 2 introduces a generic dynamic equilibrium model with stochastic volatility to fix notation and discuss how to solve it. Section 3 explains the evaluation of the likelihood of the model. Section 4 compares our approach with continuous-time methods. Section 5 presents our application. Section 6 concludes. An extensive technical appendix includes additional material.

2. Dynamic Equilibrium Models with Stochastic Volatility

2.1. The Model

The set of equilibrium conditions of a wide class of dynamic equilibrium models can be written as

$$\mathbb{E}_t f\left(\mathcal{Y}_{t+1}, \mathcal{Y}_t, \mathcal{S}_{t+1}, \mathcal{S}_t, \mathcal{Z}_{t+1}, \mathcal{Z}_t; \gamma\right) = 0, \tag{1}$$

where $\mathbb{E}_t$ is the conditional expectation operator at time t, $\mathcal{Y}_t = (\mathcal{Y}_{1t}, \mathcal{Y}_{2t}, \ldots, \mathcal{Y}_{kt})'$ is the $k \times 1$ vector of observables at time t, $\mathcal{S}_t = (\mathcal{S}_{1t}, \mathcal{S}_{2t}, \ldots, \mathcal{S}_{nt})'$ is the $n \times 1$ vector of endogenous states at time t, $\mathcal{Z}_t = (\mathcal{Z}_{1t}, \mathcal{Z}_{2t}, \ldots, \mathcal{Z}_{mt})'$ is the $m \times 1$ vector of structural shocks at time t, f maps $\mathbb{R}^{2(k+n+m)}$ into $\mathbb{R}^{k+n+m}$, and γ is the $n_\gamma \times 1$ vector of parameters that describe preferences and technology. In this paper, γ is also the vector of parameters to be estimated.

We will consider models where $\mathcal{Z}_{it+1}$ follow a stochastic volatility process of the form

$$\mathcal{Z}_{it+1} = \rho_i \mathcal{Z}_{it} + \Lambda \sigma_i \sigma_{it+1} \varepsilon_{it+1} \tag{2}$$

for all $i \in \{1, \ldots, m\}$, where Λ is a perturbation parameter, σ_i is the mean volatility, and $\log \sigma_{it+1}$, the percentage deviation of the standard deviation of the innovations to the structural shocks with respect to its mean, evolves as

$$\log \sigma_{it+1} = \vartheta_i \log \sigma_{it} + \Lambda \left(1 - \vartheta_i^2\right)^{\frac{1}{2}} \eta_i u_{it+1} \tag{3}$$

for all $i \in \{1, \ldots, m\}$. The combination of levels in (2) and logs in (3) ensures a positive σ_{it+1}. We multiply the innovation in (3) by $\left(1 - \vartheta_i^2\right)^{\frac{1}{2}}$ to normalize its size by the persistence of σ_{it}. It will be clear momentarily why we specify (2) and (3) in terms of the perturbation parameter Λ.

It is also convenient to write, for all $i \in \{1, \ldots, m\}$, the laws of motions for $\mathcal{Z}_{it}$ and $\log \sigma_{it}$

$$\mathcal{Z}_{it} = \rho_i \mathcal{Z}_{it-1} + \sigma_i \sigma_{it} \varepsilon_{it} \tag{4}$$

and

$$\log \sigma_{it} = \vartheta_i \log \sigma_{it-1} + \left(1 - \vartheta_i^2\right)^{\frac{1}{2}} \eta_i u_{it} \tag{5}$$

Note that Λ appears only in equations (2) and (3) but not in equations (4) and (5). This is because this parameter is used to eliminate, when we later determine the point around which we approximate the equilibrium dynamics of the model, uncertainty about the future. Given the information set in equation (1), there is uncertainty about both $\mathcal{Z}_{it+1}$ and $\log \sigma_{it+1}$ for all $i \in \{1, \ldots, m\}$, but there is no uncertainty about either $\mathcal{Z}_{it}$ or $\log \sigma_{it}$ for any $i \in \{1, \ldots, m\}$.

Let $\Sigma_t = (\log \sigma_{1t}, \ldots, \log \sigma_{mt})'$ be the $m \times 1$ vector of volatility shocks, $\mathcal{E}_t = (\varepsilon_{1t}, \ldots, \varepsilon_{mt})'$ the $m \times 1$ vector of innovations to the structural shocks, and $\mathcal{U}_t = (u_{1t}, \ldots, u_{mt})'$ the $m \times 1$ vector of innovations to the volatility shocks. We assume that $\mathcal{E}_t \sim \mathcal{N}(\mathbf{0}, \mathbf{I})$ and $\mathcal{U}_t \sim \mathcal{N}(\mathbf{0}, \mathbf{I})$, where $\mathbf{0}$ is an $m \times 1$ vector of zeros and $\mathbf{I}$ is an $m \times m$ identity matrix. To ease notation, we assume that all structural shocks face volatility shocks, that the volatility shocks are uncorrelated, and that $\mathcal{E}_t$ and $\mathcal{U}_t$ are normally distributed. It is straightforward, yet cumbersome, to generalize the notation to other cases. In particular, as we will see below, to implement our particle filter, we only need to be able to simulate $\mathcal{E}_t$ and evaluate the density of $\mathcal{U}_t$.

2.2. The Solution

Given equations (1)-(5), the solution to the model -if one exists- that embodies equilibrium dynamics (that is, agents' optimization and market clearing conditions) is characterized by a policy function describing the evolution of the endogenous state variables

$$\mathcal{S}_{t+1} = h\left(\mathcal{S}_t, \mathcal{Z}_{t-1}, \Sigma_{t-1}, \mathcal{E}_t, \mathcal{U}_t, \Lambda; \gamma\right), \tag{6}$$

and two policy functions describing the law of motion of the observables

$$\mathcal{Y}_t = g\left(\mathcal{S}_t, \mathcal{Z}_{t-1}, \Sigma_{t-1}, \mathcal{E}_t, \mathcal{U}_t, \Lambda; \gamma\right) \tag{7}$$

and

$$\mathcal{Y}_{t+1} = g\left(\mathcal{S}_{t+1}, \mathcal{Z}_t, \Sigma_t, \Lambda\mathcal{E}_{t+1}, \Lambda\mathcal{U}_{t+1}, \Lambda; \gamma\right), \tag{8}$$

together with equations (4) and (5) describing the laws of motion of the structural and volatility shocks. The policy functions h and g map $\mathbb{R}^{n+4m+1}$ into $\mathbb{R}^n$ and $\mathbb{R}^k$, respectively, and are indexed by γ.

For our purposes, it is important to define the steady state of the model. Our assumptions about the stochastic processes imply that, in the steady state, $\mathcal{Z} = \mathbf{0}$ and $\Sigma = \mathbf{0}$. Given γ and equations (1)-(8), the steady state of the model is a $k \times 1$ vector of observables $\mathcal{Y} = (\mathcal{Y}_1, \mathcal{Y}_2, \ldots, \mathcal{Y}_k)'$ and an $n \times 1$ vector of endogenous states $\mathcal{S} = (\mathcal{S}_1, \mathcal{S}_2, \ldots, \mathcal{S}_n)'$ such that

$$f\left(g\left(h\left(\mathcal{S}, \mathbf{0}, \mathbf{0}, \mathbf{0}, \mathbf{0}, 0; \gamma\right), \mathbf{0}, \mathbf{0}, \mathbf{0}, \mathbf{0}, 0; \gamma\right), g\left(\mathcal{S}, \mathbf{0}, \mathbf{0}, \mathbf{0}, \mathbf{0}, 0; \gamma\right), h\left(\mathcal{S}, \mathbf{0}, \mathbf{0}, \mathbf{0}, \mathbf{0}, 0; \gamma\right), \mathcal{S}, \mathbf{0}, \mathbf{0}; \gamma\right) = 0. \tag{9}$$

In addition, in the steady state, the following two relationships hold

$$\mathcal{S} = h\left(\mathcal{S}, \mathbf{0}, \mathbf{0}, \mathbf{0}, \mathbf{0}, 0; \gamma\right), \tag{10}$$

and

$$\mathcal{Y} = g\left(\mathcal{S}, \mathbf{0}, \mathbf{0}, \mathbf{0}, \mathbf{0}, 0; \gamma\right). \tag{11}$$

Note that, if $\Lambda = 0$, the model is in the steady state, since we eliminate any uncertainty about the future. If $\Lambda \neq 0$, the model is not in the steady state and conditions (9)-(11) do not hold. For instance, in general $\mathcal{S} \neq h\left(\mathcal{S}, \mathbf{0}, \mathbf{0}, \mathbf{0}, \mathbf{0}, \Lambda; \gamma\right)$ because of the precautionary behavior of agents.

2.3. The State-Space Representation

Given the solution to the model -the policy functions (6)-(8) together with equations (4) and (5)- we can characterize the equilibrium dynamics of the model by its state-space representation written in terms of the transition and the observation equations.

We stack equations (4) to (6) in a transition equation

$$\mathbb{S}_{t+1} = \widetilde{h}\left(\mathbb{S}_t, \Lambda; \gamma\right) + \Xi \mathbb{W}_{t+1} \tag{12}$$

that describe the evolution of the states (endogenous states, structural shocks, volatility shocks, and their innovations) as a function of lag states, the perturbation parameter, and the vector of parameters, where $\mathbb{S}_t = \left(\mathcal{S}'_t, \mathcal{Z}'_{t-1}, \Sigma'_{t-1}, \mathcal{E}'_t, \mathcal{U}'_t\right)'$ is the $(n + 4m) \times 1$ vector of the states and $\widetilde{h}$ maps $\mathbb{R}^{n+4m+1}$ into $\mathbb{R}^{n+4m}$. Also, $\mathbb{W}_{t+1} = \left(\mathcal{W}'_{1t+1}, \mathcal{W}'_{2t+1}\right)'$ is a $2m \times 1$ vector of random variables, $\mathcal{W}_{1t+1}$ and $\mathcal{W}_{2t+1}$ are $m \times 1$ vectors with distributions $\mathcal{W}_{1t+1} \sim \mathcal{N}\left(\mathbf{0}, \mathbf{I}\right)$ and $\mathcal{W}_{2t+1} \sim \mathcal{N}\left(\mathbf{0}, \mathbf{I}\right)$, and Ξ is a $(n + 4m) \times 2m$ matrix with the the top $n + 2m$ rows equal to zero and the bottom $2m \times 2m$ matrix equal to the identity matrix. $\mathcal{W}_{1t+1}$ and $\mathcal{W}_{2t+1}$ share distributions with $\mathcal{E}_{t+1}$ and $\mathcal{U}_{t+1}$ respectively. If we were to change distributions for either $\mathcal{E}_{t+1}$ or $\mathcal{U}_{t+1}$ we would need to do the same with $\mathcal{W}_{1t+1}$ and $\mathcal{W}_{2t+1}$. Let us define $n_s = n + 4m$. The linearity of the second term of the right-hand side is a consequence of the autoregressive specification of the structural shocks and the evolution of their volatilities. However, through the function $\widetilde{h}$, those shocks and their volatilities can affect $\mathcal{S}_{t+1}$ non-linearly.

The measurement equation uses the policy function (7) to describe the relationship of the observables with the states, the perturbation parameter, and the vector of parameters

$$\mathcal{Y}_t = g\left(\mathbb{S}_t, \Lambda; \gamma\right). \tag{13}$$

2.4. Approximating the State-Space Representation

In general, when we deal with the class of dynamic equilibrium models with stochastic volatility, the policy functions h and g cannot be found explicitly. Thus, we cannot build the state-space representation described by (12) and (13). Instead, we will approximate numerically the solution of the model and use the result to generate an approximated state-space representation.

There are many different solution algorithms for dynamic equilibrium models. Among them, the perturbation method has emerged as a popular way (see Judd and Guu, 1997 and Aruoba *et al.*, 2006) to obtain higher-order Taylor series approximations to the policy functions (6)-(7) together with equations (4) and (5) around the steady state. We also get the Taylor expansion of (4) because it is a non-linear function. Beyond being extremely fast for systems with a large number of state variables, perturbations are highly accurate even far away from the perturbation point (Aruoba, *et al.*, 2006, and, for cases with stochastic volatility, Caldara *et al.*, 2012).

The perturbation method allows the researcher to approximate the solution to the model up to any order. Since we want to analyze models with volatility shocks, we must go beyond a first-order approximation. First-order approximations are certainty equivalent, and hence, they are silent about stochastic volatility. As we will see in section 3.1, volatility shocks only appear starting in the second-order approximation. But since we want to evaluate the likelihood function, we stop at a second-order approximation. Because of dimensionality issues, a higher-order approximation would make the evaluation of the likelihood function exceedingly challenging for current computers for models with a reasonable number of state variables.

Given a second-order approximation to the policy functions (6)-(7) together with equations (4) and (5) around the steady state, the approximated state-space representation can be written in terms of two equations: the approximated transition equation and the approximated measurement equation. The approximated transition equation is

$$\widehat{\mathbb{S}}_{t+1} = \begin{pmatrix} \Psi^1_{s,1}\widehat{\mathbb{S}}_t \\ \vdots \\ \Psi^1_{s,n_s}\widehat{\mathbb{S}}_t \end{pmatrix} + \frac{1}{2}\begin{pmatrix} \widehat{\mathbb{S}}_t'\Psi^2_{s,1}\widehat{\mathbb{S}}_t \\ \vdots \\ \widehat{\mathbb{S}}_t'\Psi^2_{s,n_s}\widehat{\mathbb{S}}_t \end{pmatrix} + \frac{1}{2}\begin{pmatrix} \Psi^\Lambda_{s,1} \\ \vdots \\ \Psi^\Lambda_{s,n_s} \end{pmatrix} + \Xi\mathbb{W}_{t+1} \tag{14}$$

where $\widehat{\mathbb{S}}_t = \mathbb{S}_t - \mathbb{S}$ is the $n_s \times 1$ vector of deviations of the states from their steady-state value and $\mathbb{S} = (\mathcal{S}', \mathbf{0}', \mathbf{0}', \mathbf{0}', \mathbf{0}')'$. The approximated measurement equation is

$$\mathcal{Y}_t - \mathcal{Y} = \begin{pmatrix} \Psi^1_{y,1}\widehat{\mathbb{S}}_t \\ \vdots \\ \Psi^1_{y,k}\widehat{\mathbb{S}}_t \end{pmatrix} + \frac{1}{2}\begin{pmatrix} \widehat{\mathbb{S}}_t'\Psi^2_{y,1}\widehat{\mathbb{S}}_t \\ \vdots \\ \widehat{\mathbb{S}}_t'\Psi^2_{y,k}\widehat{\mathbb{S}}_t \end{pmatrix} + \frac{1}{2}\begin{pmatrix} \Psi^\Lambda_{y,1} \\ \vdots \\ \Psi^\Lambda_{y,k} \end{pmatrix}. \tag{15}$$

where $\mathcal{Y}$ is the steady-state value of $\mathcal{Y}_t$.

In these equations, $\Psi^1_{s,i}$ is a $1 \times n_s$ vector and $\Psi^2_{s,i}$ is an $n_s \times n_s$ matrix for $i = 1, \ldots, n_s$. The first term is the linear approximation to the transition equation for the states, while the second term is the quadratic component of the second-order approximation. Similarly, $\Psi^1_{y,i}$ is a $1 \times n_s$ vector and $\Psi^2_{y,i}$ an $n_s \times n_s$ matrix for $i = 1, \ldots, k$. The interpretation of each term is the same as before, but for the measurement equations. The term $\Psi^\Lambda_{s,i}$ is the constant that appears in the second-order perturbation that corrects for risk in the evolution of state $i = 1, \ldots, n_s$. Similarly, the term $\Psi^{\Lambda}_{y,i}$ is the constant correction for risk of observable $i = 1, \ldots, k$. All these vectors and matrices are non-linear functions of γ. It is important to emphasize that we are not assuming the presence of any measurement error. We will return to this point in a few paragraphs.

3. Stochastic Volatility and Evaluation of the Likelihood

In this section, we explain how to evaluate the likelihood function of our class of dynamic equilibrium models with volatility shocks in equation (1) using the approximated transition and the measurement equations (14) and (15). If we allow $\mathbb{Y}_t$ to be the data counterpart of our observables $\mathcal{Y}_t$, and $\mathbb{Y}^t = (\mathbb{Y}_1, \ldots, \mathbb{Y}_t)$ (with $\mathbb{Y}^0 = \{\varnothing\}$) to be their history up to time t, given γ, we can write the likelihood of $\mathbb{Y}^T$ as

$$\prod_{t=1}^{T} p\left(\mathcal{Y}_t = \mathbb{Y}_t | \mathbb{Y}^{t-1}; \gamma\right),$$

where

$$p\left(\mathcal{Y}_t = \mathbb{Y}_t | \mathbb{Y}^{t-1}; \gamma\right) =$$

$$\int\int\int\int p\left(\mathcal{Y}_t = \mathbb{Y}_t | \mathcal{S}_t, \mathcal{Z}_{t-1}, \Sigma_{t-1}, \mathcal{E}_t; \gamma\right) p\left(\mathcal{S}_t, \mathcal{Z}_{t-1}, \Sigma_{t-1}, \mathcal{E}_t | \mathbb{Y}^{t-1}; \gamma\right) d\mathcal{S}_t d\mathcal{Z}_{t-1} d\Sigma_{t-1} d\mathcal{E}_t \quad (16)$$

for all $t \in \{2, \ldots, T\}$ and

$$p\left(\mathcal{Y}_1 = \mathbb{Y}_1; \gamma\right)$$

$$= \int\int\int\int p\left(\mathcal{Y}_1 = \mathbb{Y}_1 | \mathcal{S}_1, \mathcal{Z}_0, \Sigma_0, \mathcal{E}_1; \gamma\right) p\left(\mathcal{S}_1, \mathcal{Z}_0, \Sigma_0, \mathcal{E}_1; \gamma\right) d\mathcal{S}_1 d\mathcal{Z}_0 d\Sigma_0 d\mathcal{E}_1. \quad (17)$$

Note that the $\mathcal{U}_t$'s do not show up in these two expressions. It will be momentarily clear why this comes directly from our procedure below to evaluate the likelihood.

Computing this likelihood is difficult. Since we do not have analytic forms for the terms inside the integral, it cannot be evaluated exactly and deterministic numerical integration algorithms are too slow for practical use (we have four integrals per period over large dimensions). As a feasible alternative, we will show how to use a simple particle filter to obtain a simulation-based estimate of (16). Künsch (2005) proves, under weak conditions, that the particle filter delivers a consistent estimator of the likelihood function and that a central limit theorem applies. A particle filter is a sequential simulation device for filtering of non-linear and/or non-Gaussian space models (Pitt and Shephard, 1999, and Doucet *et al.*, 2001). In economics the particle filter was introduced by Fernández-Villaverde and Rubio-Ramírez (2007).

As mentioned before, the particle filter has minimal requirements: the ability to evaluate the approximated measurement density associated with the approximated measurement equation, to simulate from the approximated dynamics of the state using the approximated transition equation, and to draw from the unconditional density of the states implied by the approximated transition equation. Usually, the first requirement is the hardest. These three requirements are formally described in the following assumption.

Assumption 1. *To implement the particle filter, we assume that:*

1. *We can evaluate the approximated measurement density*

$$p\left(\mathcal{Y}_t = \mathbb{Y}_t | \mathcal{S}_t, \mathcal{Z}_{t-1}, \Sigma_{t-1}, \mathcal{E}_t; \gamma\right).$$

2. *We can simulate from the approximated transition equation*

$$\left(\mathcal{S}'_{t+1}, \mathcal{Z}'_t, \Sigma'_t, \mathcal{E}'_{t+1}\right)' \mid \left(\mathcal{S}'_t, \mathcal{Z}'_{t-1}, \Sigma'_{t-1}, \mathcal{E}'_t\right)', \mathcal{F}\left(\mathbb{Y}^t\right); \gamma$$

for all $t \in \{1, \ldots, T\}$, *where* $\mathcal{F}\left(\mathbb{Y}^t\right)$ *is the filtration of* $\mathbb{Y}^t$.

3. *We can draw from the unconditional distribution implied by the approximated transition equation*

$$p\left(\mathcal{S}_t, \mathcal{Z}_{t-1}, \Sigma_{t-1}, \mathcal{E}_t; \gamma\right).$$

The second requirement asks for the filtration of $\mathbb{Y}^t$, $\mathcal{F}\left(\mathbb{Y}^t\right)$, because we will need to evaluate the volatility shocks. The last requirement can be easily implemented using the results in Santos and Peralta-Alva (2005). Given our assumption about $\mathcal{E}_{t+1}$ and the quadratic form of the approximated transition equation (14), the second requirement easily holds. A key novelty of this paper is that we show how the class of dynamic equilibrium models with volatility shocks considered here also satisfies the first requirement.

For our class of models, conditional on having N draws of $\left\{s_t^i, z_{t-1}^i, \sigma_{t-1}^i, \varepsilon_t^i\right\}_{i=1}^N$ from the density $p\left(\mathcal{S}_t, \mathcal{Z}_{t-1}, \Sigma_{t-1}, \mathcal{E}_t | \mathbb{Y}^{t-1}; \gamma\right)$, each integral (16) can be consistently approximated by

$$p\left(\mathcal{Y}_t = \mathbb{Y}_t | \mathbb{Y}^{t-1}; \gamma\right) \simeq \frac{1}{N} \sum_{i=1}^{N} p\left(\mathcal{Y}_t = \mathbb{Y}_t | s_t^i, z_{t-1}^i, \sigma_{t-1}^i, \varepsilon_t^i; \gamma\right) \tag{18}$$

for all $t \in \{2, \ldots, T\}$. For $t = 1$, we need N draws from the density $p\left(\mathcal{S}_t, \mathcal{Z}_{t-1}, \Sigma_{t-1}, \mathcal{E}_t; \gamma\right)$, so that the integral (17) can be consistently approximated by

$$p\left(\mathcal{Y}_1 = \mathbb{Y}_1; \gamma\right) \simeq \frac{1}{N} \sum_{i=1}^{N} p\left(\mathcal{Y}_1 = \mathbb{Y}_1 | s_1^i, z_0^i, \sigma_0^i, \varepsilon_1^i; \gamma\right). \tag{19}$$

We know that we can make the draws because requirement 3 in assumption 1 holds.

In our framework, checking whether requirement 1 in assumption 1 holds means checking whether we can evaluate, for each draw in $\left\{s_t^i, z_{t-1}^i, \sigma_{t-1}^i, \varepsilon_t^i\right\}_{i=1}^N$, the approximated measurement density

$$p\left(\mathcal{Y}_t = \mathbb{Y}_t | s_t^i, z_{t-1}^i, \sigma_{t-1}^i, \varepsilon_t^i; \gamma\right) \tag{20}$$

for all $t \in \{1, \ldots, T\}$. This evaluation step is crucial, not only because it is required to compute (18) and (19) but also because, as we will explain momentarily, our particle filter needs to evaluate (20) to resample from $p\left(\mathcal{S}_t, \mathcal{Z}_{t-1}, \Sigma_{t-1}, \mathcal{E}_t | \mathbb{Y}^{t-1}; \gamma\right)$ and get draws from $p\left(\mathcal{S}_{t+1}, \mathcal{Z}_t, \Sigma_t, \mathcal{E}_{t+1} | \mathbb{Y}^t; \gamma\right)$ to obtain $\left\{s_t^i, z_{t-1}^i, \sigma_{t-1}^i, \varepsilon_t^i\right\}_{i=1}^N$ for all $t \in \{2, \ldots, T\}$ recursively.

To check how we can evaluate the approximated measurement density (20), we rewrite (15) in terms of draws $\left(s_t^{i\prime}, z_{t-1}^{i\prime}, \sigma_{t-1}^{i\prime}, \varepsilon_t^{i\prime}\right)'$ and $\mathbb{Y}_t$, instead of $\left(\mathcal{S}_t', \mathcal{Z}_{t-1}', \Sigma_{t-1}', \mathcal{E}_t'\right)'$ and $\mathcal{Y}_t$. Thus, the approximated measurement equation (15) becomes

$$\mathbb{Y}_t - \mathcal{Y} = \begin{pmatrix} \Psi_{y,1}^1 \widehat{\mathbb{S}}_t^i \\ \vdots \\ \Psi_{y,k}^1 \widehat{\mathbb{S}}_t^i \end{pmatrix} + \frac{1}{2} \begin{pmatrix} \widehat{\mathbb{S}}_t^{i\prime} \Psi_{y,1}^2 \widehat{\mathbb{S}}_t^i \\ \vdots \\ \widehat{\mathbb{S}}_t^{i\prime} \Psi_{y,k}^2 \widehat{\mathbb{S}}_t^i \end{pmatrix} + \frac{1}{2} \begin{pmatrix} \Psi_{y,1}^\Lambda \\ \vdots \\ \Psi_{y,k}^\Lambda \end{pmatrix} \tag{21}$$

where $\widehat{\mathbb{S}}_t^i = \mathbb{S}_t^i - \mathbb{S}$ and $\mathbb{S}_t^i = \left(s_t^{i\prime}, z_{t-1}^{i\prime}, \sigma_{t-1}^{i\prime}, \varepsilon_t^{i\prime}, \mathcal{U}_t'\right)'$. The new approximated measurement equation (21) implies that evaluating the approximated measurement density (20) involves solving the system of quadratic equations

$$\mathbb{Y}_t - \mathcal{Y} - \begin{pmatrix} \Psi_{y,1}^1 \widehat{\mathbb{S}}_t^i \\ \vdots \\ \Psi_{y,k}^1 \widehat{\mathbb{S}}_t^i \end{pmatrix} - \frac{1}{2} \begin{pmatrix} \widehat{\mathbb{S}}_t^{i\prime} \Psi_{y,1}^2 \widehat{\mathbb{S}}_t^i \\ \vdots \\ \widehat{\mathbb{S}}_t^{i\prime} \Psi_{y,k}^2 \widehat{\mathbb{S}}_t^i \end{pmatrix} - \frac{1}{2} \begin{pmatrix} \Psi_{y,1}^\Lambda \\ \vdots \\ \Psi_{y,k}^\Lambda \end{pmatrix} = 0 \tag{22}$$

for $\mathcal{U}_t$ given $\mathbb{Y}_t, s_t^i, z_{t-1}^i, \sigma_{t-1}^i$, and ε_t^i.

Solving this system is non-trivial. Since the system is quadratic, we may have either no solution or several different ones. In fact, it is even hard to know how many solutions there are. But even if we knew the number of solutions, we are not aware of any accurate and efficient method to solve quadratic problems that finds all the solutions. This difficulty seemingly prevents us from achieving our goal of evaluating the likelihood function.

A solution would be to introduce, as Fernández-Villaverde and Rubio-Ramírez (2007) did, a $k \times 1$ vector of linear measurement errors and solve for those instead of $\mathcal{U}_t$. In this case the system would have a unique, easy-to-find solution. However, there are three reasons, in increasing order of importance, why this solution is not satisfactory:

1. Although measurement errors are plausible, their presence complicates the interpretation of any empirical results. In particular, we are interested in measuring how heteroscedastic structural shocks help in accounting for the data and measurement errors can confound us.

2. The absence of measurement errors will help us to illustrate below how dynamic equilibrium models with volatility shocks have a profusion of shocks that we can exploit in our estimation.

3. As we will also show below, volatility shocks would enter linearly (conditional on the draw) in the system equations. Since, by definition, linear measurement errors would also enter in the same fashion, it would be hard to identify one apart from the others.

Our alternative in this paper is to realize that considering stochastic volatility converts the above-described quadratic system into a linear one. Hence, if a rank condition is satisfied, the system (22) has only one solution and the solution can be found by inverting a matrix. Thus, requirement 1 in assumption 1 holds and we can use the particle filter. The core of the argument is to note that, when volatility shocks are considered, the policy functions share a peculiar pattern that we can exploit.

3.1. Structure of the Solution

Our first step will characterize the first- and second-order derivatives of the policy functions h and g evaluated at the steady state. Then, we will describe an interesting pattern in these derivatives. The second step will take advantage of the pattern to show that, when the number of volatility shocks equals the number of observables, our quadratic system becomes a linear one. This characterization is important both for estimation and, more generally, for the analysis of perturbation solutions to dynamic equilibrium models with stochastic volatility.

3.1.1. First- and Second-order Derivatives of the Policy Functions

Let us begin with the characterization of the first- and second-order derivatives of the policy functions. The following theorem shows that the first-order derivatives of h and g with respect to any component of $\mathcal{U}_t$ and Σ_{t-1} evaluated at the steady state are zero; that is, volatility shocks and their innovations do not affect the linear component of the optimal decision rule of the agents. The same occurs with the perturbation parameter Λ. A similar result has been established by Schmitt-Grohé and Uribe (2004) for the homoscedastic shocks case.

Theorem 2. *Let us denote $[\Upsilon_\omega]_j^i$ as the derivative of the $i-th$ element of generic function Υ with respect to the $j-th$ element of generic variable ω evaluated at the non-stochastic steady state (where we drop this index if ω is unidimensional). Then, for the dynamic equilibrium model specified in equation (1), we have that $\left[h_{\Sigma_{t-1}}\right]_j^{i_1} = \left[g_{\Sigma_{t-1}}\right]_j^{i_2} = [h_{\mathcal{U}_t}]_j^{i_1} = [g_{\mathcal{U}_t}]_j^{i_2} = [h_\Lambda]^{i_1} = [g_\Lambda]^{i_2} = 0$ for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, and $j \in \{1, \ldots, m\}$.*

Proof. See appendix 2.1. ■

The second theorem shows, among other things, that the second partial derivatives of h and g with respect to either $\log \sigma_{it-1}$ or $u_{i,t}$ and any other variable but $\varepsilon_{i,t}$ are also zero for any $i \in \{1, \ldots, m\}$.

Theorem 3. *Furthermore, if we denote $[\Upsilon_{\omega\xi}]^{i}_{j_1,j_2}$ as the derivative of the $i-th$ element of generic function Υ with respect to the $j_1 - th$ element of generic variable ω and the $j_2 - th$ element of generic variable ξ evaluated at the non-stochastic steady state (where again we drop the index for unidimensional variables), we have that $[h_{\Lambda,\mathcal{S}_t}]^{i_1}_{j} = [g_{\Lambda,\mathcal{S}_t}]^{i_2}_{j} = 0$ for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, and $j \in \{1, \ldots, n\}$,*

$$\left[h_{\Lambda,\mathcal{Z}_{t-1}}\right]^{i_1}_{j} = \left[g_{\Lambda,\mathcal{Z}_{t-1}}\right]^{i_2}_{j} = \left[h_{\Lambda,\Sigma_{t-1}}\right]^{i_1}_{j} = \left[g_{\Lambda,\Sigma_{t-1}}\right]^{i_2}_{j} = \left[h_{\Lambda,\mathcal{E}_t}\right]^{i_1}_{j} = \left[g_{\Lambda,\mathcal{E}_t}\right]^{i_2}_{j} = \left[h_{\Lambda,\mathcal{U}_t}\right]^{i_1}_{j} = \left[g_{\Lambda,\mathcal{U}_t}\right]^{i_2}_{j} = 0$$

for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, and $j \in \{1, \ldots, m\}$,

$$\left[h_{\mathcal{S}_t,\Sigma_{t-1}}\right]^{i_1}_{j_1,j_2} = \left[g_{\mathcal{S}_t,\Sigma_{t-1}}\right]^{i_2}_{j_1,j_2} = \left[h_{\mathcal{S}_t,\mathcal{U}_t}\right]^{i_1}_{j_1,j_2} = \left[g_{\mathcal{S}_t,\mathcal{U}_t}\right]^{i_2}_{j_1,j_2} = 0$$

for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, $j_1 \in \{1, \ldots, n\}$, and $j_2 \in \{1, \ldots, m\}$,

$$\left[h_{\mathcal{Z}_{t-1},\Sigma_{t-1}}\right]^{i_1}_{j_1,j_2} = \left[g_{\mathcal{Z}_{t-1},\Sigma_{t-1}}\right]^{i_2}_{j_1,j_2} = \left[h_{\Sigma_{t-1},\Sigma_{t-1}}\right]^{i_1}_{j_1,j_2} = \left[g_{\Sigma_{t-1},\Sigma_{t-1}}\right]^{i_2}_{j_1,j_2} = 0$$

and

$$\left[h_{\mathcal{Z}_{t-1},\mathcal{U}_t}\right]^{i_1}_{j_1,j_2} = \left[g_{\mathcal{Z}_{t-1},\mathcal{U}_t}\right]^{i_2}_{j_1,j_2} = \left[h_{\Sigma_{t-1},\mathcal{U}_t}\right]^{i_1}_{j_1,j_2} = \left[g_{\Sigma_{t-1},\mathcal{U}_t}\right]^{i_2}_{j_1,j_2} = \left[h_{\mathcal{U}_t,\mathcal{U}_t}\right]^{i_1}_{j_1,j_2} = \left[g_{\mathcal{U}_t,\mathcal{U}_t}\right]^{i_2}_{j_1,j_2} = 0$$

for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, *and* $j_1, j_2 \in \{1, \ldots, m\}$, *and*

$$\left[h_{\mathcal{E}_t,\Sigma_{t-1}}\right]^{i_1}_{j_1,j_2} = \left[g_{\mathcal{E}_t,\Sigma_{t-1}}\right]^{i_2}_{j_1,j_2} = \left[h_{\mathcal{E}_t,\mathcal{U}_t}\right]^{i_1}_{j_1,j_2} = \left[g_{\mathcal{E}_t,\mathcal{U}_t}\right]^{i_2}_{j_1,j_2} = 0$$

for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, *and* $j_1, j_2 \in \{1, \ldots, m\}$ *if* $j_1 \neq j_2$.

Proof. See appendix 2.2. ∎

We clarify the statement of theorem 3 with table 3.1, in which we characterize the second derivatives of the functions h and g with respect to the different variables $(\mathcal{S}_t, \mathcal{Z}_{t-1}, \Sigma_{t-1}, \mathcal{E}_t, \mathcal{U}_t, \Lambda)$.[1] This pattern is both interesting and useful. The way to read table 3.1 is as follows. Take an arbitrary entry, for instance, entry (1,2), $\mathcal{S}_t\mathcal{Z}_{t-1} \neq 0$. In this entry, we state that the cross-derivatives of h and g with respect to $\mathcal{S}_t$ and $\mathcal{Z}_{t-1}$ are different from zero (the table is upper triangular because, given the symmetry of second derivatives, we do not need to report those entries). Similarly, entry (3,5), $\Sigma_{t-1}\mathcal{U}_t = 0$ tells us that the cross-derivatives of h and g with respect to Σ_{t-1} and $\mathcal{U}_t$ are all zero. Entries (3,4) and (4,5) have a "*" to denote that the only cross-derivatives of those entries that are different from zero are those that correspond to the same index j (that is, the cross-derivatives of each innovation to the structural shocks with respect to its own volatility shock and the cross-derivatives of the innovation to the structural shocks to the innovation to its own volatility shock). The lower triangular part of the table is empty because of the symmetry of second derivatives.

Table 3.1 tells us that, of the 21 possible sets of second derivatives, 12 are zero and 9 are not. The implications for the decision rules of agents and for the equilibrium function are striking. The perturbation parameter, Λ, will only have a coefficient different from zero in the term where

[1] For ease of exposition, in table 3.1 we are not being explicit about the dimensions of the matrices: it is a qualitative description of the relevant derivatives.

it appears in a square by itself. This term is a constant that corrects for precautionary behavior induced by risk. Volatility shocks, Σ_{t-1} , appear with coefficients different from zero only in the term $\Sigma_{t-1}\mathcal{E}_t$ where they are multiplied by the innovation to its own structural shock $\mathcal{E}_t$. Finally, innovations to the volatility shocks, $\mathcal{U}_t$, also appear with coefficients different from zero when they show up with the innovation to their own structural shock $\mathcal{E}_t$. Hence, of the terms that complicate the evaluation of the approximated measurement density, only the ones associated with $[h_{\mathcal{E}_t,\mathcal{U}_t}]^{i_1}_{j_1,j_1}$ and $[g_{\mathcal{E}_t,\mathcal{U}_t}]^{i_2}_{j_1,j_1}$ are non-zero.

3.1.2. Evaluating the Likelihood Using the Particle Filter

The second step is to use theorems 2 and 3 to show that the system (22) is linear and has only one solution. Corollary 4 shows that the pattern described in table 3.1. has an important implication for the structure of the approximated measurement equation (21).

Corollary 4. *The approximated measurement equation (21) can be written as*

$$\mathbb{Y}_t - \mathcal{Y} = \begin{pmatrix} \widetilde{\Psi}^1_{y,1}\widetilde{\widetilde{\mathbb{S}}}^i_t \\ \vdots \\ \widetilde{\Psi}^1_{y,k}\widetilde{\widetilde{\mathbb{S}}}^i_t \end{pmatrix} + \frac{1}{2}\begin{pmatrix} \widetilde{\widetilde{\mathbb{S}}}^{i\prime}_t\widetilde{\Psi}^{2,1}_{y,1}\widetilde{\widetilde{\mathbb{S}}}^i_t \\ \vdots \\ \widetilde{\widetilde{\mathbb{S}}}^{i\prime}_t\widetilde{\Psi}^{2,1}_{y,k}\widetilde{\widetilde{\mathbb{S}}}^i_t \end{pmatrix} + \frac{1}{2}\begin{pmatrix} \Psi^{\Lambda}_{y,1} \\ \vdots \\ \Psi^{\Lambda}_{y,k} \end{pmatrix} + \begin{pmatrix} \varepsilon^{i\prime}_t\widetilde{\Psi}^{2,2}_{y,1} \\ \vdots \\ \varepsilon^{i\prime}_t\widetilde{\Psi}^{2,2}_{y,k} \end{pmatrix}\sigma^i_{t-1} + \begin{pmatrix} \varepsilon^{i\prime}_t\widetilde{\Psi}^{2,3}_{y,1} \\ \vdots \\ \varepsilon^{i\prime}_t\widetilde{\Psi}^{2,3}_{y,k} \end{pmatrix}\mathcal{U}_t$$

where $\widetilde{\mathbb{S}}^i_t = \left(s^{i\prime}_t, z^{i\prime}_{t-1}, \varepsilon^{i\prime}_t\right)'$ *is the* $(n+2m)\times 1$ *vector of the simulated states without the stochastic volatility components (that is, endogenous states, structural shocks, and their innovations),* $\widetilde{\mathbb{S}} = (\mathcal{S}', \mathbf{0}', \mathbf{0}')'$ *is its steady state, and* $\widetilde{\widetilde{\mathbb{S}}}^i_t = \widetilde{\mathbb{S}}^i_t - \widetilde{\mathbb{S}}$ *is its deviation from the steady state. Let us define* $\widetilde{n}_s = n + 2m$. *The matrix* $\widetilde{\Psi}^1_{y,j}$ *is a* $1\times\widetilde{n}_s$ *vector that represents the first-order component of the second-order approximation to the law of motion for the measurement equation as a function of* $\widetilde{\widetilde{\mathbb{S}}}_t$, *where* $\widetilde{\mathbb{S}}_t = \left(\mathcal{S}'_t, \mathcal{Z}'_{t-1}, \mathcal{E}'_t\right)'$ *and* $\widetilde{\widetilde{\mathbb{S}}}_t = \widetilde{\mathbb{S}}_t - \widetilde{\mathbb{S}}$, *for* $j = 1,\ldots,k$. *The matrix* $\widetilde{\Psi}^{2,1}_{y,j}$ *is an* $\widetilde{n}_s\times\widetilde{n}_s$

matrix that represents the second-order component of the second-order approximation to the law of motion for the measurement equation as a function of $\widetilde{\widetilde{\mathbb{S}}}_t$ *for* $j = 1, \ldots, k$. *The matrix* $\widetilde{\Psi}^{2,2}_{y,j}$ *is an* $m \times m$ *matrix that represents the second-order component of the second-order approximation to the law of motion for the measurement equation as a function of* $\mathcal{E}_t$ *and* Σ_{t-1} *for* $j = 1, \ldots, k$. *The matrix* $\widetilde{\Psi}^{2,3}_{y,j}$ *is an* $m \times m$ *matrix that represents the second-order term of the approximated law of motion for the measurement equation as a function of* $\mathcal{E}_t$ *and* $\mathcal{U}_t$ *for* $j = 1, \ldots, k$.

We are now ready to show that the system (22) is linear, and if a rank condition is satisfied, it has only one solution.

Define

$$\mathbb{A}\left(\mathbb{Y}_t, s^i_t, z^i_{t-1}, \sigma^i_{t-1}, \varepsilon^i_t; \gamma\right)$$

$$\equiv \mathbb{Y}_t - \mathcal{Y} - \begin{pmatrix} \widetilde{\Psi}^1_{y,1}\widetilde{\widetilde{\mathbb{S}}}^i_t \\ \vdots \\ \widetilde{\Psi}^1_{y,k}\widetilde{\widetilde{\mathbb{S}}}^i_t \end{pmatrix} - \frac{1}{2}\begin{pmatrix} \widetilde{\widetilde{\mathbb{S}}}^{i\prime}_t \widetilde{\Psi}^{2,1}_{y,1}\widetilde{\widetilde{\mathbb{S}}}^i_t \\ \vdots \\ \widetilde{\widetilde{\mathbb{S}}}^{i\prime}_t \widetilde{\Psi}^{2,1}_{y,k}\widetilde{\widetilde{\mathbb{S}}}^i_t \end{pmatrix} - \frac{1}{2}\begin{pmatrix} \Psi^{\Lambda}_{y,1} \\ \vdots \\ \Psi^{\Lambda}_{y,k} \end{pmatrix} - \begin{pmatrix} \varepsilon^{i\prime}_t \widetilde{\Psi}^{2,2}_{y,1} \\ \vdots \\ \varepsilon^{i\prime}_t \widetilde{\Psi}^{2,2}_{y,k} \end{pmatrix} \sigma^i_{t-1}$$

and

$$\mathbb{B}\left(\varepsilon^i_t; \gamma\right) \equiv \begin{pmatrix} \left(\varepsilon^{i\prime}_t \widetilde{\Psi}^{2,3}_{y,1}\right)' & \ldots & \left(\varepsilon^{i\prime}_t \widetilde{\Psi}^{2,3}_{y,k}\right)' \end{pmatrix}'.$$

Let $k = m$, then $\mathbb{B}\left(\varepsilon^i_t; \gamma\right)$ is a $k \times k$ matrix. If $\mathbb{B}\left(\varepsilon^i_t; \gamma\right)$ is full rank, the solution to the system (22) can be written as

$$\mathcal{U}_t = \mathbb{B}^{-1}\left(\varepsilon^i_t; \gamma\right) \mathbb{A}\left(\mathbb{Y}_t, s^i_t, z^i_{t-1}, \sigma^i_{t-1}, \varepsilon^i_t; \gamma\right).$$

The next theorem shows how to use this solution to evaluate the approximated measurement density.

Theorem 5. *Let $k = m$, then $\mathbb{B}(\varepsilon_t^i;\gamma)$ is a $k \times k$ matrix. If $\mathbb{B}(\varepsilon_t^i;\gamma)$ is full rank, the approximated measurement density can be written as*

$$p\left(\mathcal{Y}_t = \mathbb{Y}_t | s_t^i, z_{t-1}^i, \sigma_{t-1}^i, \varepsilon_t^i; \gamma\right) = \det \mathbb{B}^{-1}\left(\varepsilon_t^i;\gamma\right) p\left(\mathcal{U}_t = \mathbb{B}^{-1}\left(\varepsilon_t^i;\gamma\right) \mathbb{A}\left(\mathbb{Y}_t, s_t^i, z_{t-1}^i, \sigma_{t-1}^i, \varepsilon_t^i;\gamma\right)\right) \tag{23}$$

for each draw in $\left\{s_t^i, z_{t-1}^i, \sigma_{t-1}^i, \varepsilon_t^i\right\}_{i=1}^N$ for all $t \in \{1, \ldots, T\}$, which can be evaluated given that we know $\mathbb{B}^{-1}(\varepsilon_t^i;\gamma)$, $\mathbb{A}\left(\mathbb{Y}_t, s_t^i, z_{t-1}^i, \sigma_{t-1}^i, \varepsilon_t^i;\gamma\right)$, and the distribution of $\mathcal{U}_t$.

Proof. The theorem is a straightforward application of the change of variables theorem. ■

Theorem 5 shows that requirement 1 in assumption 1 holds and, thus, we can apply our particle filter. We are also requiring $B(\varepsilon_t^i;\gamma)$ to be full rank. When can $B(\varepsilon_t^i;\gamma)$ not be full rank? $B(\varepsilon_t^i;\gamma)$ would fail to have full rank when the impact of volatility innovations is identical across several elements of $\mathbb{Y}_t$. This would mean that $\mathcal{Y}_t$ lacks enough information to tell volatility shocks apart and that, to estimate the model, we need a new set of observables.

Note that theorem 5 assumes $k = m$. Given the notation in section 2.1, this means that the number of structural shocks equals the number of observables. This is not always necessary. What the theorem needs is that the number of volatility shocks equals the number of observables. Since, to simplify notation, we have assumed that all structural shocks face volatility shocks, the number of structural shocks equals the number of observables. As mentioned in section 2.1, we could have structural shocks that do not face volatility shocks (this will be the case in our application to follow). In that case, we could have more structural shocks than observables. From the theorem, it is also clear that if we used $\mathcal{E}_t$ rather than $\mathcal{U}_t$ to compute the approximated measurement equation, we would have to solve a quadratic system, a challenging task.

An outline of the algorithm in pseudo-code is:

Step 0: `Set` $t \rightsquigarrow 1$. `Sample` N `values` $\left\{s_t^i, z_{t-1}^i, \sigma_{t-1}^i, \varepsilon_t^i\right\}_{i=1}^N$ `from` $p\left(\mathcal{S}_t, \mathcal{Z}_{t-1}, \Sigma_{t-1}, \mathcal{E}_t; \gamma\right)$.

Step 1: `Compute`

$$p\left(\mathcal{Y}_t = \mathbb{Y}_t | \mathbb{Y}^{t-1}; \gamma\right) \simeq \frac{1}{N} \sum_{i=1}^{N} \det \mathbb{B}^{-1}\left(\varepsilon_t^i; \gamma\right) p\left(\mathcal{U}_t = \mathbb{B}^{-1}\left(\varepsilon_t^i; \gamma\right) \mathbb{A}\left(\mathbb{Y}_t, s_t^i, z_{t-1}^i, \sigma_{t-1}^i, \varepsilon_t^i; \gamma\right)\right)$$

`using expression (23) and the importance weights for each draw`

$$q_t^i = \frac{\det \mathbb{B}^{-1}\left(\varepsilon_t^i; \gamma\right) p\left(\mathcal{U}_t = \mathbb{B}^{-1}\left(\varepsilon_t^i; \gamma\right) \mathbb{A}\left(\mathbb{Y}_t, s_t^i, z_{t-1}^i, \sigma_{t-1}^i, \varepsilon_t^i; \gamma\right)\right)}{\sum_{i=1}^{N} \det \mathbb{B}^{-1}\left(\varepsilon_t^i; \gamma\right) p\left(\mathcal{U}_t = \mathbb{B}^{-1}\left(\varepsilon_t^i; \gamma\right) \mathbb{A}\left(\mathbb{Y}_t, s_t^i, z_{t-1}^i, \sigma_{t-1}^i, \varepsilon_t^i; \gamma\right)\right)}.$$

Step 2: `Sample` N `times with replacement from` $\left\{s_{t|t-1}^i, z_{t-1|t-1}^i, \sigma_{t-1|t-1}^i, \varepsilon_{t|t-1}^i\right\}_{i=1}^N$ `and probability` $\left\{q_t^i\right\}_{i=1}^N$. `This delivers` $\left\{s_{t|t}^i, z_{t-1|t}^i, \sigma_{t-1|t}^i, \varepsilon_{t|t}^i\right\}_{i=1}^N$.

Step 3: `Simulate` $\left\{s_{t+1}^i, z_t^i, \sigma_t^i, \varepsilon_{t+1}^i\right\}_{i=1}^N$ `from the approximated transition equation`

$$\left(\mathcal{S}_{t+1}', \mathcal{Z}_t', \Sigma_t', \mathcal{E}_{t+1}'\right)' \mid \left(s_{t|t}^{i\prime}, z_{t-1|t}^{i\prime}, \sigma_{t-1|t}^{i\prime}, \varepsilon_{t|t}^{i\prime}\right)', \mathcal{F}\left(\mathbb{Y}^t\right); \gamma.$$

Step 4: `If` $t < T$, `set` $t \rightsquigarrow t+1$ `and go to step 1. Otherwise stop.`

Once we have evaluated the likelihood, we can nest this algorithm either with an McMc to perform Bayesian inference (as done in our application; see Flury and Shephard, 2011, for technical details) or with some optimization algorithm to undertake maximum likelihood estimation (as done, in a model without volatility shocks, by Van Binsbergen *et al.*, 2012). In this last case, care must be taken to use an optimization algorithm that does not rely on derivatives, as the particle filter implies an evaluation of the likelihood function that is not differentiable.

4. Comparison with Continuous-Time Models

As is common in the business-cycle literature, we wrote our generic dynamic equilibrium model in discrete time. However, much research in finance and, increasingly, in macroeconomics is using continuous-time models. Thus, it is useful to sketch how we could adapt our framework to continuous time:

1. We would write the equilibrium conditions of the continuous-time model as in equation (1). The main difference with discrete time is that, often, it is not possible to eliminate from those conditions the value functions (and their partial derivatives) of the agents of the model. This is not particularly problematic beyond increasing the number of equilibrium conditions (as we will need to have the concentrated Hamilton-Bellman-Jacobi equations defining those value functions in a recursive way).

2. We would solve for the policy functions of the agents using the continuous-time version of the perturbation method outlined in section 2.4 of this paper. Judd (1998, chapters 13 and 14) discusses how to apply perturbation methods to continuous-time dynamic equilibrium models. Parra-Álvarez (2013) applies the method to the solution of business cycle models. The solution of the model would give us a multivariate diffusion process for the evolution of the states (the equivalent of our transition equation 12) and a density for the observables (the equivalent of our transition equation 7).[2]

3. We would then use the diffusion process and the density to build a continuous-time state-space representation analogous to equations (14) and (15). This is done, for example, in Chib, Pitt, and Shephard (2010) for several finance models.

[2] Another possibility would be solving the Hamilton-Bellman-Jacobi equation of the agents using a projection method as in Fernández-Villaverde, Rubio-Ramírez, and Posch (2013).

4. We would then use the methods proposed by Aït-Sahalia (2002 and 2008), and Aït-Sahalia and Kimmel (2007) to find closed-form expansions for the log-likelihood function of the model. As documented in those papers, since the coefficients of the expansion are calculated explicitly by exploiting the special structure afforded by the diffusion model, the computations are fast and efficient. Then, we can either maximize the log-likelihood or nest it inside an McMc algorithm (Stramer, Bognar, and Schneider, 2010).

While this approach is promising, it has not been applied in macroeconomics and it remains to assess its performance in real-life applications. In comparison, the discrete-time approach to the solution and estimation of dynamic equilibrium models has been tested in dozens of empirical applications. Therefore (and in addition to the fact that discrete time is still more popular in macroeconomics), we prefer to explore how to handle dynamic equilibrium models with stochastic volatility first in a discrete-time framework and leave the analysis of the continuous-time case for ongoing research.

5. An Application: A Business Cycle Model with Stochastic Volatility

As an illustration of our procedure, we estimate a business cycle model of the U.S. economy with nominal rigidities and stochastic volatility. We will show: 1) how we can characterize posterior distributions of the parameters of interest and 2) how we can recover and analyze the smoothed structural and volatility shocks. Those are two of the most relevant exercises in terms of the estimation of dynamic equilibrium models. Once the estimation has been undertaken, there are many potential exercises. For instance, in the appendix, we include several of them such as: 1) finding the impulse response functions (IRFs) of the model; 2) evaluating the fit of the model in comparison with some alternatives; and 3) building counterfactuals and running alternative histories of the evolution of the U.S. economy.

The model we present is a natural example for this paper because it is the base of much applied policy analysis. We will depart only along two dimensions from the standard specification: we will have stochastic volatility in the shocks that drive the dynamics of the economy and parameter drifting in the monetary policy rule. In that way, the likelihood has the chance of picking between two of the alternatives that the literature has highlighted to account for the well-documented time-varying volatility of the U.S. aggregate time series, either a reduced volatility of the shocks that hit the economy (Sims and Zha, 2006) or a different monetary policy (Clarida *et al.*, 2000), which makes the application of interest in itself.

5.1. Households

The economy is populated by a continuum of households indexed by j and preferences:

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t d_t \left\{ \log\left(c_{jt} - h c_{jt-1}\right) + \upsilon \log\left(\frac{m_{jt}}{p_t}\right) - \varphi_t \psi \frac{l_{jt}^{1+\vartheta}}{1+\vartheta} \right\},$$

which are separable in consumption, c_{jt}, real money balances, m_{jt}/p_t, and hours worked, l_{jt}. In our notation, $\mathbb{E}_0$ is the conditional expectations operator, β is the discount factor, h controls habit persistence, ϑ is the inverse of the Frisch labor supply elasticity, d_t is a shifter to intertemporal preference that follows $\log d_t = \rho_d \log d_{t-1} + \sigma_d \sigma_{dt} \varepsilon_{dt}$ where $\varepsilon_{dt} \sim \mathcal{N}(0,1)$, and φ_t is a labor supply shifter that evolves as $\log \varphi_t = \rho_\varphi \log \varphi_{t-1} + \sigma_\varphi \sigma_{\varphi t} \varepsilon_{\varphi t}$ where $\varepsilon_{\varphi t} \sim \mathcal{N}(0,1)$. The two preference shocks are common to all households.

The principal novelty of these preferences is that, for both shifters d_t and φ_t, the standard deviations, σ_{dt} and $\sigma_{\varphi t}$, of their innovations, ε_{dt} and $\varepsilon_{\varphi t}$, are indexed by time; that is, they stochastically move according to:

$$\log \sigma_{dt} = \rho_{\sigma_d} \log \sigma_{dt-1} + \left(1 - \rho_{\sigma_d}^2\right)^{\frac{1}{2}} \eta_d u_{dt} \text{ where } u_{dt} \sim \mathcal{N}(0,1)$$

and

$$\log \sigma_{\varphi t} = \rho_{\sigma_\varphi} \log \sigma_{\varphi t-1} + \left(1 - \rho_{\sigma_\varphi}^2\right)^{\frac{1}{2}} \eta_\varphi u_{\varphi t} \text{ where } u_{\varphi t} \sim \mathcal{N}(0,1).$$

This parsimonious specification introduces only four new parameters, ρ_{σ_d}, ρ_{σ_φ}, η_d, and η_φ, while being surprisingly powerful in capturing important features of the data (Shephard, 2008). All the shocks and innovations throughout the model are observed by the agents when they are realized. Agents have, as well, rational expectations about how these shocks (and all the other shocks to the economy) evolve over time. We can interpret the shocks to preferences and to their volatility as reflecting the random evolution of more complicated phenomena, such as changing demographics (see Fernández-Villaverde and Rubio-Ramirez, 2008).

Although we assume complete financial markets, to ease notation we drop the Arrow securities implied by that assumption from the budget constraints (they are in net zero supply at the aggregate level). Households also hold b_{jt} government bonds that pay a nominal gross interest rate of R_{t-1}. Therefore, the $j-th$ household's budget constraint is given by:

$$c_{jt} + x_{jt} + \frac{m_{jt}}{p_t} + \frac{b_{jt+1}}{p_t} = w_{jt} l_{jt} + \left(r_t u_{jt} - \mu_t^{-1} \Phi\left[u_{jt}\right]\right) k_{jt-1} + \frac{m_{jt-1}}{p_t} + R_{t-1} \frac{b_{jt}}{p_t} + T_t + \digamma_t$$

where x_t is investment, w_{jt} is the real wage, r_t is the real rental price of capital, $u_{jt} > 0$ is the rate of use of capital, $\mu_t^{-1} \Phi\left[u_{jt}\right]$ is the cost of using capital at rate u_{jt} in terms of the final good, μ_t, is an investment-specific technological level, T_t is a lump-sum transfer, and $\digamma_t$ is firms' profits. We specify that $\Phi\left[u\right] = \Phi_1 (u-1) + \frac{\Phi_2}{2} (u-1)^2$, a form that satisfies that $\Phi\left[1\right] = 0$, $\Phi'\left[\cdot\right] = 0$, and $\Phi''[\cdot] > 0$. This function carries the normalization that $u = 1$ in the balanced growth path of the economy. Using the relevant first-order conditions, we can find $\Phi_1 = \Phi'[1] = \widetilde{r}$ where $\widetilde{r}$ is the (rescaled) steady-state rental price of capital (determined by the other parameters in the model). This leaves us with only one free parameter, Φ_2.

Given a depreciation rate δ and an investment adjustment cost parameter κ, the capital accumulated by household j at the end of period t is given by:

$$k_{jt} = (1-\delta)\, k_{jt-1} + \mu_t \left(1 - \frac{\kappa}{2}\left(\frac{x_{jt}}{x_{jt-1}} - \Lambda_x\right)^2\right) x_{jt}.$$

This function is written in deviations with respect to the balanced growth rate of investment, Λ_x. The investment-specific technology level μ_t, follows a random walk in logs, $\log \mu_t = \Lambda_\mu + \log \mu_{t-1} + \sigma_\mu \sigma_{\mu t} \varepsilon_{\mu t}$ with $\varepsilon_{\mu t} \sim \mathcal{N}(0,1)$ and where Λ_μ is the drift of the process and $\varepsilon_{\mu t}$ is the innovation to its growth rate. The standard deviation $\sigma_{\mu t}$ also evolves as:

$$\log \sigma_{\mu t} = \rho_{\sigma_\mu} \log \sigma_{\mu t-1} + \left(1 - \rho_{\sigma_\mu}^2\right)^{\frac{1}{2}} \eta_\mu u_{\mu t} \text{ where } u_{\mu t} \sim \mathcal{N}(0,1).$$

Again, we can interpret this stochastic volatility as a stand-in for a more detailed explanation of technological progress in capital production that we do not model explicitly.

Each household j supplies a different type of labor services l_{jt} that are aggregated by a labor packer into homogeneous labor l_t^d with the production function $l_t^d = \left(\int_0^1 l_{jt}^{\frac{\eta-1}{\eta}} dj\right)^{\frac{\eta}{\eta-1}}$ that is rented to intermediate good producers at wage w_t. The labor packer is perfectly competitive and it takes all wages as given. Households set their wages with a Calvo pricing mechanism. At the start of every period, a randomly selected fraction $1-\theta_w$ of households can reoptimize their wages (where, by a law of large numbers, individual probabilities and aggregate fractions are equal). All other households index their wages given past inflation with an indexation parameter $\chi_w \in [0,1]$.

5.2. Firms

There is one final good producer that aggregates a continuum of intermediate goods according to:

$$y_t = \left(\int_0^1 y_{it}^{\frac{\varepsilon-1}{\varepsilon}} di \right)^{\frac{\varepsilon}{\varepsilon-1}} \tag{24}$$

where ε is the elasticity of substitution. The final good producer is perfectly competitive and minimizes its costs subject to the production function (24) and taking as given all intermediate goods prices p_{ti} and the final good price p_t.

Each intermediate good is produced by a monopolistic competitor with technology $y_{it} = A_t k_{it-1}^{\alpha} \left(l_{it}^d \right)^{1-\alpha}$, where k_{it-1} is the capital rented by the firm, l_{it}^d is the amount of the "packed" labor input rented by the firm, and A_t is neutral productivity. Productivity evolves as $\log A_t = \Lambda_A + \log A_{t-1} + \sigma_A \sigma_{At} \varepsilon_{At}$ where Λ_A is the drift of the process and $\varepsilon_{At} \sim \mathcal{N}(0,1)$ is the innovation to its growth rate. The time-varying standard deviation of this innovation follows:

$$\log \sigma_{At} = \rho_{\sigma_A} \log \sigma_{At-1} + \left(1 - \rho_{\sigma_A}^2\right)^{\frac{1}{2}} \eta_A u_{At} \text{ where } u_{At} \sim \mathcal{N}(0,1).$$

Intermediate good producers meet the quantity demanded by the final good producer by renting l_{it}^d and k_{it-1} at prices w_t and r_t. Given their demand function, these producers set prices to maximize profits. However, when they do so, they follow a Calvo pricing scheme. In each period, a fraction $1 - \theta_p$ of intermediate good producers reoptimize their prices. All other firms partially index their prices by past inflation with an indexation parameter $\chi \in [0,1]$.

5.3. The Monetary Authority

A monetary authority sets the nominal interest rate R_t (as a deviation with respect to R, the balanced growth path nominal interest rate) by following a Taylor rule:

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\gamma_R} \left(\left(\frac{\Pi_t}{\Pi}\right)^{\gamma_\Pi \gamma_{\Pi,t}} \left(\frac{y_t^d}{y_{t-1}^d} / \exp\left(\Lambda_{y^d}\right)\right)^{\gamma_y \gamma_{y,t}}\right)^{1-\gamma_R} \xi_t. \tag{25}$$

The first term on the right-hand side represents a desire for interest rate smoothing. The second term responds to the deviation of inflation from its balanced growth path level Π. The third term is a "growth gap": the ratio between the growth rate of the economy and Λ_{y^d}, the balanced path gross growth rate of y_t^d, where y_t^d is aggregate demand (defined precisely in appendix 3). The last term is the monetary policy shock, where $\log \xi_t = \sigma_\xi \sigma_{\xi,t} \varepsilon_{\xi t}$ with an innovation $\varepsilon_{\xi t} \sim \mathcal{N}(0,1)$ and a time-varying standard deviation, $\sigma_{\xi,t}$, that follows an autoregressive process

$$\log \sigma_{\xi t} = \rho_{\sigma_\xi} \log \sigma_{\xi t-1} + \left(1 - \rho_{\sigma_\xi}^2\right)^{\frac{1}{2}} \eta_\xi u_{\xi,t} \text{ where } u_{\xi,t} \sim \mathcal{N}(0,1).$$

In this policy rule, we have two drifting parameters: the responses of the monetary authority to the inflation gap and the growth gap. The parameters drift over time as:

$$\log \gamma_{\Pi t} = \rho_{\gamma_\Pi} \log \gamma_{\Pi t-1} + \sigma_\pi \varepsilon_{\pi t} \text{ and } \log \gamma_{yt} = \rho_{\gamma_y} \log \gamma_{yt-1} + \sigma_y \varepsilon_{yt} \text{ where } \varepsilon_{\pi t}, \varepsilon_{yt} \sim \mathcal{N}(0,1).$$

For simplicity, the volatility of the innovation to this processes is fixed over time. The agents perfectly observe these changes in monetary policy parameters.

5.4. Equilibrium and Solution

We characterize the equilibrium of the model in appendix 3. The equilibrium conditions are non-stationary because we have two unit roots in the processes for technology. We circumvent this problem by rescaling the model using the variable $z_t = A_t^{\frac{1}{1-\alpha}} \mu_t^{\frac{\alpha}{1-\alpha}}$ in the form: $\widetilde{k}_t = \frac{k_t}{z_t \mu_t}$, $\widetilde{c}_t = \frac{c_t}{z_t}$, $\widetilde{x}_t = \frac{x_t}{z_t}$, $\widetilde{y}_t = \frac{y_t}{z_t}$, $\widetilde{w}_t = \frac{w_t}{z_t}$, $\widetilde{r}_t = \mu_t r_t$, $\widetilde{A}_t = \frac{A_t}{\exp(\Lambda_A) A_{t-1}}$, and $\widetilde{\mu}_t = \frac{\mu_t}{\exp(\Lambda_\mu)\mu_{t-1}}$. In the notation of section 2.1 we have that:

1. The states of the (rescaled) economy are

$$\mathcal{S}_t = \left(\log \widetilde{k}_{t-1}, \log \widetilde{c}_{t-1}, \log \widetilde{x}_{t-1}, \log \widetilde{y}_{t-1}, \log \upsilon_{t-1}^p, \log \upsilon_{t-1}^w, \log \widetilde{w}_{t-1}, \log R_{t-1}, \log \Pi_{t-1}\right)'.$$

2. The structural shocks are $\mathcal{Z}_t = \left(\log d_t, \log \varphi_t, \log \widetilde{\mu}_t, \log \widetilde{A}_t, \log \xi_t, \log \gamma_{\Pi t}, \log \gamma_{yt}\right)'$. The parameter drifts are handled as structural shocks in the state-space representation.

3. The volatility shocks are $\Sigma_t = (\log \sigma_{dt}, \log \sigma_{\varphi t}, \log \sigma_{\mu t}, \log \sigma_{At}, \log \sigma_{\xi t}, 0, 0)'$, where the last two zeros correspond to the processes for parameter drifting, which have constant volatilities (see also in vector $\mathcal{U}_t$ below). Here, we can see that we do not need as many volatility shocks (5 of them) as structural shocks (7 of them).

4. The innovations to the structural and the volatility shocks are $\mathcal{E}_t = (\varepsilon_{dt}, \varepsilon_{\varphi t}, \varepsilon_{\mu t}, \varepsilon_{At}, \varepsilon_{\xi t}, \varepsilon_{\pi t}, \varepsilon_{yt})'$ and $\mathcal{U}_t = (u_{dt}, u_{\varphi t}, u_{\mu t}, u_{At}, u_{\xi t}, 0, 0)'$, respectively.

We pick as observables the first difference of the log of the relative price of investment, the log federal funds rate, log inflation, the first difference of log output, and the first difference of log real wages, in our notation $\mathcal{Y}_t = (-\triangle \log \mu_t, \log R_t, \log \Pi_t, \triangle \log y_t, \triangle \log w_t)'$. We select these variables because they bring us information about aggregate behavior (output), the stance of monetary policy (the interest rate and inflation), and the different shocks (the relative price of investment about investment-specific technological change, the other four variables about technology and preference shocks) that we are concerned about. Note that we have the same number of observables as we do of volatility shocks, as required by theorem 5.

Also, note that a second-order approximation is even more relevant in our application than in the standard case of dynamic equilibrium models with stochastic volatility because a linearization would also imply that the parameter drift in the Taylor rule would disappear as well from the equilibrium dynamics (see appendix 4 for more details).

5.5. A User's Guide to Computing the Results

In this subsection, we outline a user's guide to the computation of our result. The main steps involved are:

1. We rescale the equilibrium conditions of the model to make them stationary and write them in `Mathematica`.

2. We ask `Mathematica` to take all the analytic derivatives required to solve for the second-order approximation of the model. We take advantage of the symbolic computation capabilities of `Mathematica` to express them as functions of parameters of the model. In that way, we do not need to recompute the derivatives, the most time-intensive step, for each set of parameter values in our estimation.

3. Once we have all the relevant derivatives, we export them into `Fortran` files. At this stage, we have a set of `Fortran` files that solves the second-order approximation of the dynamics of the model as a function of the parameters (steps 2 and 3 take about 3 hours).

4. Then, we compile the resulting files with the `Intel Fortran Compiler` version 10.1.025 with IMSL. Compilation takes about 18 hours. The project has 1798 files and occupies 2.33 Gbytes of memory.

5. Given some parameter values, we use the derivatives from step 3 to solve for the second-order approximation of the model. For this task, `Fortran` takes around 5 seconds (remember that we have 9 states, 7 structural shocks, and 5 volatility shocks).

6. We build, in `Fortran`, the state-space representation associated with the second-order approximation.

7. We approximate the likelihood with the particle filter using $10,000$ particles. This number delivered a good compromise between accuracy and time to compute the likelihood. Hence, the solution of the model plus the evaluation of one likelihood requires 22 seconds on a Dell server with 8 processors.

8. We use steps 2 to 7 within a random-walk Metropolis-Hastings algorithm to draw from the posterior of the parameters. Drawing 5,000 times from the posterior takes around 38 hours. In order to initialize the chain, we extensively search on a grid parameter for high values of the likelihood.

The `Mathematica` and `Fortran` codes were highly optimized in order to 1) keep the size of the project within reasonable dimensions (otherwise, the compiler cannot parse the files) and 2) provide a rapid solution of the model and a fast computation of the likelihood. Perhaps the most important task in that optimization was the parallelization of the `Fortran` code using `OPENMP` as well as the compilation options: `OG` (global optimizations) and `Loop Unroll`. Without the parallelization, the solution of the model and evaluation of its likelihood take about 70 seconds.

Also, note that implementing corollary 1 needed in step 7 requires the solution of a linear system of equations and the computation of a Jacobian. For our application, we found that the following sequence of `LAPACK` operations delivered the fastest solution:

1. `DGESV` (computes the solution to a real system of linear equations $A * X = B$).

2. `DGETRI` (computes the inverse of a matrix using the LU factorization from the previous line).

3. `DGETRF` (helps to compute the determinant of the inverse from the previous line).

With respect to the random-walk Metropolis-Hastings, we performed an intensive process of fine-tuning of the chain, both in terms of initial conditions as well as in terms of getting the right acceptance level. While the tuning was time-intensive, it did not involve any non-standard step. The only other important remark is to remember to keep the random numbers used for resampling in the particle filter constant across draws of the Markov chain. This is required to reduce the numerical variance of the procedure, which was a serious concern for us given the complexity of our problem.

5.6. Data and Estimation

We estimate our model using the five time series for the U.S. economy described above. Our sample covers 1959.Q1 to 2007.Q1, with 192 observations. We stop at 2007 to avoid having to deal with the financial crisis, which would make it difficult to appreciate the points we want to illustrate about how to econometrically deal with stochastic volatility. This could be fixed at the cost of a lengthier discussion. Appendix 5 explains how we construct the series.

Once we have evaluated the likelihood, we combine it with a prior. We pick flat priors on a bounded support for all the parameters. The bounds are either natural economic restrictions (for instance, the Calvo and indexation parameters lie between 0 and 1) or are so wide that the likelihood assigns (numerically) zero probability to values outside them. Bounded flat priors induce a proper posterior, a convenient feature for our exercises below. We resort to flat priors for two reasons. First, to reduce the impact of presample information and show that our results arise mainly from the shape of the likelihood and not from the prior (although, of course, flat priors are not invariant to reparameterization). Thus, we could interpret our posterior modes as maximum likelihood point estimates. Second, as we learned in Fernández-Villaverde *et al.* (2010c), eliciting priors for stochastic volatility is difficult, since we deal with unfamiliar units, such as the variance of volatility shocks, about which we do not have clear beliefs. Flat priors come, though, at a price: before proceeding to the estimation, we have to fix several parameters to reduce the dimensionality of the problem.

Table 5.1 lists the fixed parameters. Our guiding criterion in selecting them was to pick conventional values. The discount factor, $\beta = 0.99$, is a default choice, habit persistence, $h = 0.9$, matches the observed sluggish response of consumption to shocks, the parameter controlling the level of labor supply, $\psi = 8$, captures the average amount of hours in the data, and the depreciation rate, $\delta = 0.025$, induces the appropriate capital-output ratio. The elasticities of substitution, $\varepsilon = \eta = 10$, deliver average mark-ups of around 10 percent, a common value in these models. We set the cost of capital utilization, Φ_2, to a small number to introduce some curvature in this decision. Three parameter values are borrowed from Fernández-Villaverde *et al.* (2009). The first is the inverse of the Frisch labor elasticity, $\vartheta = 1.17$. This aggregate elasticity is compatible with the micro data, once we allow for intensive and extensive margins on labor supply. The second is the coefficient of the intermediate goods production function, $\alpha = 0.21$. This value is lower than the common calibration in real business cycle models because, in our environment, we have positive profits that appear as capital income in the National Income and Product Accounts. Finally, the adjustment cost, $\kappa = 9.5$, is in line with other estimates from similar models (κ would be particularly hard to identify, since investment is not one of our observables).

The autoregressive parameter of the evolution of the response to inflation, ρ_{γ_Π}, is set to 0.95. In preliminary estimations, we discovered that the likelihood pushed this parameter to 1. When this happened, the simulations became numerically unstable: after a series of positive innovations to $\log \gamma_{\Pi t}$, the reaction of nominal interest rates to inflation could be too tepid for too long. The 0.95 value seems to be the highest value of ρ_{γ_Π} such that the problem does not appear. The last two parameters, ρ_{γ_y} and σ_y, are equal to zero because, also in exploratory estimations, the likelihood favored values of $\sigma_y \approx 0$. Thus, we decided to forget about them and make $\gamma_{y,t} = 1$.

To find the posterior, we proceed as follows. First, we define a grid of parameter values and check for the regions of high posterior density by evaluating the likelihood function in each point of the grid. This is a time-consuming procedure, but it ensures that we are searching in the right zone of the parameter space. Once we have identified the global maximum in the grid, we initialize a random-walk Metropolis-Hastings algorithm from this point. After an extensive fine-tuning of the algorithm, we use 10,000 draws from the chain to compute posterior moments.

5.7. Results I: Parameter Estimates

Our first empirical result is the parameter estimates. To ease the discussion, we group them in different tables, one for each set of parameters dealing with related aspects of the model. In all cases, we report the mode of the posterior and the standard deviation in parenthesis below (in the interest of space, we do not include the whole histograms of the posterior).

Table 5.2 presents the results for the nominal rigidities and the stochastic processes for the structural shock parameters. Our estimates indicate an economy with substantial rigidities in prices, which are reoptimized roughly once every five quarters, and in wages, which are reoptimized approximately every three quarters. Moreover, since the standard deviations are small, there is enough information in the data about this result. At the same time, there is a fair amount of indexation, between 0.62-0.63, which brings a strong persistence of inflation. While it is tempting to compare our estimates with the micro evidence on the individual duration of prices, in our model all prices and wages change every quarter. That is why, to a naive observer, our economy would look like one displaying tremendous price flexibility.

We estimate a low persistence of the intertemporal preference shock and a high persistence of the intratemporal one. The low estimate of ρ_d produces the quick variations in marginal utilities of consumption that match output growth and inflation fluctuations. The intratemporal shock is persistent to account for long-lived movements in hours worked. We estimate mean growth rates of technology of 0.0034 (neutral) and 0.0028 (investment-specific). Those numbers give us an average growth of the economy of 0.44 percent per quarter (0.46 in the data). Technology shocks, in our model, are deviations with respect to these drifts. Thus, we estimate that A_t falls in only 8 of the 192 quarters in our sample (which roughly corresponds to the percentage of quarters where measured productivity falls in the data), even if we estimate negative innovations to neutral technology in 103 quarters.

The results for the parameters of the stochastic volatility processes appear in table 5.3. In all cases, the ρ's and the η's are far away from zero: the likelihood strongly favors values where stochastic volatility plays an important role. The standard deviations of the innovations of the intertemporal preference shock and of the monetary policy shock are the most persistent, while the standard deviation of the innovation of the intratemporal preference shock is the least persistent. The standard deviation of the innovations of the volatility shock to the intratemporal preference shock, $\eta_\varphi = 2.8316$, is large: the model asks for fast changes in the size of movements in marginal utilities of leisure to reproduce the hours data.

In table 5.4., we have the estimates of the policy parameters. The autoregressive component of the federal funds rate is high, 0.7855, although somewhat smaller than in estimations without parameter drift. The value of γ_y (0.24 in levels) is similar to other results in the literature and shows that the likelihood clearly likes parameter drifting, although with mild persistence. The estimated value of Π plus the correction on equilibrium inflation implied by second-order effects of the solution match the average inflation in the data.[3] Finally, the estimated value of γ_Π (1.045 in levels) guarantees local determinacy of the equilibrium even if $\gamma_{\Pi,t}$ is temporarily below 1 (see appendix **??** for details).

In appendix 6.2 we plot the impulse response functions of the model implied by our estimates. This exercise allows us to check that the estimates are sensible and that the behavior of the model is consistent with the behavior of related models in the literature. In appendix 6.3 we compare our model against an alternative version without parameter drifting but still with stochastic volatility. That is, we ask whether, once we have included stochastic volatility, it is still important to allow for changes in the monetary policy rule to account for the time-varying volatility of U.S. aggregate data over the last several decades. The results show that, even after controlling for stochastic volatility, the data strongly prefer a specification where the monetary policy rule has changed over time. In appendix 6.4 we show that this finding does not imply that volatility shocks did not play an important role in the time-varying volatilities of U.S. aggregate time series. In other words, both stochastic volatility and parameter drifting are key parts of a successful dynamic equilibrium

[3] Also, these second-order effects complicate the introduction of time-variation in Π. The likelihood wants to match the moments of the ergodic distribution of inflation, not the level of Π, which is inflation along the balanced growth path. When we have non-linearities, the mean of that ergodic distribution may be far from Π. Thus, learning about Π is hard. Learning about a time-varying Π is even harder.

model of the U.S. economy.

5.8. Results II: Smoothed Shocks

Figure 5.1 reports the log-deviations with respect to their means for the smoothed intertemporal, intratemporal, and monetary shocks and deviations of the growth rate of the investment and technological shocks with respect to their means (± 2 standard deviations). We color different vertical bars to represent each of the periods at the Federal Reserve: the Martin years from the start of our sample in 1959 to the appointment of Burns in February 1970 (white), the Burns-Miller era (light blue), the Volcker interlude from August 1979 to August 1987 (grey), the Greenspan times (orange), and Bernanke's tenure from February 2006 (yellow).

We see in the top left panel of figure 5.1 that the intertemporal shock, $\log d_t$, is particularly high in the 1970s. This increases households' desire for current consumption (for instance, because of the entrance of baby boomers into adulthood). A higher aggregate demand triggers, in the model, the higher inflation observed in the data for those years. The shock has a dramatic drop in the second quarter of 1980. This is precisely the quarter in which the Carter administration invoked the Credit Control Act (March 14, 1980). Schreft (1990) documents that this measure caused turmoil in financial markets and, most likely, distorted intertemporal choices of households, which is reflected in the large negative innovation to $\log d_t$. The low values of $\log d_t$ in the 1990s with respect to the 1970s and 1980s eased the inflationary pressures in the economy.

The shock to the utility of leisure, $\log \varphi_t$, grows in the 1970s and falls in the 1980s to stabilize at a very low value in the 1990s. The likelihood wants to track, in this way, the path of average hours worked: low in the 1970s, increasing in the 1980s, and stabilizing in the 1990s. Higher hours also lower the marginal cost of firms (wages fall relative to the technology level). The reduction in marginal costs also helped to reduce inflation during Greenspan's tenure.

The evolution of the investment-specific technology, $\log \widetilde{\mu}_t$, shows a sharp drop after 1973 (when it is likely that energy-intensive capital goods suffered the consequences of the oil shocks in the form of economic obsolescence) and large positive realizations in the late 1990s (our model interprets the sustained boom of those years as the consequence of strong improvements in investment technology). These positive realizations were an additional help to contain inflation during the 1990s. In comparison, the neutral-technology shocks, $\log \widetilde{A}_t$, have been stable since 1959, with only a few big shocks at the end of the sample.

The evolution of the monetary policy shock, $\log \xi_t$, reveals large innovations in the early 1980s. This is due both to the fast change in policy brought about by Volcker and to the fact that a Taylor rule might not fully capture the dynamics of monetary policy during a period in which money growth targeting was attempted. Sims and Zha (2006) also find that the Volcker period appears to be one with large disturbances to the policy rule and argue that the Taylor rule formalism can be a misleading perspective from which to view policy during that time. Our evidence from the estimated intertemporal, intratemporal, and investment shocks suggests that monetary authorities faced a more difficult environment in the 1970s and early 1980s than in the 1990s.

As a way to gauge the level of uncertainty of our smoothed estimates, we also plot in figure 5.1 the same shock (± 2 standard deviations). In all cases, the data are informative about the history we just narrated.

We plot, in figure 5.2, the evolution of the volatility shocks, all of them in log-deviations with respect to their estimated means (plus/minus two standard deviations). We see in this figure that the standard deviation of the intertemporal shock was particularly high in the 1970s and only slowly went down during the 1980s and early 1990s. By the end of the sample, the standard deviation of the intertemporal shock was roughly at the level where it started. In comparison, the standard deviation of all the other shocks is relatively stable except, perhaps, for a large drop in the standard deviation of the monetary policy shock in the early 1980s as well as large changes in the standard deviation of the investment shock during the period of the oil price shocks. Hence, the 1970s and the 1980s were more volatile than the 1960s and the 1990s, creating a tougher environment for monetary policy. This result also confirms Blanchard and Simon's (2001) and Nason and Smith's (2008) observation that volatility had a downward trend in the 20th century with an abrupt and temporal increase in the 1970s. Also, from the size of the plus/minus two standard deviations, we conclude that the big movements in the different series that we report can be ascertained with a reasonable degree of confidence.

Finally, in figure 5.3, we plot the evolution of the response of monetary policy to inflation plus/minus a two-standard-deviation interval. In particular, we graph $\gamma_{\Pi}\gamma_{\Pi t}$. This graph shows us an intriguing narrative. The parameter started the sample around its estimated mean, slightly over 1, and it grew more or less steadily during the 1960s until reaching a peak in early 1968. After that year, it suffered a fast collapse that took it below 1 in 1971. To put this evolution in perspective, it is useful to remember that Burns was appointed chairman in February 1970. The parameter stayed below 1 for all of the 1970s. The arrival of Volcker is quickly picked up by our smoothed estimates: it increases to over 2 after a few months and stays high during all the years of Volcker's tenure. Our estimate captures well the observation by Goodfriend and King (2007) that monetary policy tightened in the spring of 1980 as inflation and long-run inflation expectations continued to grow. Its level stayed roughly constant at this high during the remainder of Volcker's tenure. But as quickly as it rose when Volcker arrived, it went down again when he departed. Greenspan's tenure at the Fed meant that, by 1990, the response of the monetary authority to inflation was again below 1. Moreover, our estimates are relatively tight. Fernández-Villaverde *et* *al.* (2010a) discuss how the results of the estimation relate to historical evidence.

6. Conclusion

In this paper, we have shown how to estimate dynamic equilibrium models with stochastic volatility. The key to the procedure is to realize that a second-order perturbation to the solution of this class of models has a very particular structure that can be easily exploited to build an efficient particle filter. The recent boom in the literature on dynamic equilibrium models with stochastic volatility suggests that this procedure may have many uses. Our characterization of the solution might also be, on many occasions, of interest in itself to understand the dynamic properties of the equilibrium even if the researcher does not want to estimate the model.

As an application to illustrate how the procedure works we have estimated a business cycle model with both stochastic volatility in the structural shocks that drive the economy and parameter drifting in the monetary policy rule. Such a model is motivated by the need to have an empirical framework where we can account for the time-varying volatility of U.S. aggregate time series. In particular, we have explained how you obtain point estimates in such a model and how to recover and analyze the smoothed structural and volatility shocks. Finally, through different comments -even if brief and not exhaustive- we have discussed the different empirical lessons that one can learn from all these steps.

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Table 3.1: Second Derivatives

$\mathcal{S}_t\mathcal{S}_t \neq 0$	$\mathcal{S}_t\mathcal{Z}_{t-1} \neq 0$	$\mathcal{S}_t\Sigma_{t-1} = 0$	$\mathcal{S}_t\mathcal{E}_t \neq 0$	$\mathcal{S}_t\mathcal{U}_t = 0$	$\mathcal{S}_t\Lambda = 0$
	$\mathcal{Z}_{t-1}\mathcal{Z}_{t-1} \neq 0$	$\mathcal{Z}_{t-1}\Sigma_{t-1} = 0$	$\mathcal{Z}_{t-1}\mathcal{E}_t \neq 0$	$\mathcal{Z}_{t-1}\mathcal{U}_t = 0$	$\mathcal{Z}_{t-1}\Lambda = 0$
		$\Sigma_{t-1}\Sigma_{t-1} = 0$	$\Sigma_{t-1}\mathcal{E}_t \neq 0^*$	$\Sigma_{t-1}\mathcal{U}_t = 0$	$\Sigma_{t-1}\Lambda = 0$
			$\mathcal{E}_t\mathcal{E}_t \neq 0$	$\mathcal{E}_t\mathcal{U}_t \neq 0^*$	$\mathcal{E}_t\Lambda = 0$
				$\mathcal{U}_t\mathcal{U}_t = 0$	$\mathcal{U}_t\Lambda = 0$
					$\Lambda\Lambda \neq 0$

Table 5.1: Fixed Parameters

β	h	ψ	ϑ	δ	α	κ	ε	η	Φ_2	ρ_{γ_Π}	ρ_{γ_y}	σ_y
0.99	0.9	8	1.17	0.025	0.21	9.5	10	10	0.001	0.95	0	0

Table 5.2: Posterior, Parameters of Nominal Rigidities and Structural Shocks

θ_p	χ	θ_w	χ_w	ρ_d	ρ_φ	Λ_μ	Λ_A
0.8139 (0.0143)	0.6186 (0.024)	0.6869 (0.0432)	0.6340 (0.0074)	0.1182 (0.0049)	0.9331 (0.0425)	0.0034 ($6.6e{-5}$)	0.0028 ($4.1e{-5}$)

Table 5.3: Posterior, Parameters of the Stochastic Processes for Volatility Shocks

$\log\sigma_d$	$\log\sigma_\varphi$	$\log\sigma_\mu$	$\log\sigma_A$	$\log\sigma_\xi$
-1.9834 (0.0726)	-2.4983 (0.0917)	-6.0283 (0.1278)	-3.9013 (0.0745)	-6.000 (0.1471)
ρ_{σ_d}	ρ_{σ_φ}	ρ_{σ_μ}	ρ_{σ_a}	ρ_{σ_ξ}
0.9506 (0.0298)	0.1275 (0.0032)	0.7508 (0.035)	0.2411 (0.005)	0.8550 (0.0231)
η_d	η_φ	η_μ	η_a	η_ξ
0.1007 (0.0083)	2.8316 (0.0669)	0.3115 (0.006)	0.7720 (0.013)	0.5723 (0.0185)

Table 5.4: Posterior, Policy Parameters

γ_R	$\log\gamma_y$	Π	$\log\gamma_\Pi$	σ_π
0.7855 (0.0162)	−1.4034 (0.0498)	1.0005 (0.0043)	0.0441 (0.0005)	0.145 (0.002)

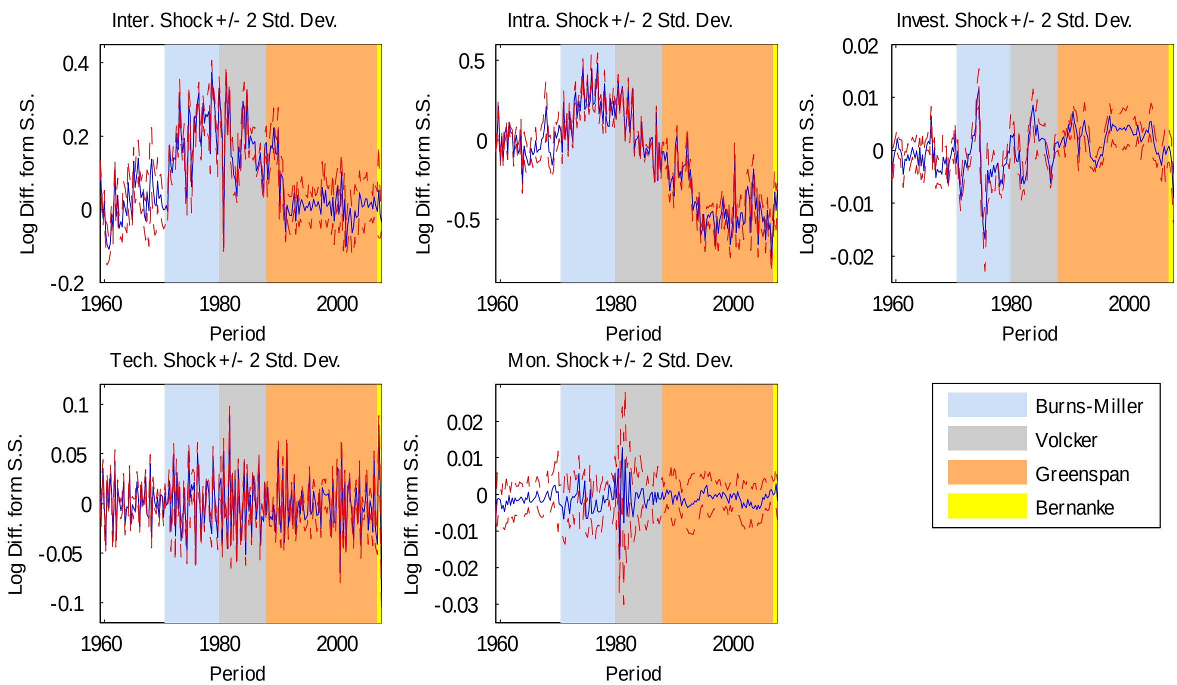

Figure 5.1: Smoothed intertemporal ($\log d_t$) shock, intratemporal ($\log\varphi_t$) shock, investment-specific ($\log\widetilde{\mu}_t$) shock, technology ($\log\widetilde{A}_t$) shock, and monetary policy ($\log\xi_t$) shock +/- 2 s.d.

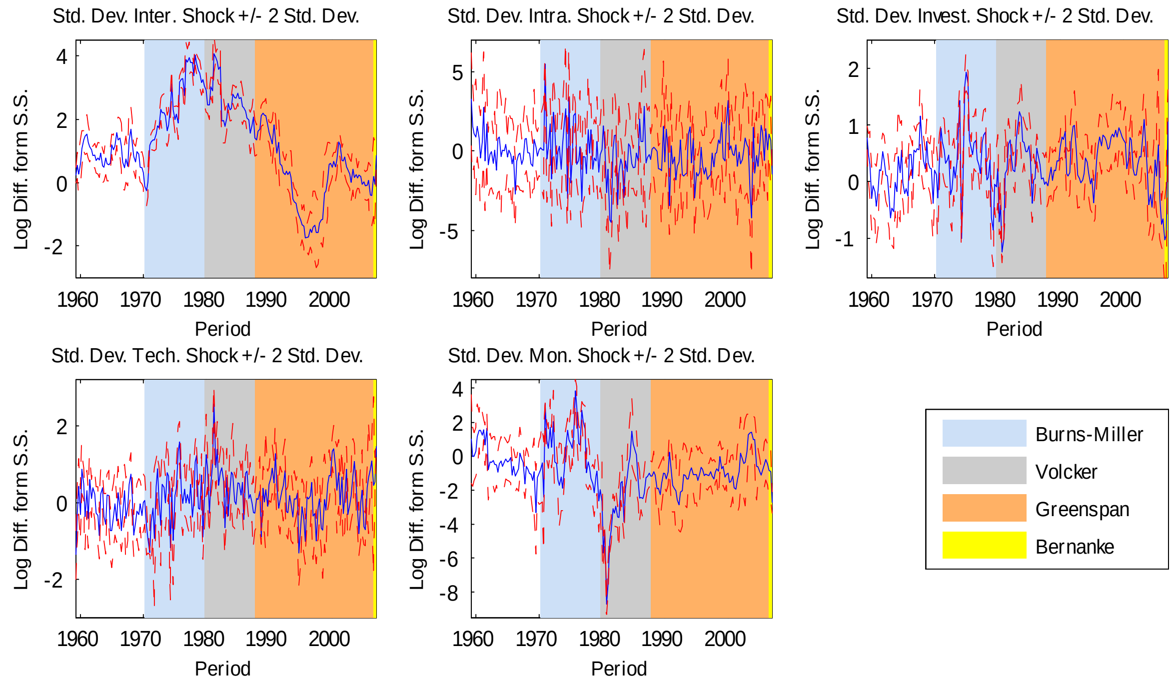

Figure 5.2: Smoothed standard deviation shocks to the intertemporal ($\log \sigma_{dt}$) shock, the intratemporal ($\log \sigma_{\phi t}$) shock, the investment-specific ($\log \sigma_{\mu t}$) shock, the technology ($\log \sigma_{At}$) shock, and the monetary policy ($\log \sigma_{\xi t}$) shock +/- 2 s.d.

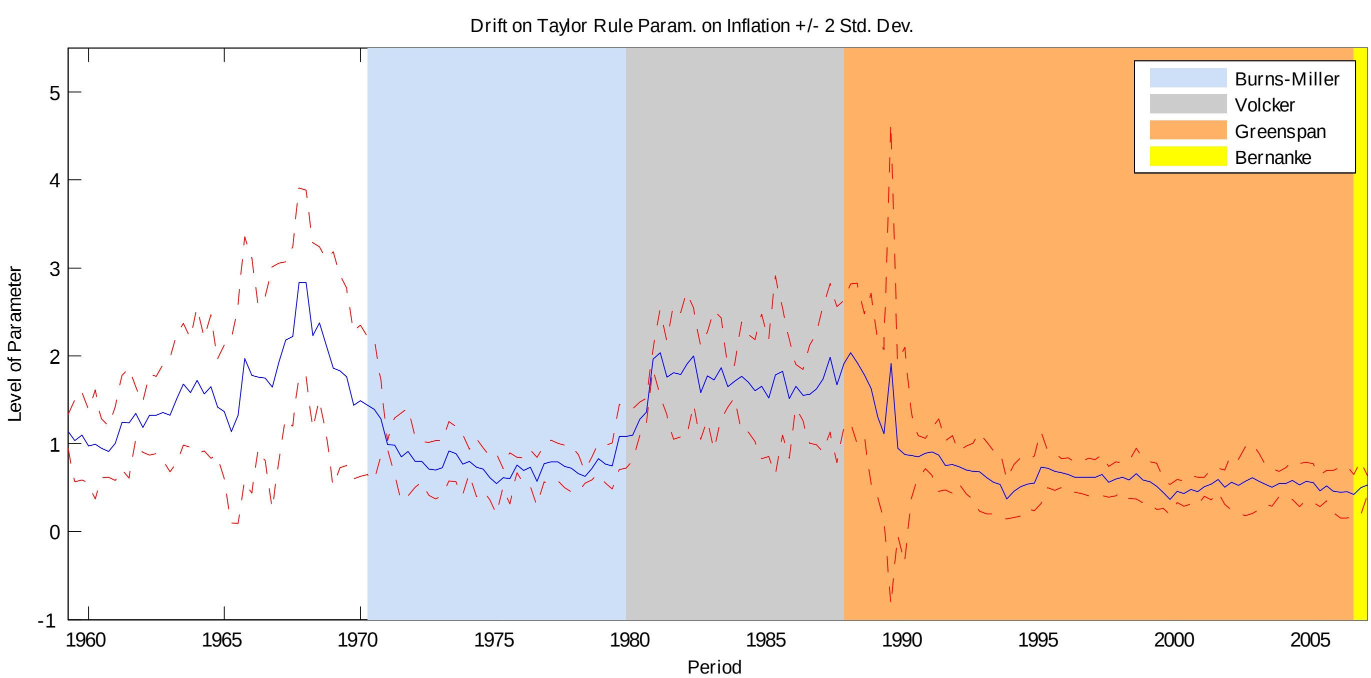

Figure 5.3: Smoothed path for the Taylor rule parameter on inflation +/- 2 standard deviations.

1. Technical Appendix (Not for Publication)

This technical appendix is organized as follows. First, it presents the proofs of theorems 2 and 3. Second, it describes the equilibrium of the model in more detail. Third, it shows how parameter drifting in the monetary policy rule does not appear in the first-order approximation. Fourth, it offers details on how we built the data. Finally, it includes some additional empirical results.

2. Proofs

2.1. Theorem 2

We start by proving theorem 2, which characterizes the first-order derivatives of the policy functions h and g evaluated at the steady state. We first show that the first partial derivatives of h and g with respect to any component of Σ_{t-1}, $\mathcal{U}_t$, or Λ evaluated at the steady state are zero (in other words, that the first-order approximation of the policy functions do not depend on volatility shocks nor their innovations nor on the perturbation parameter). Before proceeding, note that using (2), we can write $\mathcal{Z}_{t+1}$, in a compact manner, as a function of $\mathcal{Z}_t, \Sigma_t, \mathcal{E}_{t+1}$, $\mathcal{U}_{t+1}$, and Λ

$$\mathcal{Z}_{t+1} = \varsigma\left(\mathcal{Z}_t, \Sigma_t, \Lambda\mathcal{E}_{t+1}, \Lambda\mathcal{U}_{t+1}; \gamma\right), \tag{26}$$

that using (3) Σ_{t+1} can be expressed as a function of Σ_t, $\mathcal{U}_{t+1}$, and Λ

$$\Sigma_{t+1} = \vartheta\Sigma_t + \eta\Lambda\mathcal{U}_{t+1}, \tag{27}$$

that using (4) we can write $\mathcal{Z}_t$ as a function of $\mathcal{Z}_{t-1}, \Sigma_{t-1}, \mathcal{E}_t$, and $\mathcal{U}_t$

$$\mathcal{Z}_t = \varsigma\left(\mathcal{Z}_{t-1}, \Sigma_{t-1}, \mathcal{E}_t, \mathcal{U}_t; \gamma\right), \tag{28}$$

and that using (5) Σ_t can be expressed as

$$\Sigma_t = \vartheta\Sigma_{t-1} + \eta\mathcal{U}_t \tag{29}$$

where ϑ and η are both $m \times m$ diagonal matrices with diagonal elements equal to ϑ_i and $\left(1-\vartheta_i^2\right)^{\frac{1}{2}}\eta_i$ respectively. If we substitute the policy functions (6)-(8) and (26)-(29) into the set of equilibrium conditions (1), we get that

$$F\left(\mathcal{S}_t, \mathcal{Z}_{t-1}, \Sigma_{t-1}, \mathcal{E}_t, \mathcal{U}_t, \Lambda\right) \equiv$$

$$\mathbb{E}_t f \left(\begin{array}{c} g\left(h\left(\mathcal{S}_t, \mathcal{Z}_{t-1}, \Sigma_{t-1}, \mathcal{E}_t, \mathcal{U}_t, \Lambda\right), \varsigma\left(\mathcal{Z}_{t-1}, \Sigma_{t-1}, \mathcal{E}_t, \mathcal{U}_t\right), \vartheta\Sigma_{t-1} + \eta\mathcal{U}_t, \Lambda\mathcal{E}_{t+1}, \Lambda\mathcal{U}_{t+1}, \Lambda\right), \\ g\left(\mathcal{S}_t, \mathcal{Z}_{t-1}, \Sigma_{t-1}, \mathcal{E}_t, \mathcal{U}_t, \Lambda\right), h\left(\mathcal{S}_t, \mathcal{Z}_{t-1}, \Sigma_{t-1}, \mathcal{E}_t, \mathcal{U}_t, \Lambda\right), \mathcal{S}_t, \\ \varsigma\left(\varsigma\left(\mathcal{Z}_{t-1}, \Sigma_{t-1}, \mathcal{E}_t, \mathcal{U}_t\right), \vartheta\Sigma_{t-1} + \eta\mathcal{U}_t, \Lambda\mathcal{E}_{t+1}, \Lambda\mathcal{U}_{t+1}\right), \varsigma\left(\mathcal{Z}_{t-1}, \Sigma_{t-1}, \mathcal{E}_t, \mathcal{U}_t\right) \end{array} \right) = 0$$

where, to ease notation, we do not explicitly write that the functions above depend on γ.

Proof. We want to show that

$$\left[h_{\Sigma_{t-1}}\right]_j^{i_1} = \left[g_{\Sigma_{t-1}}\right]_j^{i_2} = \left[h_{\mathcal{U}_t}\right]_j^{i_1} = \left[g_{\mathcal{U}_t}\right]_j^{i_2} = \left[h_\Lambda\right]^{i_1} = \left[g_\Lambda\right]^{i_2} = 0$$

for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, and $j \in \{1, \ldots, m\}$.

We show this result in three steps that basically repeat the same argument based on the homogeneity of a system of linear equations:

1. We write the derivative of the $i-th$ element of F with respect to the $j-th$ element of Σ_{t-1} as

$$\left[F_{\Sigma_{t-1}}\right]_j^i = \left[f_{\mathcal{Y}_{t+1}}\right]_{i_2}^i \left(\left[g_{\mathcal{S}_t}\right]_{i_1}^{i_2} \left[h_{\Sigma_{t-1}}\right]_j^{i_1} + \left[g_{\Sigma_{t-1}}\right]_j^{i_2} \vartheta_j\right) + \left[f_{\mathcal{Y}_t}\right]_{i_2}^i \left[g_{\Sigma_{t-1}}\right]_j^{i_2} + \left[f_{\mathcal{S}_{t+1}}\right]_{i_1}^i \left[h_{\Sigma_{t-1}}\right]_j^{i_1} = 0$$

for $i \in \{1, \ldots, k+n+m\}$ and $j \in \{1, \ldots, m\}$. This is a homogeneous system on $\left[h_{\Sigma_{t-1}}\right]_j^{i_1}$ and $\left[g_{\Sigma_{t-1}}\right]_j^{i_2}$ for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, and $j \in \{1, \ldots, m\}$. Thus

$$\left[h_{\Sigma_{t-1}}\right]_j^{i_1} = \left[g_{\Sigma_{t-1}}\right]_j^{i_2} = 0$$

for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, and $j \in \{1, \ldots, m\}$.

2. We write the derivative of the $i-th$ element of F with respect to the $j-th$ element of $\mathcal{U}_t$ as

$$\left[F_{\mathcal{U}_t}\right]_j^i = \left[f_{\mathcal{Y}_{t+1}}\right]_{i_2}^i \left(\left[g_{\mathcal{S}_t}\right]_{i_1}^{i_2} \left[h_{\mathcal{U}_t}\right]_j^{i_1} + \left[g_{\Sigma_{t-1}}\right]_j^{i_2} \left(1-\vartheta_j^2\right)^{\frac{1}{2}} \eta_j\right) + \left[f_{\mathcal{Y}_t}\right]_{i_2}^i \left[g_{\mathcal{U}_t}\right]_j^{i_2} + \left[f_{\mathcal{S}_{t+1}}\right]_{i_1}^i \left[h_{\mathcal{U}_t}\right]_j^{i_1} = 0$$

for $i \in \{1, \ldots, k+n+m\}$ and $j \in \{1, \ldots, m\}$. Since we have already shown that $\left[g_{\Sigma_{t-1}}\right]_j^{i_2} =$

0 for $i_2 \in \{1, \dots, k\}$ and $j \in \{1, \dots, m\}$, this is a homogeneous system on $[h_{\mathcal{U}_t}]_j^{i_1}$ and $[g_{\mathcal{U}_t}]_j^{i_2}$ for $i_1 \in \{1, \dots, n\}$, $i_2 \in \{1, \dots, k\}$, and $j \in \{1, \dots, m\}$. Thus

$$[h_{\mathcal{U}_t}]_j^{i_1} = [g_{\mathcal{U}_t}]_j^{i_2} = 0$$

for $i_1 \in \{1, \dots, n\}$, $i_2 \in \{1, \dots, k\}$, and $j \in \{1, \dots, m\}$.

3. Finally, we write the derivative of the $i - th$ element of F with respect to Λ as

$$[F_\Lambda]^i = \left[f_{\mathcal{Y}_{t+1}}\right]_{i_2}^i \left([g_{\mathcal{S}_t}]_{i_1}^{i_2} [h_\Lambda]^{i_1} + [g_\Lambda]^{i_2} \right) + [f_{\mathcal{Y}_t}]_{i_2}^i [g_\Lambda]^{i_2} + \left[f_{\mathcal{S}_{t+1}}\right]_{i_1}^i [h_\Lambda]^{i_1} = 0$$

for $i \in \{1, \dots, k+n+m\}$. Since this is a homogeneous system on $[h_\Lambda]^{i_1}$ and $[g_\Lambda]^{i_2}$ for $i_1 \in \{1, \dots, n\}$ and $i_2 \in \{1, \dots, k\}$, we have that

$$[h_\Lambda]^{i_1} = [g_\Lambda]^{i_2} = 0$$

for $i_1 \in \{1, \dots, n\}$ and $i_2 \in \{1, \dots, k\}$.

■

2.2. Theorem 3

Let us now prove theorem 3. We show, among other things, that the second partial derivatives of h and g with respect to either $\log \sigma_{it}$ or $u_{i,t}$ and any other variable but $\varepsilon_{i,t}$ are also zero for any $i \in \{1, \dots, m\}$. We divide the proof into three parts.

Proof, part 1. The first part of the proof deals with the cross-derivatives of the policy functions h and g with respect to Λ and any of $\mathcal{S}_t$, $\mathcal{Z}_{t-1}$, Σ_{t-1}, $\mathcal{E}_t$, or $\mathcal{U}_t$ and it shows that all of them are equal to zero. In particular, we want to show that

$$[h_{\Lambda,\mathcal{S}_t}]_j^{i_1} = [g_{\Lambda,\mathcal{S}_t}]_j^{i_2} = 0$$

for $i_1 \in \{1, \dots, n\}$, $i_2 \in \{1, \dots, k\}$, and $j \in \{1, \dots, n\}$ and

$$\left[h_{\Lambda,\mathcal{Z}_{t-1}}\right]_j^{i_1} = \left[g_{\Lambda,\mathcal{Z}_{t-1}}\right]_j^{i_2} = \left[h_{\Lambda,\Sigma_{t-1}}\right]_j^{i_1} = \left[g_{\Lambda,\Sigma_{t-1}}\right]_j^{i_2} = [h_{\Lambda,\mathcal{E}_t}]_j^{i_1} = [g_{\Lambda,\mathcal{E}_t}]_j^{i_2} = [h_{\Lambda,\mathcal{U}_t}]_j^{i_1} = [g_{\Lambda,\mathcal{U}_t}]_j^{i_2} = 0$$

for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, and $j \in \{1, \ldots, m\}$.

We show this result in five steps. We again exploit the homogeneity of a system of linear equations.

1. We consider the cross-derivative of the $i-th$ element of F with respect to Λ and the $j-th$ element of $\mathcal{S}_t$

   $$[F_{\Lambda,\mathcal{S}_t}]^i_j = \left[f_{\mathcal{Y}_{t+1}}\right]^i_{i_2} \left([g_{\mathcal{S}_t}]^{i_2}_{i_1} [h_{\Lambda,\mathcal{S}_t}]^{i_1}_j + [g_{\Lambda,\mathcal{S}_t}]^{i_2}_{i_1} [h_{\mathcal{S}_t}]^{i_1}_j\right) + [f_{\mathcal{Y}_t}]^i_{i_2} [g_{\Lambda,\mathcal{S}_t}]^{i_2}_j + \left[f_{\mathcal{S}_{t+1}}\right]^i_{i_1} [h_{\Lambda,\mathcal{S}_t}]^{i_1}_j = 0$$

   for $i \in \{1, \ldots, k+n+m\}$ and $j \in \{1, \ldots, n\}$. This is a homogeneous system on $[h_{\Lambda,\mathcal{S}_t}]^{i_1}_j$ and $[g_{\Lambda,\mathcal{S}_t}]^{i_2}_j$ for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, and $j \in \{1, \ldots, n\}$. Thus

   $$[h_{\Lambda,\mathcal{S}_t}]^{i_1}_j = [g_{\Lambda,\mathcal{S}_t}]^{i_2}_j = 0$$

   for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, and $j \in \{1, \ldots, n\}$.

2. We consider the cross-derivative of the $i-th$ element of F with respect to Λ and the $j-th$ element of $\mathcal{Z}_{t-1}$

   $$\left[F_{\Lambda,\mathcal{Z}_{t-1}}\right]^i_j = \left[f_{\mathcal{Y}_{t+1}}\right]^i_{i_2} \left([g_{\mathcal{S}_t}]^{i_2}_{i_1} \left[h_{\Lambda,\mathcal{Z}_{t-1}}\right]^{i_1}_j + [g_{\Lambda,\mathcal{S}_t}]^{i_2}_{i_1} \left[h_{\mathcal{Z}_{t-1}}\right]^{i_1}_j + \left[g_{\Lambda,\mathcal{Z}_{t-1}}\right]^{i_2}_j \rho_j\right)$$
   $$+ [f_{\mathcal{Y}_t}]^i_{i_2} \left[g_{\Lambda,\mathcal{Z}_{t-1}}\right]^{i_2}_j + \left[f_{\mathcal{S}_{t+1}}\right]^i_{i_1} \left[h_{\Lambda,\mathcal{Z}_{t-1}}\right]^{i_1}_j = 0$$

   for $i \in \{1, \ldots, k+n+m\}$ and $j \in \{1, \ldots, m\}$. Since $[g_{\Lambda,\mathcal{S}_t}]^{i_2}_j = 0$ for $i_2 \in \{1, \ldots, k\}$ and $j \in \{1, \ldots, n\}$, this is a homogeneous system on $\left[h_{\Lambda,\mathcal{Z}_{t-1}}\right]^{i_1}_j$ and $\left[g_{\Lambda,\mathcal{Z}_{t-1}}\right]^{i_2}_j$ for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, and $j \in \{1, \ldots, m\}$. Hence

   $$\left[h_{\Lambda,\mathcal{Z}_{t-1}}\right]^{i_1}_j = \left[g_{\Lambda,\mathcal{Z}_{t-1}}\right]^{i_2}_j = 0$$

   for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, and $j \in \{1, \ldots, m\}$.

3. We consider the cross-derivative of the $i-th$ element of F with respect to Λ and the $j-th$

element of Σ_{t-1}

$$\left[F_{\Lambda,\Sigma_{t-1}}\right]_j^i = \left[f_{\mathcal{Y}_{t+1}}\right]_{i_2}^i \left(\left[g_{\mathcal{S}_t}\right]_{i_1}^{i_2} \left[h_{\Lambda,\Sigma_{t-1}}\right]_j^{i_1} + \left[g_{\Lambda,\Sigma_{t-1}}\right]_j^{i_2} \vartheta_j \right)$$
$$+ \left[f_{\mathcal{Y}_t}\right]_{i_2}^i \left[g_{\Lambda,\Sigma_{t-1}}\right]_j^{i_2} + \left[f_{\mathcal{S}_{t+1}}\right]_{i_1}^i \left[h_{\Lambda,\Sigma_{t-1}}\right]_j^{i_1} = 0$$

for $i \in \{1, \ldots, k+n+m\}$ and $j \in \{1, \ldots, m\}$. This is a homogeneous system on $\left[h_{\Lambda,\Sigma_{t-1}}\right]_j^{i_1}$ and $\left[g_{\Lambda,\Sigma_{t-1}}\right]_j^{i_2}$ for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, and $j \in \{1, \ldots, m\}$. Hence

$$\left[h_{\Lambda,\Sigma_{t-1}}\right]_j^{i_1} = \left[g_{\Lambda,\Sigma_{t-1}}\right]_j^{i_2} = 0$$

for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, and $j \in \{1, \ldots, m\}$.

4. We consider the cross-derivative of the $i-th$ element of F with respect to Λ and the $j-th$ element of $\mathcal{E}_t$

$$\left[F_{\Lambda,\mathcal{E}_t}\right]_j^i = \left[f_{\mathcal{Y}_{t+1}}\right]_{i_2}^i \left(\left[g_{\mathcal{S}_t}\right]_{i_1}^{i_2} \left[h_{\Lambda,\mathcal{E}_t}\right]_j^{i_1} + \left[g_{\Lambda,\mathcal{S}_t}\right]_{i_1}^{i_2} \left[h_{\mathcal{E}_t}\right]_j^{i_1} + \left[g_{\Lambda,\mathcal{Z}_{t-1}}\right]_j^{i_2} \sigma_j \exp^{\vartheta_j \log \sigma_{j,t-1}} \right)$$
$$+ \left[f_{\mathcal{Y}_t}\right]_{i_2}^i \left[g_{\Lambda,\mathcal{E}_t}\right]_j^{i_2} + \left[f_{\mathcal{S}_{t+1}}\right]_{i_1}^i \left[h_{\Lambda,\mathcal{E}_t}\right]_j^{i_1} = 0$$

for $i \in \{1, \ldots, k+n+m\}$ and $j \in \{1, \ldots, m\}$. Since $\left[g_{\Lambda,\mathcal{Z}_{t-1}}\right]_j^{i_2} = 0$ for $i_2 \in \{1, \ldots, k\}$ and $j \in \{1, \ldots, m\}$ and $\left[g_{\Lambda,\mathcal{S}_t}\right]_j^{i_2} = 0$ for $i_2 \in \{1, \ldots, k\}$ and $j \in \{1, \ldots, n\}$, this is a homogeneous system on $\left[h_{\Lambda,\mathcal{E}_t}\right]_j^{i_1}$ and $\left[g_{\Lambda,\mathcal{E}_t}\right]_j^{i_2}$ for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, and $j \in \{1, \ldots, m\}$. Thus

$$\left[h_{\Lambda,\mathcal{E}_t}\right]_j^{i_1} = \left[g_{\Lambda,\mathcal{E}_t}\right]_j^{i_2} = 0$$

for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, and $j \in \{1, \ldots, m\}$.

5. We consider the cross-derivative of the $i-th$ element of F with respect to Λ and the $j-th$ element of $\mathcal{U}_t$

$$\left[F_{\Lambda,\mathcal{U}_t}\right]_j^i = \left[f_{\mathcal{Y}_{t+1}}\right]_{i_2}^i \left(\left[g_{\mathcal{S}_t}\right]_{i_1}^{i_2} \left[h_{\Lambda,\mathcal{U}_t}\right]_j^{i_1} + \left[g_{\Lambda,\Sigma_{t-1}}\right]_j^{i_2} \left(1-\vartheta_j^2\right)^{\frac{1}{2}} \eta_j \right)$$
$$+ \left[f_{\mathcal{Y}_t}\right]_{i_2}^i \left[g_{\Lambda,\mathcal{U}_t}\right]_j^{i_2} + \left[f_{\mathcal{S}_{t+1}}\right]_{i_1}^i \left[h_{\Lambda,\mathcal{U}_t}\right]_j^{i_1} = 0$$

for $i \in \{1, \ldots, k+n+m\}$ and $j \in \{1, \ldots, m\}$. Since we have shown that $\left[g_{\Lambda,\Sigma_{t-1}}\right]_j^{i_2} = 0$ for

$i_2 \in \{1, \ldots, k\}$ and $j \in \{1, \ldots, m\}$, we have that the above system is a homogeneous system on $[h_{\Lambda,\mathcal{U}_t}]_j^{i_1}$ and $[g_{\Lambda,\mathcal{U}_t}]_j^{i_2}$ for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, and $j \in \{1, \ldots, m\}$. Then

$$[h_{\Lambda,\mathcal{U}_t}]_j^{i_1} = [g_{\Lambda,\mathcal{U}_t}]_j^{i_2} = 0$$

for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, and $j \in \{1, \ldots, m\}$.

■

Proof, part 2. The second part of the proof deals with the cross-derivatives of the policy functions h and g with respect to Σ_{t-1} and any of $\mathcal{S}_t$, $\mathcal{Z}_{t-1}$, Σ_{t-1}, or $\mathcal{E}_t$ and it shows that all of them are equal to zero with one exception. In particular, we want to show that

$$\left[h_{\mathcal{S}_t,\Sigma_{t-1}}\right]_{j_1,j_2}^{i_1} = \left[g_{\mathcal{S}_t,\Sigma_{t-1}}\right]_{j_1,j_2}^{i_2} = 0$$

for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, $j_1 \in \{1, \ldots, n\}$, and $j_2 \in \{1, \ldots, m\}$,

$$\left[h_{\mathcal{Z}_{t-1},\Sigma_{t-1}}\right]_{j_1,j_2}^{i_1} = \left[g_{\mathcal{Z}_{t-1},\Sigma_{t-1}}\right]_{j_1,j_2}^{i_2} = \left[h_{\Sigma_{t-1},\Sigma_{t-1}}\right]_{j_1,j_2}^{i_1} = \left[g_{\Sigma_{t-1},\Sigma_{t-1}}\right]_{j_1,j_2}^{i_2} = 0$$

for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, and $j_1, j_2 \in \{1, \ldots, m\}$, and

$$\left[h_{\mathcal{E}_t,\Sigma_{t-1}}\right]_{j_1,j_2}^{i_1} = \left[g_{\mathcal{E}_t,\Sigma_{t-1}}\right]_{j_1,j_2}^{i_2} = 0$$

for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, and $j_1, j_2 \in \{1, \ldots, m\}$ if $j_1 \neq j_2$.

We show this result in four steps (and where we have already taken advantage of the terms that we know to be equal to zero from previous derivations).

1. We consider the cross-derivative of the $i-th$ element of F with respect to the j_1-th element of $\mathcal{S}_t$ and the $j_2 - th$ element of Σ_{t-1}

$$\left[F_{\mathcal{S}_t,\Sigma_{t-1}}\right]_{j_1,j_2}^{i} = \left[f_{\mathcal{Y}_{t+1}}\right]_{i_2}^{i} \left([g_{\mathcal{S}_t}]_{i_1}^{i_2} \left[h_{\mathcal{S}_t,\Sigma_{t-1}}\right]_{j_1,j_2}^{i_1} + \left[g_{\mathcal{S}_t,\Sigma_{t-1}}\right]_{i_1,j_2}^{i_2} [h_{\mathcal{S}_t}]_{j_1}^{i_1} \vartheta_{j_2} \right)$$
$$+ [f_{\mathcal{Y}_t}]_{i_2}^{i} \left[g_{\mathcal{S}_t,\Sigma_{t-1}}\right]_{j_1,j_2}^{i_2} + \left[f_{\mathcal{S}_{t+1}}\right]_{i_1}^{i} \left[h_{\mathcal{S}_t,\Sigma_{t-1}}\right]_{j_1,j_2}^{i_1} = 0$$

for $i \in \{1, \ldots, k+n+m\}$, $j_1 \in \{1, \ldots, n\}$, and $j_2 \in \{1, \ldots, m\}$. This is a homogeneous system on $\left[h_{\mathcal{S}_t,\Sigma_{t-1}}\right]_{j_1,j_2}^{i_1}$ and $\left[g_{\mathcal{S}_t,\Sigma_{t-1}}\right]_{j_1,j_2}^{i_2}$ for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, $j_1 \in \{1, \ldots, n\}$, and $j_2 \in \{1, \ldots, m\}$. Therefore

$$\left[h_{\mathcal{S}_t,\Sigma_{t-1}}\right]^{i_1}_{j_1,j_2} = \left[g_{\mathcal{S}_t,\Sigma_{t-1}}\right]^{i_2}_{j_1,j_2} = 0$$

for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, $j_1 \in \{1, \ldots, n\}$, and $j_2 \in \{1, \ldots, m\}$.

2. We consider the cross-derivative of the $i-th$ element of F with respect to the j_1-th element of $\mathcal{Z}_{t-1}$ and the $j_2 - th$ element of Σ_{t-1}

$$\begin{aligned} &\left[F_{\mathcal{Z}_{t-1},\Sigma_{t-1}}\right]^{i}_{j_1,j_2} \\ = \left[f_{\mathcal{Y}_{t+1}}\right]^{i}_{i_2} \Big([g_{\mathcal{S}_t}]^{i_2}_{i_1} \left[h_{\mathcal{Z}_{t-1},\Sigma_{t-1}}\right]^{i_1}_{j_1,j_2} &+ \left[g_{\mathcal{S}_t,\Sigma_{t-1}}\right]^{i_2}_{i_1,j_2} \left[h_{\mathcal{Z}_{t-1}}\right]^{i_1}_{j_1} \vartheta_{j_2} + \left[g_{\mathcal{Z}_{t-1},\Sigma_{t-1}}\right]^{i_2}_{j_1,j_2} \rho_{j_1}\vartheta_{j_2} \Big) \\ &+ [f_{\mathcal{Y}_t}]^{i}_{i_2} \left[g_{\mathcal{Z}_{t-1},\Sigma_{t-1}}\right]^{i_2}_{j_1,j_2} + \left[f_{\mathcal{S}_{t+1}}\right]^{i}_{i_1} \left[h_{\mathcal{Z}_{t-1},\Sigma_{t-1}}\right]^{i_1}_{j_1,j_2} = 0 \end{aligned}$$

for $i \in \{1, \ldots, k+n+m\}$, and $j_1, j_2 \in \{1, \ldots, m\}$. Since we just found that $\left[g_{\mathcal{S}_t,\Sigma_{t-1}}\right]^{i_2}_{j_1,j_2} = 0$ for $i_2 \in \{1, \ldots, k\}$, $j_1 \in \{1, \ldots, n\}$, and $j_2 \in \{1, \ldots, m\}$, this is a homogeneous system on $\left[h_{\mathcal{Z}_{t-1},\Sigma_{t-1}}\right]^{i_1}_{j_1,j_2}$ and $\left[g_{\mathcal{Z}_{t-1},\Sigma_{t-1}}\right]^{i_2}_{i_2,j_2}$ for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, and $j_1, j_2 \in \{1, \ldots, m\}$. Therefore

$$\left[h_{\mathcal{Z}_{t-1},\Sigma_{t-1}}\right]^{i_1}_{j_1,j_2} = \left[g_{\mathcal{Z}_{t-1},\Sigma_{t-1}}\right]^{i_2}_{j_1,j_2} = 0$$

for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, and $j_1, j_2 \in \{1, \ldots, m\}$.

3. We consider the cross-derivative of the $i-th$ element of F with respect to the j_1-th element of Σ_{t-1} and the $j_2 - th$ element of Σ_{t-1}

$$\begin{aligned} &\left[F_{\Sigma_{t-1},\Sigma_{t-1}}\right]^{i}_{j_1,j_2} = \\ \left[f_{\mathcal{Y}_{t+1}}\right]^{i}_{i_2} &\Big([g_{\mathcal{S}_t}]^{i_2}_{i_1} \left[h_{\Sigma_{t-1},\Sigma_{t-1}}\right]^{i_1}_{j_1,j_2} + \left[g_{\Sigma_{t-1},\Sigma_{t-1}}\right]^{i_2}_{j_1,j_2} \vartheta_{j_1}\vartheta_{j_2} \Big) \\ &+ [f_{\mathcal{Y}_t}]^{i}_{i_2} \left[g_{\Sigma_{t-1},\Sigma_{t-1}}\right]^{i_2}_{j_1,j_2} + \left[f_{\mathcal{S}_{t+1}}\right]^{i}_{i_1} \left[h_{\Sigma_{t-1},\Sigma_{t-1}}\right]^{i_1}_{j_1,j_2} = 0 \end{aligned}$$

for $i \in \{1, \ldots, k+n+m\}$ and $j_1, j_2 \in \{1, \ldots, m\}$. This is a homogeneous system on $\left[h_{\Sigma_{t-1},\Sigma_{t-1}}\right]^{i_1}_{j_1,j_2}$ and $\left[g_{\Sigma_{t-1},\Sigma_{t-1}}\right]^{i_2}_{j_1,j_2}$ for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, and $j_1, j_2 \in \{1, \ldots, m\}$, therefore

$$\left[h_{\Sigma_{t-1},\Sigma_{t-1}}\right]^{i_1}_{j_1,j_2} = \left[g_{\Sigma_{t-1},\Sigma_{t-1}}\right]^{i_2}_{j_1,j_2} = 0$$

for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, and $j_1, j_2 \in \{1, \ldots, m\}$.

4. We consider the cross-derivative of the $i-th$ element of F with respect to the j_1-th element of $\mathcal{E}_t$ and the j_2-th element of Σ_{t-1} if $j_1 \neq j_2$

$$\left[F_{\mathcal{E}_t,\Sigma_{t-1}}\right]^i_{j_1,j_2} =$$
$$\left[f_{\mathcal{Y}_{t+1}}\right]^i_{i_2}\left(\left[g_{\mathcal{S}_t}\right]^{i_2}_{i_1}\left[h_{\mathcal{E}_t,\Sigma_{t-1}}\right]^{i_1}_{j_1,j_2}+\left[g_{\mathcal{S}_t,\Sigma_{t-1}}\right]^{i_2}_{i_1,j_2}\left[h_{\mathcal{E}_t}\right]^{i_1}_{j_1}\vartheta_{j_2}+\left[g_{\mathcal{Z}_{t-1},\Sigma_{t-1}}\right]^{i_2}_{j_1,j_2}\sigma_{j_1}\exp^{\vartheta_{j_1}\log\sigma_{j_1,t-1}}\vartheta_{j_2}\right)$$
$$+\left[f_{\mathcal{Y}_t}\right]^i_{i_2}\left[g_{\mathcal{E}_t,\Sigma_{t-1}}\right]^{i_2}_{j_1,j_2}+\left[f_{\mathcal{S}_{t+1}}\right]^i_{i_1}\left[h_{\mathcal{E}_t,\Sigma_{t-1}}\right]^{i_1}_{j_1,j_2}=0$$

for $i \in \{1,\ldots,k+n+m\}$ and $j_1, j_2 \in \{1,\ldots,m\}$. Since we know that $\left[g_{\mathcal{Z}_{t-1},\Sigma_{t-1}}\right]^{i_2}_{j_1,j_2} = \left[g_{\mathcal{S}_t,\Sigma_{t-1}}\right]^{i_2}_{j,j_2} = 0$ for $i_2 \in \{1,\ldots,k\}$, $j \in \{1,\ldots,n\}$, and $j_1, j_2 \in \{1,\ldots,m\}$, this is a homogeneous system on $\left[h_{\mathcal{E}_t,\Sigma_{t-1}}\right]^{i_1}_{j_1,j_2}$ and $\left[g_{\mathcal{E}_t,\Sigma_{t-1}}\right]^{i_2}_{j_1,j_2}$ for $i_1 \in \{1,\ldots,n\}$, $i_2 \in \{1,\ldots,k\}$, and $j_1, j_2 \in \{1,\ldots,m\}$ if $j_1 \neq j_2$. Therefore

$$\left[h_{\mathcal{E}_t,\Sigma_{t-1}}\right]^{i_1}_{j_1,j_2} = \left[g_{\mathcal{E}_t,\Sigma_{t-1}}\right]^{i_2}_{j_1,j_2} = 0$$

for $i_1 \in \{1,\ldots,n\}$, $i_2 \in \{1,\ldots,k\}$, and $j_1, j_2 \in \{1,\ldots,m\}$ if $j_1 \neq j_2$.

Note that if $j_1 = j_2$, we have that

$$\left[F_{\mathcal{E}_t,\Sigma_{t-1}}\right]^i_{j_1,j_1} = \left[f_{\mathcal{Y}_{t+1}}\right]^i_{i_2} *$$
$$*\left(\begin{array}{c}\left[g_{\mathcal{S}_t}\right]^{i_2}_{i_1}\left[h_{\mathcal{E}_t,\Sigma_{t-1}}\right]^{i_1}_{j_1,j_1}+\left[g_{\mathcal{S}_t,\Sigma_{t-1}}\right]^{i_2}_{i_1,j_1}\left[h_{\mathcal{E}_t}\right]^{i_1}_{j_1}\vartheta_{j_1}+\\ \left(\left[g_{\mathcal{Z}_{t-1},\Sigma_{t-1}}\right]^{i_2}_{j_1,j_1}+\left[g_{\mathcal{Z}_{t-1}}\right]^{i_2}_{j_1}\right)\sigma_{j_1}\exp^{\vartheta_{j_1}\log\sigma_{j_1,t-1}}\vartheta_{j_1}\end{array}\right)$$
$$+\left[f_{\mathcal{Y}_t}\right]^i_{i_2}\left[g_{\mathcal{E}_t,\Sigma_{t-1}}\right]^{i_2}_{j_1,j_1}+\left[f_{\mathcal{S}_{t+1}}\right]^i_{i_1}\left[h_{\mathcal{E}_t,\Sigma_{t-1}}\right]^{i_1}_{j_1,j_1}$$
$$+\left(\left[f_{\mathcal{Z}_t}\right]^i_{j_1}+\left[f_{\mathcal{Z}_{t+1}}\right]^i_{j_1}\rho_{j_1}\right)\sigma_{j_1}\exp^{\vartheta_{j_1}\log\sigma_{j_1,t-1}}\vartheta_{j_1}=0$$

and since $\left[f_{\mathcal{Z}_t}\right]^i_{j_1}$ and $\left[f_{\mathcal{Z}_{t+1}}\right]^i_{j_1}$ are different from zero in general for $i \in \{1,\ldots,k+n+m\}$ and $j_1 \in \{1,\ldots,m\}$, we have that this system is not homogeneous and

$$\left[h_{\mathcal{E}_t,\Sigma_{t-1}}\right]^{i_1}_{j_1,j_1} = \left[g_{\mathcal{E}_t,\Sigma_{t-1}}\right]^{i_2}_{j_1,j_1} \neq 0$$

for $i_1 \in \{1,\ldots,n\}$, $i_2 \in \{1,\ldots,k\}$, and $j_1 \in \{1,\ldots,m\}$.

■

Proof, part 3. The final part of the proof deals with the cross-derivatives of the policy functions h and g with respect to $\mathcal{U}_t$ and any of $\mathcal{S}_t$, $\mathcal{Z}_{t-1}$, Σ_{t-1}, $\mathcal{E}_t$, or $\mathcal{U}_t$ and it shows that all of them are equal to zero with one exception. In particular, we want to show that

$$[h_{\mathcal{S}_t,\mathcal{U}_t}]^{i_1}_{j_1,j_2} = [g_{\mathcal{S}_t,\mathcal{U}_t}]^{i_2}_{j_1,j_2} = 0$$

for $i_1 \in \{1,\ldots,n\}$, $i_2 \in \{1,\ldots,k\}$, $j_1 \in \{1,\ldots,n\}$, and $j_2 \in \{1,\ldots,m\}$,

$$\left[h_{\mathcal{Z}_{t-1},\mathcal{U}_t}\right]^{i_1}_{j_1,j_2} = \left[g_{\mathcal{Z}_{t-1},\mathcal{U}_t}\right]^{i_2}_{j_1,j_2} = \left[h_{\Sigma_{t-1},\mathcal{U}_t}\right]^{i_1}_{j_1,j_2} = \left[g_{\Sigma_{t-1},\mathcal{U}_t}\right]^{i_2}_{j_1,j_2} = [h_{\mathcal{U}_t,\mathcal{U}_t}]^{i_1}_{j_1,j_2} = [g_{\mathcal{U}_t,\mathcal{U}_t}]^{i_2}_{j_1,j_2} = 0$$

for $i_1 \in \{1,\ldots,n\}$, $i_2 \in \{1,\ldots,k\}$, and $j_1, j_2 \in \{1,\ldots,m\}$, and

$$[h_{\mathcal{E}_t,\mathcal{U}_t}]^{i_1}_{j_1,j_2} = [g_{\mathcal{E}_t,\mathcal{U}_t}]^{i_2}_{j_1,j_2} = 0$$

for $i_1 \in \{1,\ldots,n\}$, $i_2 \in \{1,\ldots,k\}$, $j_1, j_2 \in \{1,\ldots,m\}$, and $j_1 \neq j_2$.

Again, we follow the same steps for each part of the result as before and use our previous findings regarding which terms are zero.

1. We consider the cross derivative of the $i-th$ element of F with respect to the j_1-th element of S_t and the j_2-th element of $\mathcal{U}_t$

$$\begin{aligned}[F_{\mathcal{S}_t,\mathcal{U}_t}]^{i}_{j_1,j_2} = \left[f_{\mathcal{Y}_{t+1}}\right]^{i}_{i_2} \left([g_{\mathcal{S}_t}]^{i_2}_{i_1} [h_{\mathcal{S}_t,\mathcal{U}_t}]^{i_1}_{j_1,j_2} + \left[g_{\mathcal{S}_t,\Sigma_{t-1}}\right]^{i_2}_{i_1,j_2} [h_{\mathcal{S}_t}]^{i_1}_{j_1} \left(1-\vartheta^2_{j_2}\right)^{\frac{1}{2}} \eta_{j_2}\right) \\ + [f_{\mathcal{Y}_t}]^{i}_{i_2} [g_{\mathcal{S}_t,\mathcal{U}_t}]^{i_2}_{j_1,j_2} + \left[f_{\mathcal{S}_{t+1}}\right]^{i}_{i_1} [h_{\mathcal{S}_t,\mathcal{U}_t}]^{i_1}_{j_1,j_2} = 0\end{aligned}$$

   for $i \in \{1,\ldots,k+n+m\}$, $j_1 \in \{1,\ldots,n\}$, and $j_2 \in \{1,\ldots,m\}$. Since $\left[g_{\mathcal{S}_t,\Sigma_{t-1}}\right]^{i_2}_{j_1,j_2} = 0$ for $i_2 \in \{1,\ldots,k\}$, $j_1 \in \{1,\ldots,n\}$, and $j_2 \in \{1,\ldots,m\}$, this is a homogeneous system on $[h_{\mathcal{S}_t,\mathcal{U}_t}]^{i_1}_{j_1,j_2}$ and $[g_{\mathcal{S}_t,\mathcal{U}_t}]^{i_2}_{j_1,j_2}$.Therefore

$$[h_{\mathcal{S}_t,\mathcal{U}_t}]^{i_1}_{j_1,j_2} = [g_{\mathcal{S}_t,\mathcal{U}_t}]^{i_2}_{j_1,j_2} = 0$$

   for $i_1 \in \{1,\ldots,n\}$, $i_2 \in \{1,\ldots,k\}$, $j_1 \in \{1,\ldots,n\}$, and $j_2 \in \{1,\ldots,m\}$.

2. We consider the cross-derivative of the $i-th$ element of F with respect to the j_1-th element

of $\mathcal{Z}_{t-1}$ and the j_2-th element of $\mathcal{U}_t$

$$\left[F_{\mathcal{Z}_{t-1},\mathcal{U}_t}\right]^{i}_{j_1,j_2} =$$

$$\left[f_{\mathcal{Y}_{t+1}}\right]^{i}_{i_2}\left(\begin{array}{c}\left[g_{\mathcal{S}_t}\right]^{i_2}_{i_1}\left[h_{\mathcal{Z}_{t-1},\mathcal{U}_t}\right]^{i_1}_{j_1,j_2}+\left[g_{\mathcal{S}_t,\Sigma_{t-1}}\right]^{i_2}_{i_1,j_2}\left[h_{\mathcal{Z}_t}\right]^{i_1}_{j_1}\left(1-\vartheta^2_{j_2}\right)^{\frac{1}{2}}\eta_{j_2}\\ +\left[g_{\mathcal{Z}_{t-1},\Sigma_{t-1}}\right]^{i_2}_{j_1,j_2}\rho_{j_1}\left(1-\vartheta^2_{j_2}\right)^{\frac{1}{2}}\eta_{j_2}\end{array}\right)$$

$$+\left[f_{\mathcal{Y}_t}\right]^{i}_{i_2}\left[g_{\mathcal{Z}_{t-1},\mathcal{U}_t}\right]^{i_2}_{j_1,j_2}+\left[f_{\mathcal{S}_{t+1}}\right]^{i}_{i_1}\left[h_{\mathcal{Z}_{t-1},\mathcal{U}_t}\right]^{i_1}_{j_1,j_2}=0$$

for $i\in\{1,\ldots,k+n+m\}$, and $j_1,j_2\in\{1,\ldots,m\}$. Since $\left[g_{\mathcal{Z}_{t-1},\Sigma_{t-1}}\right]^{i_2}_{j_1,j_2}=\left[g_{\mathcal{S}_t,\Sigma_{t-1}}\right]^{i_2}_{j,j_2}=0$ for $i_2\in\{1,\ldots,k\}$, $j\in\{1,\ldots,n\}$, and $j_1,j_2\in\{1,\ldots,m\}$, this is a homogeneous system on $\left[h_{\mathcal{Z}_{t-1},\mathcal{U}_t}\right]^{i_1}_{j_1,j_2}$ and $\left[g_{\mathcal{Z}_{t-1},\mathcal{U}_t}\right]^{i_2}_{j_1,j_2}$ for $i_1\in\{1,\ldots,n\}$, $i_2\in\{1,\ldots,k\}$, and $j_1,j_2\in\{1,\ldots,m\}$. Therefore

$$\left[h_{\mathcal{Z}_{t-1},\mathcal{U}_t}\right]^{i_1}_{j_1,j_2}=\left[g_{\mathcal{Z}_{t-1},\mathcal{U}_t}\right]^{i_2}_{j_1,j_2}=0$$

for $i_1\in\{1,\ldots,n\}$, $i_2\in\{1,\ldots,k\}$, and $j_1,j_2\in\{1,\ldots,m\}$.

3. We consider the cross-derivative of the $i-th$ element of F with respect to the j_1-th element of Σ_{t-1} and the j_2-th element of $\mathcal{U}_t$

$$\left[F_{\Sigma_{t-1},\mathcal{U}_t}\right]^{i}_{j_1,j_2} =$$

$$\left[f_{\mathcal{Y}_{t+1}}\right]^{i}_{i_2}\left(\left[g_{\mathcal{S}_t}\right]^{i_2}_{i_1}\left[h_{\Sigma_{t-1},\mathcal{U}_t}\right]^{i_1}_{j_1,j_2}+\left[g_{\Sigma_{t-1},\Sigma_{t-1}}\right]^{i_2}_{j_1,j_2}\vartheta_{j_1}\left(1-\vartheta^2_{j_2}\right)^{\frac{1}{2}}\eta_{j_2}\right)$$

$$+\left[f_{\mathcal{Y}_t}\right]^{i}_{i_2}\left[g_{\Sigma_{t-1},\mathcal{U}_t}\right]^{i_2}_{j_1,j_2}+\left[f_{\mathcal{S}_{t+1}}\right]^{i}_{i_1}\left[h_{\Sigma_{t-1},\mathcal{U}_t}\right]^{i_1}_{j_1,j_2}=0$$

for $i\in\{1,\ldots,k+n+m\}$, and $j_1,j_2\in\{1,\ldots,m\}$. Since $\left[g_{\Sigma_{t-1},\Sigma_{t-1}}\right]^{i_2}_{j_1,j_2}=0$ for $i_2\in\{1,\ldots,k\}$, and $j_1,j_2\in\{1,\ldots,m\}$, this is a homogeneous system on $\left[h_{\Sigma_{t-1},\mathcal{U}_t}\right]^{i_1}_{j_1,j_2}$ and $\left[g_{\Sigma_{t-1},\mathcal{U}_t}\right]^{i_2}_{j_1,j_2}$ for $i_1\in\{1,\ldots,n\}$, $i_2\in\{1,\ldots,k\}$, and $j_1,j_2\in\{1,\ldots,m\}$. Therefore

$$\left[h_{\Sigma_{t-1},\mathcal{U}_t}\right]^{i_1}_{j_1,j_2}=\left[g_{\Sigma_{t-1},\mathcal{U}_t}\right]^{i_2}_{j_1,j_2}=0$$

for $i_1\in\{1,\ldots,n\}$, $i_2\in\{1,\ldots,k\}$, $j_1,j_2\in\{1,\ldots,m\}$.

4. We consider the cross-derivative of the $i-th$ element of F with respect to the j_1-th element

of $\mathcal{U}_t$ and the $j_2 - th$ element of $\mathcal{U}_t$

$$\left[F_{\mathcal{U}_t,\mathcal{U}_t}\right]^i_{j_1,j_2} =$$
$$\left[f_{\mathcal{Y}_{t+1}}\right]^i_{i_2}\left(\left[g_{\Sigma_{t-1},\Sigma_{t-1}}\right]^{i_2}_{j_1,j_2}\left(1-\vartheta^2_{j_1}\right)^{\frac{1}{2}}\eta_{j_1}\left(1-\vartheta^2_{j_2}\right)^{\frac{1}{2}}\eta_{j_2}+\left[g_{\mathcal{S}_t}\right]^{i_2}_{i_1}\left[h_{\mathcal{U}_t,\mathcal{U}_t}\right]^{i_1}_{j_1,j_2}\right)$$
$$+\left[f_{\mathcal{Y}_t}\right]^i_{i_2}\left[g_{\mathcal{U}_t,\mathcal{U}_t}\right]^{i_2}_{j_1,j_2}+\left[f_{\mathcal{S}_{t+1}}\right]^i_{i_1}\left[h_{\mathcal{U}_t,\mathcal{U}_t}\right]^{i_1}_{j_1,j_2}=0$$

for $i \in \{1,\ldots,k+n+m\}$ and $j_1, j_2 \in \{1,\ldots,m\}$. Since $\left[g_{\Sigma_{t-1},\Sigma_{t-1}}\right]^{i_2}_{j_1,j_2} = 0$ for $i_1 \in \{1,\ldots,k\}$ and $j_1, j_2 \in \{1,\ldots,m\}$, this is a homogeneous system on $\left[h_{\mathcal{U}_t,\mathcal{U}_t}\right]^{i_1}_{j_1,j_2}$ and $\left[g_{\mathcal{U}_t,\mathcal{U}_t}\right]^{i_2}_{j_1,j_2}$ for $i_1 \in \{1,\ldots,n\}$, $i_2 \in \{1,\ldots,k\}$, and $j_1, j_2 \in \{1,\ldots,m\}$. Therefore

$$\left[h_{\mathcal{U}_t,\mathcal{U}_t}\right]^{i_1}_{j_1,j_2} = \left[g_{\mathcal{U}_t,\mathcal{U}_t}\right]^{i_2}_{j_1,j_2} = 0$$

for $i_1 \in \{1,\ldots,n\}$, $i_2 \in \{1,\ldots,k\}$, and $j_1, j_2 \in \{1,\ldots,m\}$.

5. Finally, consider the cross-derivative of the $i - th$ element of F with respect to the $j_1 - th$ element of $\mathcal{E}_t$ and the $j_2 - th$ element of $\mathcal{U}_t$ if $j_1 \neq j_2$

$$\left[F_{\mathcal{E}_t,\mathcal{U}_t}\right]^i_{j_1,j_2} =$$
$$\left[f_{\mathcal{Y}_{t+1}}\right]^i_{i_2}\left(\begin{array}{c}\left[g_{\mathcal{S}_t}\right]^{i_2}_{i_1}\left[h_{\mathcal{E}_t,\mathcal{U}_t}\right]^{i_1}_{j_1,j_2}+\left[g_{\mathcal{S}_t,\Sigma_{t-1}}\right]^{i_2}_{i_1,j_2}\left[h_{\mathcal{E}_t}\right]^{i_1}_{j_1}\left(1-\vartheta^2_{j_2}\right)^{\frac{1}{2}}\eta_{j_2}\\ +\left[g_{\mathcal{Z}_{t-1},\Sigma_{t-1}}\right]^{i_2}_{j_1,j_2}\sigma_{j_1}\exp^{\vartheta_{j_1}\log\sigma_{j_1,t-1}}\left(1-\vartheta^2_{j_2}\right)^{\frac{1}{2}}\eta_{j_2}\end{array}\right)$$
$$+\left[f_{\mathcal{Y}_t}\right]^i_{i_2}\left[g_{\mathcal{E}_t,\mathcal{U}_t}\right]^{i_2}_{j_1,j_2}+\left[f_{\mathcal{S}_{t+1}}\right]^i_{i_1}\left[h_{\mathcal{E}_t,\mathcal{U}_t}\right]^{i_1}_{j_1,j_2}=0$$

for $i \in \{1,\ldots,k+n+m\}$ and $j_1, j_2 \in \{1,\ldots,m\}$. Since $\left[g_{\mathcal{Z}_{t-1},\Sigma_{t-1}}\right]^{i_2}_{j_1,j_2} = \left[g_{\mathcal{S}_t,\Sigma_{t-1}}\right]^{i_2}_{j,j_2} = 0$ for $i_2 \in \{1,\ldots,k\}$, $j \in \{1,\ldots,n\}$, and $j_1, j_2 \in \{1,\ldots,m\}$, this is a homogeneous system on $\left[h_{\mathcal{E}_t,\mathcal{U}_t}\right]^{i_1}_{j_1,j_2}$ and $\left[g_{\mathcal{E}_t,\mathcal{U}_t}\right]^{i_2}_{j_1,j_2}$ for $i_1 \in \{1,\ldots,n\}$, $i_2 \in \{1,\ldots,k\}$, and $j_1, j_2 \in \{1,\ldots,m\}$ if $j_1 \neq j_2$. Therefore

$$\left[h_{\mathcal{E}_t,\mathcal{U}_t}\right]^{i_2}_{j_1,j_2} = \left[g_{\mathcal{E}_t,\mathcal{U}_t}\right]^{i_1}_{j_1,j_2} = 0$$

for $i_1 \in \{1,\ldots,n\}$, $i_2 \in \{1,\ldots,k\}$, and $j_1, j_2 \in \{1,\ldots,m\}$ if $j_1 \neq j_2$.

Note that if $j_1 = j_2$, we have that

$$\begin{gathered}\left[F_{\mathcal{E}_t,\mathcal{U}_t}\right]^{i}_{j_1,j_1} = \\ \left[f_{\mathcal{Y}_{t+1}}\right]^{i}_{i_2}\left(\begin{array}{c}\left(\left[g_{\mathcal{Z}_{t-1},\Sigma_{t-1}}\right]^{i_2}_{j_1,j_1} + \left[g_{\mathcal{Z}_{t-1}}\right]^{i_2}_{j_1}\right)\sigma_{j_1}\exp^{\vartheta_{j_1}\log\sigma_{j_1,t-1}}\left(1-\vartheta^2_{j_1}\right)^{\frac{1}{2}}\eta_{j_1} \\ + \left[g_{\mathcal{S}_t,\Sigma_{t-1}}\right]^{i_2}_{i_1,j_1}\left[h_{\mathcal{E}_t}\right]^{i_1}_{j_1}\left(1-\vartheta^2_{j_1}\right)^{\frac{1}{2}}\eta_{j_1} + \left[g_{\mathcal{S}_t}\right]^{i_2}_{i_1}\left[h_{\mathcal{E}_t,\mathcal{U}_t}\right]^{i_1}_{j_1,j_1}\end{array}\right) \\ + \left[f_{\mathcal{Y}_t}\right]^{i}_{i_2}\left[g_{\mathcal{E}_t,\mathcal{U}_t}\right]^{i_2}_{j_1,j_1} + \left[f_{\mathcal{S}_{t+1}}\right]^{i}_{i_1}\left[h_{\mathcal{E}_t,\mathcal{U}_t}\right]^{i_1}_{j_1,j_1} \\ + \left(\left[f_{\mathcal{Z}_t}\right]^{i}_{j_1} + \rho_{j_1}\left[f_{\mathcal{Z}_{t+1}}\right]^{i}_{j_1}\right)\sigma_{j_1}\exp^{\vartheta_{j_1}\log\sigma_{j_1,t-1}}\left(1-\vartheta^2_{j_1}\right)^{\frac{1}{2}}\eta_{j_1} = 0\end{gathered}$$

and since $\left[f_{\mathcal{Z}_t}\right]^{i}_{j_1}$ and $\left[f_{\mathcal{Z}_{t+1}}\right]^{i}_{j_1}$ are different from zero in general for $i \in \{1, \ldots, k+n+m\}$ and $j_1 \in \{1, \ldots, m\}$, we have that this system is not homogeneous and hence

$$\left[h_{\mathcal{E}_t,\mathcal{U}_t}\right]^{i_2}_{j_1,j_1} = \left[g_{\mathcal{E}_t,\mathcal{U}_t}\right]^{i_1}_{j_1,j_1} \neq 0$$

for $i_1 \in \{1, \ldots, n\}$, $i_2 \in \{1, \ldots, k\}$, and $j_1 \in \{1, \ldots, m\}$. ■

3. Equilibrium

In this section we describe the equilibrium conditions of the model. First, we introduce the ones related to the household, then the ones related to the firm and the monetary authority, and finally we present the market clearing and aggregation conditions.

3.1. Households

We can define two Lagrangian multipliers, λ_{jt}, the multiplier associated with the budget constraint, and q_{jt} (the marginal Tobin's Q), the multiplier associated with the investment adjustment constraint normalized by λ_{jt}. Thus, the first-order conditions of the household problem with respect to c_{jt}, b_{jt}, u_{jt}, k_{jt}, and x_{jt} can be written as:

$$d_t\left(c_{jt} - hc_{jt-1}\right)^{-1} - b\beta\mathbb{E}_t d_{t+1}\left(c_{jt+1} - hc_{jt}\right)^{-1} = \lambda_{jt}, \tag{30}$$

$$\lambda_{jt} = \beta\mathbb{E}_t\{\lambda_{jt+1}\frac{R_t}{\Pi_{t+1}}\}, \tag{31}$$

$$r_t = \mu_t^{-1}\Phi'\left[u_{jt}\right], \tag{32}$$

$$q_{jt} = \beta \mathbb{E}_t \left\{ \frac{\lambda_{jt+1}}{\lambda_{jt}} \left((1-\delta) q_{jt+1} + r_{t+1} u_{jt+1} - \mu_{t+1}^{-1} \Phi \left[u_{jt+1} \right] \right) \right\}, \tag{33}$$

and

$$1 = q_{jt} \mu_t \left(1 - V \left[\frac{x_{jt}}{x_{jt-1}} \right] - V' \left[\frac{x_{jt}}{x_{jt-1}} \right] \frac{x_{jt}}{x_{jt-1}} \right) + \beta \mathbb{E} q_{jt+1} \mu_{t+1} \frac{\lambda_{jt+1}}{\lambda_{jt}} V' \left[\frac{x_{jt+1}}{x_{jt}} \right] \left(\frac{x_{jt+1}}{x_{jt}} \right)^2. \tag{34}$$

The first-order conditions of the "labor packer" imply a demand function for labor:

$$l_{jt} = \left(\frac{w_{jt}}{w_t} \right)^{-\eta} l_t^d \qquad \forall j$$

and, together with a zero profit condition $w_t l_t^d = \int_0^1 w_{jt} l_{jt} dj$, an expression for the wage:

$$w_t = \left(\int_0^1 w_{jt}^{1-\eta} dj \right)^{\frac{1}{1-\eta}}.$$

Households follow a Calvo scheme when they set their wages. At the start of every period, a randomly selected fraction $1 - \theta_w$ of households can reoptimize their wages. All other households index their nominal wages given past inflation with an indexation parameter $\chi_w \in [0, 1]$.

Since we postulated in the main text both complete financial markets for the households and separable utility in consumption, the marginal utilities of consumption are the same for all households. Thus, in equilibrium, $c_{jt} = c_t$, $u_{jt} = u_t$, $k_{jt-1} = k_t$, $x_{jt} = x_t$, $q_{jt} = q_t$, $\lambda_{jt} = \lambda_t$, and $w_{jt}^* = w_t^*$.

The last two equalities tell us that the shadow cost of consumption is equated across households and that all households that can reset their wages optimally will do it at the same level w_t^*. With these two results, and after several steps of algebra, we find that the evolution of wages is described by two recursive equations:

$$f_t = \frac{\eta - 1}{\eta} \left(w_t^* \right)^{1-\eta} \lambda_t w_t^\eta l_t^d + \beta \theta_w \mathbb{E}_t \left(\frac{\Pi_t^{\chi_w}}{\Pi_{t+1}} \right)^{1-\eta} \left(\frac{w_{t+1}^*}{w_t^*} \right)^{\eta - 1} f_{t+1} \tag{35}$$

and

$$f_t = \psi d_t \varphi_t \left(\frac{w_t}{w_t^*} \right)^{\eta(1+\vartheta)} \left(l_t^d \right)^{1+\vartheta} + \beta \theta_w \mathbb{E}_t \left(\frac{\Pi_t^{\chi_w}}{\Pi_{t+1}} \right)^{-\eta(1+\vartheta)} \left(\frac{w_{t+1}^*}{w_t^*} \right)^{\eta(1+\vartheta)} f_{t+1} \tag{36}$$

on the auxiliary variable f_t.

Taking advantage of the expression for the wage and that, in every period, a fraction $1 - \theta_w$

of households set w_t^* as their wage and the remaining fraction θ_w partially index their nominal wage by past inflation, we can write the law of motion of real wage as:

$$w_t^{1-\eta} = \theta_w \left(\frac{\Pi_{t-1}^{\chi_w}}{\Pi_t} \right)^{1-\eta} w_{t-1}^{1-\eta} + (1-\theta_w)\, w_t^{*1-\eta}. \tag{37}$$

3.2. Firms

The final good producer is perfectly competitive and minimizes its costs subject to the production function (24) and taking as given all intermediate goods prices p_{ti} and the final good price p_t. The optimality conditions of this problem result in a demand function for each intermediate good with the classic form:

$$y_{it} = \left(\frac{p_{it}}{p_t} \right)^{-\varepsilon} y_t^d \qquad \forall i$$

where y_t^d is the aggregate demand and a price for the final good:

$$p_t = \left(\int_0^1 p_{it}^{1-\varepsilon} di \right)^{\frac{1}{1-\varepsilon}}.$$

Each of the intermediate goods is produced by a monopolistic competitor. Intermediate good producers produce the quantity demanded of the good by renting l_{it}^d and k_{it-1} at prices w_t and r_t. Then, by minimization, we have a marginal cost of:

$$mc_t = \left(\frac{1}{1-\alpha} \right)^{1-\alpha} \left(\frac{1}{\alpha} \right)^{\alpha} \frac{w_t^{1-\alpha} r_t^{\alpha}}{A_t} \tag{38}$$

The marginal cost is constant for all firms and all production levels given A_t, w_t, and r_t.

Given the demand function, the intermediate good producers set prices to maximize profits. However, when they do so, they follow the same Calvo pricing scheme as households. In each period, a fraction $1-\theta_p$ of intermediate good producers reoptimize their prices. All other firms partially index their prices by past inflation with an indexation parameter $\chi \in [0,1]$.

The solution for the firm's pricing problem has a recursive structure in two new auxiliary variables g_t^1 and g_t^2 that take the form:

$$g_t^1 = \lambda_t mc_t y_t^d + \beta\theta_p \mathbb{E}_t \left(\frac{\Pi_t^{\chi}}{\Pi_{t+1}} \right)^{-\varepsilon} g_{t+1}^1, \tag{39}$$

$$g_t^2 = \lambda_t \Pi_t^* y_t^d + \beta\theta_p \mathbb{E}_t \left(\frac{\Pi_t^\chi}{\Pi_{t+1}}\right)^{1-\varepsilon} \left(\frac{\Pi_t^*}{\Pi_{t+1}^*}\right) g_{t+1}^2, \tag{40}$$

and

$$\varepsilon g_t^1 = (\varepsilon - 1) g_t^2 \tag{41}$$

where

$$\Pi_t^* = \frac{p_t^*}{p_t} \tag{42}$$

is the ratio between the optimal new price (common across all firms that can reset their prices) and the price of the final good. With this structure, the inflation follows:

$$1 = \theta_p \left(\frac{\Pi_{t-1}^\chi}{\Pi_t}\right)^{1-\varepsilon} + (1-\theta_p)\, \Pi_t^{*1-\varepsilon}. \tag{43}$$

3.3. The Monetary Authority

The model is closed with a monetary authority that sets the nominal interest rates by a modified Taylor rule described in (25).

3.4. Market Clearing and Aggregation

Aggregate demand is given by:

$$y_t^d = c_t + x_t + \mu_t^{-1} \Phi\left[u_t\right] k_{t-1}. \tag{44}$$

By relying on the observation that the capital-labor ratio is constant across firms, we can derive that aggregate supply is:

$$y_t^s = \frac{A_t \left(u_t k_{t-1}\right)^\alpha \left(l_t^d\right)^{1-\alpha} - \phi z_t}{v_t^p} \tag{45}$$

where:

$$v_t^p = \int_0^1 \left(\frac{p_{it}}{p_t}\right)^{-\varepsilon} di$$

is the aggregate loss of efficiency induced by price dispersion of the intermediate goods.

Market clearing requires that

$$y_t = y_t^d = y_t^s. \tag{46}$$

By the properties of Calvo's pricing:

$$\upsilon_t^p = \theta_p \left(\frac{\Pi_{t-1}^{\chi}}{\Pi_t} \right)^{-\varepsilon} \upsilon_{t-1}^p + (1-\theta_p) \Pi_t^{*-\varepsilon}. \tag{47}$$

Finally, demanded labor is given by:

$$l_t^d = \frac{1}{\upsilon_t^w} \int_0^1 l_{jt} dj = l_t \tag{48}$$

where:

$$\upsilon_t^w = \int_0^1 \left(\frac{w_{jt}}{w_t} \right)^{-\eta} dj.$$

is the aggregate loss of labor input induced by wage dispersion among differentiated types of labor. Again, by Calvo's pricing, this inefficiency evolves as:

$$\upsilon_t^w = \theta_w \left(\frac{w_{t-1}}{w_t} \frac{\Pi_{t-1}^{\chi_w}}{\Pi_t} \right)^{-\eta} \upsilon_{t-1}^w + (1-\theta_w) \left(\Pi_t^{w*} \right)^{-\eta}. \tag{49}$$

Thus an equilibrium is characterized by equations (30)-(49), the Taylor rule (25), the law of motion for the structural shocks (augmented with the parameter drifts), and the law of motion for the volatility shocks.

4. Non-linearities in Parameter Drifting

We argued in the main text that, since we consider the effects of stochastic volatility on our model, it was of the essence to deal with higher-order approximations. In this section we argue that higher-order approximations are also key to dealing with parameter drifting in the Taylor rule. The reason is that parameter drifting disappears from a linear solution. To see this, take the Taylor rule defined in (25) (assuming only in this paragraph and to simplify notation that $\gamma_y = 0$ and $\log \sigma_{\xi t} = 0$) and let us rewrite it:

$$f\left(\widehat{R}_t, \widehat{R}_{t-1}, \widehat{\Pi}_t, \widehat{\gamma}_{\Pi,t}, \varepsilon_{\xi t}\right) = \exp^{\widehat{R}_t} - \exp^{\gamma_R \widehat{R}_{t-1} + (1-\gamma_R)\gamma_\Pi \exp^{\widehat{\gamma}_{\Pi,t}} \widehat{\Pi}_t + \sigma_\xi \varepsilon_{\xi t}} = 0.$$

where we have expressed each variable var_t in terms of log deviation with respect to the steady state, $\widehat{var}_t = \log var_t - \log var$. The log-linear approximation of f around the steady state is

$$f\left(\widehat{R}_t, \widehat{R}_{t-1}, \widehat{\Pi}_t, \widehat{\gamma}_{\Pi,t}, \varepsilon_{\xi t}\right) \simeq f_1(\mathbf{0})\,\widehat{R}_t + f_2(\mathbf{0})\,\widehat{R}_{t-1} + f_3(\mathbf{0})\,\widehat{\Pi}_t + f_4(\mathbf{0})\,\widehat{\gamma}_{\Pi,t} + f_5(\mathbf{0})\,\varepsilon_{\xi t}.$$

where $f_i(\mathbf{0})$ is the first derivative of the function f evaluated at $(0,0,0,0,0)$ with respect to the variable i. Note that:

$$f_4\left(\widehat{R}_t, \widehat{R}_{t-1}, \widehat{\Pi}_t, \widehat{\gamma}_{\Pi,t}, \varepsilon_{\xi t}\right) = -(1-\gamma_R)\,\gamma_\Pi \widehat{\Pi}_t \exp^{\widehat{\gamma}_{\Pi,t}} \exp^{\gamma_R \widehat{R}_{t-1} + (1-\gamma_R)\gamma_\Pi \exp^{\widehat{\gamma}_{\Pi,t}} \widehat{\Pi}_t + \sigma_\xi \varepsilon_{\xi t}}.$$

Clearly, $f_4(\mathbf{0}) = 0$ and $\widehat{\gamma}_{\Pi,t}$ does not play any role in this first-order approximation. This is the consequence of one variable (Π_t) being raised to another variable ($\gamma_{\Pi,t}$). Thus, the log-linear approximation of the Taylor rule is:

$$f\left(\widehat{R}_t, \widehat{R}_{t-1}, \widehat{\Pi}_t, \widehat{\gamma}_{\Pi,t}, \varepsilon_{mt}\right) \simeq \widehat{R}_t - \gamma_R \widehat{R}_{t-1} - (1-\gamma_R)\,\gamma_\Pi \widehat{\Pi}_t + \sigma_\xi \varepsilon_{\xi t} \tag{50}$$

which does not depend on $\gamma_{\Pi,t}$, but only on the steady state γ_Π and it is exactly the same expression as the one without parameter drifting. Hence, in order to capture parameter drifting in the Taylor rule, we *need*, at least, to perform a second-order approximation.

5. Construction of Data

When we estimate the model, we make the series provided by the National Income and Product Accounts (NIPA) consistent with the definition of variables in the theory. The main adjustment we undertake is to express both real output and real gross investment in consumption units. Our model implies that there is a numeraire in terms of which all the other prices need to be quoted. We pick consumption as the numeraire. The NIPA, in comparison, uses an index of all prices to transform nominal GDP and investment into real values. In the presence of changing relative prices, such as the ones we have seen in the U.S. over the last several decades with the fall in the relative price of capital, NIPA's procedure biases the valuation of different series in real terms.

We map theory into the data by computing our own series of real output and real investment. To do so, we use the relative price of investment, defined as the ratio of an investment deflator and a deflator for consumption. The denominator is easily derived from the deflators of non-durable goods and services reported in the NIPA. It is more complicated to obtain the numerator because, historically, NIPA investment deflators were poorly constructed. Instead, we rely on the investment deflator computed by Fisher (2006). Since the series ends early in 2000.Q4, we have extended it to 2007.Q1 by following Fisher's methodology.

For the real output per capita series, we first define nominal output as nominal consumption plus nominal gross investment. We define nominal consumption as the sum of personal consumption expenditures on non-durable goods and services. We define nominal gross investment as the sum of personal consumption expenditures on durable goods, private residential investment, and non-residential fixed investment. Per capita nominal output is equal to the ratio between our nominal output series and the civilian non-institutional population between 16 and 65. To obtain per capita values, we divide the previous series by the civilian non-institutional population between 16 and 65. Finally, real wages are defined as compensation per hour in the non-farm business sector divided by the CPI deflator.

6. Additional Empirical Results

6.1. Determinacy of Equilibrium

We mentioned in the main text that the estimated value of γ_Π (1.045 in levels) guarantees local determinacy of the equilibrium. To see this, note that, for local determinacy, the relevant part of the solution of the model is *only* the linear first-order component. This component depends on γ_Π, the mean policy response, and not on the current value of $\gamma_{\Pi t}$. The economic intuition is that local unicity survives even if $\gamma_{\Pi t}$ temporarily violates the Taylor principle as long as there is reversion to the mean in the policy response and, thus, the agents have the expectation that $\gamma_{\Pi t}$ will satisfy the Taylor principle on average. For a related result in models with Markov-switching regime changes, see Davig and Leeper (2006). While we cannot find an analytical expression for the determinacy region, numerical experiments show that, conditional on the other point estimates, values of γ_Π above 0.98 ensure uniqueness. Since the likelihood assigns zero probability to values of γ_Π lower than 1.01, well inside the determinacy region, multiplicity of local equilibria is not an issue in our application.

6.2. Impulse Response Functions

As a check of our estimates, we plot the IRFs generated by the model to a monetary policy shock. This exercise is an important test. If the IRFs match the shapes and sizes of those gathered by time series methods such as SVARs, it will strengthen our belief in the rest of our results. Otherwise, we should at least understand where the differences come from.

Auspiciously, the answer is positive: our model generates dynamic responses that are close to the ones from SVARs (see, for instance, Sims and Zha, 2006). The left panel of figure 6.1 plots the IRFs to a monetary shock of three variables commonly discussed in monetary models: the federal funds rate, output growth, and inflation. Since we have a non-linear model, in all the figures in this section, we report the generalized IRFs starting from the mean of the ergodic distribution (Koop, Pesaran, and Potter, 1996). After a one-standard-deviation shock to the federal funds rate, inflation goes down in a hump-shaped pattern for many quarters and output growth drops.

The right panel of figure 6.1 plots the IRFs after a one-standard-deviation innovation to the monetary policy shock computed conditional on fixing $\gamma_{\Pi t}$ to the estimated mean during the tenure of each of three different chairmen of the Board of Governors: the combination Burns-Miller, Volcker, and Greenspan. This exercise tells us how the variation in the systematic component of monetary policy has affected the dynamics of aggregate variables. Furthermore, it allows a comparison with numerous similar exercises done in the literature with SVARs where the IRFs are estimated on different subsamples.

The most interesting difference is that the response of output growth under Volcker was the mildest: the estimated average stance of monetary policy under his tenure reduces the volatility of output. Inflation responds moderately as well since the agents have the expectation that future shocks will be smoothed out by the monetary authority. This finding also explains why the IRFs of the interest rate are nearly on top of each other for all three periods: while we estimate that monetary policy responded more during Volcker's years for any given level of inflation than under Burns-Miller or Greenspan, this policy lowers inflation deviations and hence moderates the actual movement along the equilibrium path of the economy. Moreover, this second set of IRFs already points out one important result of this paper: we estimate that monetary policy under Burns-Miller and Greenspan was similar, while it was different under Volcker. This finding will be reinforced by the results we present in the main body of the text.

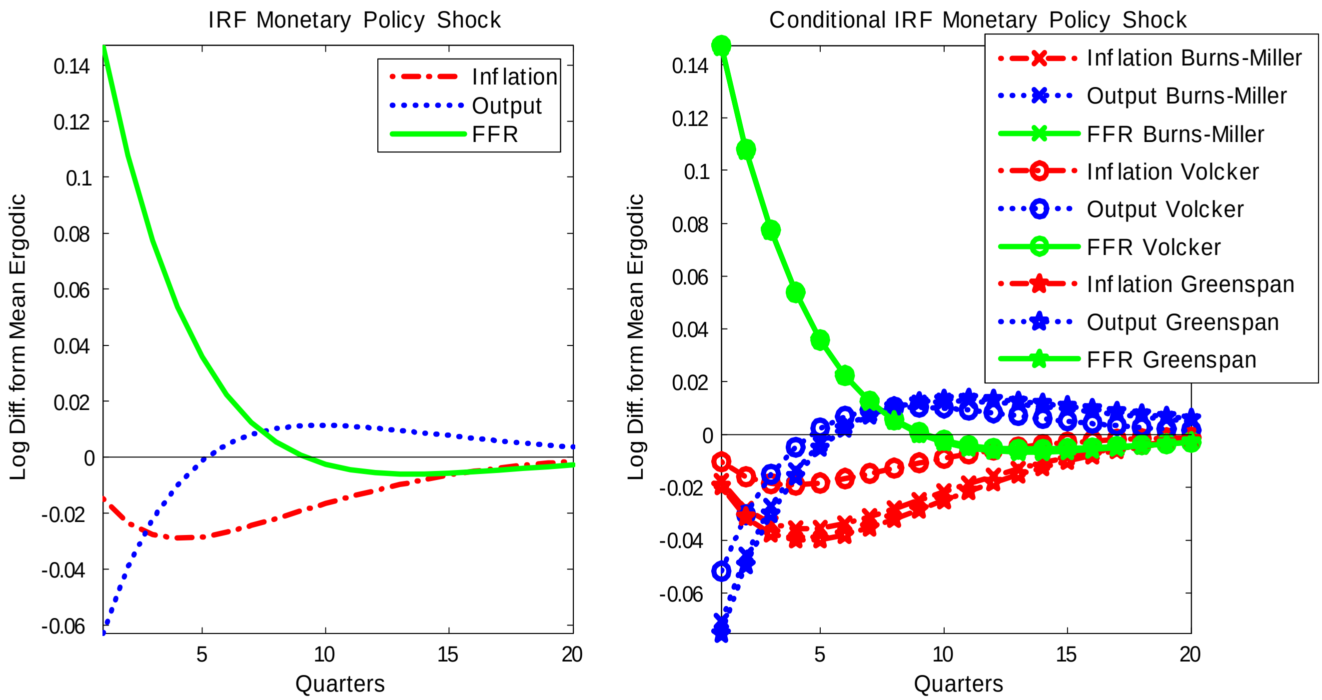

Figure 6.1: IRFs to a Monetary Policy Shock, Unconditional and Conditional

For completeness, we also plot, in figure 6.2, the IRFs to each of the other four shocks in our model: the two preference shocks (intertemporal and intratemporal) and the two technology shocks (investment-specific and neutral). The behavior of the model is standard. A one-standard-deviation intertemporal preference shock raises output growth and inflation because there is an increase in the desire for consumption in the current period. The intratemporal shock lowers output because labor becomes less attractive, driving up the marginal costs and, with it, prices. The two supply shocks raise output growth and lower inflation by increasing productivity. All of those IRFs show that the behavior of the model is standard.

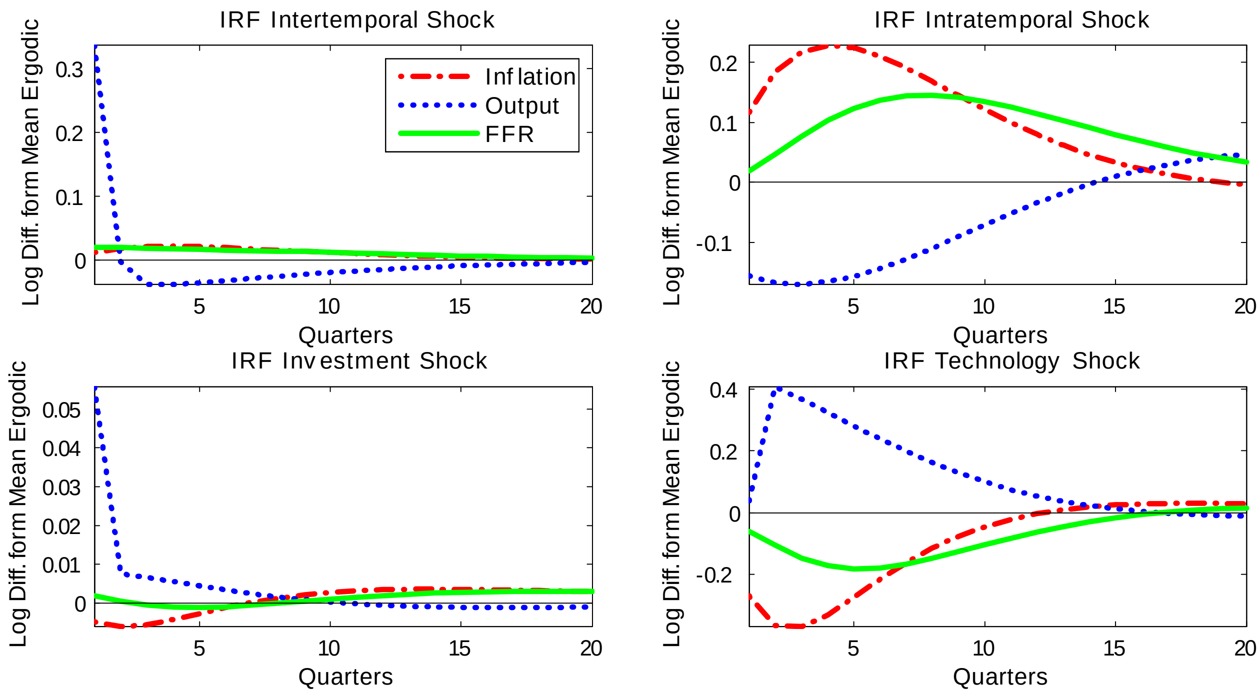

Figure 6.2: IRFs of inflation, output growth, and the federal funds rate to an intertemporal demand (ε_{dt}) shock, an intratemporal demand ($\varepsilon_{\varphi t}$) shock, an investment-specific ($\varepsilon_{\mu t}$) shock, and a neutral technology (ε_{At}) shock. The responses are measured as log differences with respect to the mean of the ergodic distribution.

6.3. Model Comparison

Another use of our procedure to evaluate the likelihood function is to compare our model against alternative models -or alternative versions of the same model. For instance, a natural question is to compare our benchmark model with stochastic volatility and parameter drifting with a version without parameter drifting but with stochastic volatility. That is: once we have included stochastic volatility, is it still important to allow for changes in monetary policy to account for the time-varying volatility of aggregate data in the U.S.?

Given our Bayesian framework, a natural approach for model comparison is the computation of log marginal data densities (log MDD) and log Bayes factors. Let us focus on the proposed example of comparing the full model with stochastic volatility and parameter drifting (*drift*) with a version without parameter drifting (*no drift*) but with stochastic volatility. In this second case, we have two fewer parameters, ρ_{γ_Π} and σ_π (but we still have γ_Π). To ease notation, we partition the parameter vector γ as $\gamma = \left(\widetilde{\gamma}, \rho_{\gamma_\Pi}, \sigma_\pi\right)$, where $\widetilde{\gamma}$ is the vector of all the other parameters, common to the two versions of the model.

Given that our priors are 1) uniform, 2) independent of each other, and 3) cover all the areas where the likelihood is (numerically) positive, and that 4) the priors on $\widetilde{\gamma}$ are common across the two specifications of the model, we can write

$$\log p\left(\mathbb{Y}^T = \mathbb{Y}^{data,T}; drift\right) = \log \int p\left(\mathbb{Y}^T = \mathbb{Y}^{data,T}; \gamma, drift\right) d\gamma + \log p\left(\widetilde{\gamma}\right) + \log p\left(\rho_{\gamma_\Pi}\right) + \log p\left(\sigma_\pi\right),$$

where $\log p\left(\widetilde{\gamma}\right)$, $\log p\left(\rho_{\gamma_\Pi}\right)$, and $\log p\left(\sigma_\pi\right)$ are constants and

$$\log p\left(\mathbb{Y}^T = \mathbb{Y}^{data,T}; no\ drift\right) = \log \int p\left(\mathbb{Y}^T = \mathbb{Y}^{data,T}; \widetilde{\gamma}, no\ drift\right) d\widetilde{\gamma} + \log p\left(\widetilde{\gamma}\right).$$

Thus

$$\begin{aligned}
\log B_{drift,\ no\ drift} &= \log p\left(\mathbb{Y}^T = \mathbb{Y}^{data,T}; drift\right) - \log p\left(\mathbb{Y}^T = \mathbb{Y}^{data,T}; no\ drift\right) \\
&= \log \int p\left(\mathbb{Y}^T = \mathbb{Y}^{data,T}; \gamma, drift\right) d\widetilde{\gamma} - \log \int p\left(\mathbb{Y}^T = \mathbb{Y}^{data,T}; \widetilde{\gamma}, no\ drift\right) d\widetilde{\gamma} \\
&\quad - \log p\left(\rho_{\gamma_\Pi}\right) - \log p\left(\sigma_\pi\right).
\end{aligned}$$

The difference

$$\log \int p\left(\mathbb{Y}^T = \mathbb{Y}^{data,T}; \gamma, drift\right) d\gamma - \log \int p\left(\mathbb{Y}^T = \mathbb{Y}^{data,T}; \widetilde{\gamma}, no\ drift\right) d\widetilde{\gamma}$$

tells us how much better the version with parameter drift fits the data in comparison with the version with no drift. The last two terms, $\log p\left(\rho_{\gamma_\Pi}\right) + \log p\left(\sigma_\pi\right)$, penalize for the presence of two extra parameters.

We estimate the log MDDs following Geweke's (1998) harmonic mean method. This requires us to generate a new draw of the posterior of the model for the specification with no parameter drift to compute $\log \int p\left(\mathbb{Y}^T = \mathbb{Y}^{data,T}; \widetilde{\gamma}, no\ drift\right) d\widetilde{\gamma}$. After doing so, we find that

$$\log B_{drift,\ no\ drift} = 126.1331 + \log p\left(\rho_{\gamma_\Pi}\right) + \log p\left(\sigma_\pi\right)$$

This expression shows a potential problem of Bayes factors: by picking uniform priors for ρ_{γ_Π} and σ_π spread out over a sufficiently large interval, we could overcome any difference in fit. But the prior for ρ_{γ_Π} is pinned down by our desire to keep that process stationary, which imposes natural bounds in $[-1, 1]$ and makes $\log p\left(\rho_{\gamma_\Pi}\right) = -0.6931$. Thus, there is only one degree of freedom left: our choice of $\log p\left(\sigma_\pi\right)$. Any sensible prior for σ_π will only put mass in a relatively small interval: the point estimate is 0.1479, the standard deviation is 0.002, and the likelihood is numerically zero for values bigger than 0.2. Hence, we can safely impose that $\log p\left(\sigma_\pi\right) > -1$ ($\log p\left(\sigma_\pi\right) = -1$ would imply a uniform prior between 0 and 2.7183, a considerably wider support than any evidence in the data), and conclude that $\log B_{drift,\ no\ drift} > 124.4400$. This is conventionally considered overwhelming evidence in favor of the model with parameter drift (Jeffreys, 1961, for instance, suggests that differences bigger than 5 are decisive). Thus, even after controlling for stochastic volatility, the data strongly prefer a specification where monetary policy has changed over time. This finding, however, does not imply that volatility shocks did not play an important role in the time-varying volatilities of U.S. aggregate time series. In fact, as we will see in the next section of this appendix, they were a key mechanism in accounting for it.

A formal comparison with the case without stochastic volatility is more difficult, since we are taking advantage of its presence to evaluate the likelihood. Fortunately, Justiniano and Primiceri (2008) and Fernández-Villaverde and Rubio-Ramírez (2007) estimate models similar to ours with and without stochastic volatility (in the first case, using only a first-order approximation to the decision rules of the agents and in the second with measurement errors). Both papers find that the fit of the model improves substantially when we include stochastic volatility. Finally, Fernández-Villaverde and Rubio-Ramírez (2008) compare a model with parameter drifting and no stochastic volatility with a model without parameter drifting and no stochastic volatility and report that parameter drifting is also strongly preferred by the likelihood.

It has been noted that the estimation of log MDDs is dangerous because of numerical instabilities in the evaluation of the integral log marginal data density (log MDD). This concern is particularly relevant in our case, since we have a large model saddled with burdensome computation. Thus, as a robustness analysis, we also computed the Bayesian Information Criterion (BIC) (Schwarz, 1978). The BIC, which avoids the need to handle the integral in the log MDD, can be understood as an asymptotic approximation of the Bayes factor that also automatically penalizes for extra parameters. The BIC of model i is defined:

$$BIC_i = -2 \ln p\left(\mathbb{Y}^T = \mathbb{Y}^{data,T}; \widehat{\gamma}, i\right) + k_i \ln n$$

where $\widehat{\gamma}$ is the maximum likelihood estimator (or, given our flat priors, the mode of the posterior), k_i is the number of parameters, and n is the number of observations. Then, the BIC of the model with stochastic volatility and parameter drifting is $BIC_{drift} = -2*3885+28*\ln 192 = -7,622.8$. If we eliminate parameter drifting and the parameters ρ_{γ_Π} and σ_π associated with it (and, of course, with a new point estimate of the other parameters) $BIC_{no\ drift} = -2 * 3810.7 + 26 * \ln 192 = -7,484.7$. The difference is, therefore, over 138 log points, which is again overwhelming evidence in favor of the model with parameter drifting.

6.4. Historical Counterfactuals

One important additional exercise is to quantify how much of the observed changes in the volatility of aggregate U.S. variables can be accounted for by changes in the standard deviations of shocks and how much by changes in policy. To accomplish this, we build a number of historical counterfactuals. In these exercises, we remove one source of variation at a time and we measure how aggregate variables would have behaved when hit only by the remaining shocks. Since our model is structural in the sense of Hurwicz (1962) (it is invariant to interventions, including shocks by nature such as the ones we are postulating), we will obtain an answer that is robust to the Lucas critique.

In the next two subsections, we will always plot the same three basic variables that we used in section 5 of the main text: inflation, output growth, and the federal funds rate. Counterfactual histories of other variables could be built analogously. Also, we will have vertical bars for the tenure of each chairman, following the same color scheme as in section 5.

6.4.1. Counterfactual I: Switching Chairmen

In our first counterfactual, we move one chairman from his mandate to an alternative time period. For example, we appoint Greenspan as chairman during the Burns-Miller years. By that, we mean that the Fed would have followed the policy rule dictated by the average $\gamma_{\Pi t}$ estimated during Greenspan's time while starting from the same states as Burns-Miller and suffering the same shocks (both structural and of volatility). We repeat this exercise with all the other possible combinations: Volcker in the Burns-Miller decade, Burns-Miller in Volcker's mandate, Greenspan in Volcker's time, Burns-Miller in the Greenspan years, and, finally, Volcker in Greenspan's time.

It is important to be careful in interpreting this exercise. By appointing Greenspan at Volcker's time, we do not literally mean Greenspan as a person, but Greenspan as a convenient label for a particular monetary policy response to shocks that according to our model were observed during his tenure. The real Greenspan could have behaved in a different way, for example, as a result of some non-linearities in monetary policy that are not properly captured by a simple rule such as the one postulated in section 3. The argument could be pushed one step further and we could think about the appointment of Volcker as an endogenous response of the political-economic equilibrium to high inflation. In our model agents have a probability distribution regarding possible changes in monetary policy in the next periods, but those changes are uncorrelated with current conditions. Therefore, our model cannot capture the endogeneity of policy selection.

Another issue that we sidelined is the evolution of expectations. In our model, agents have rational expectations and observe the changes in monetary policy parameters. This hypothesis may be a poor approximation of the agents' behavior in real life. It could be the case that $\gamma_{\Pi t}$ was high in 1984, even though inflation was already low by that time, because of the high inflationary expectations that economic agents held during most of the 1980s (this point is also linked to issues of commitment and credibility that our model does not address). While we see all these arguments as interesting lines of research, we find it important to focus first on our basic counterfactual.

Moments In table 6.1, we report the mean and the standard deviation of inflation, output growth, and the federal funds rate in the observed data and in the sets of counterfactual data. Inflation was high with Burns-Miller, fell with Volcker, and stayed low with Greenspan. Output growth went down during the Volcker years to recover with Greenspan. The federal funds rate reached its peak with Volcker. The standard deviation of output growth fell from 4.7 in Burns-Miller's time to 2.45 with Greenspan, a cut in half. Similarly, inflation volatility fell nearly 54 percent and the federal funds rate volatility 5 percent.

But table 6.1 also tells us one important result: time-varying monetary policy significantly affected average inflation. In particular, Volcker's response to inflation was strong and switching him to either Burns-Miller's or Greenspan's time would have reduced average inflation dramatically. But it also tells us other things: contrary to the conventional wisdom, our estimates suggest that the stance of monetary policy against inflation under Greenspan was not strong. In Burns-Miller's time, the monetary policy under Greenspan would have delivered slightly higher average inflation, 6.83 versus the observed 6.23, accompanied by a lower federal funds rate and lower output growth, 1.89 versus the observed 2.03. The difference is even bigger in Volcker's time, during which average inflation would have been nearly 1.4 percent higher, while output growth would have been virtually identical (1.34 versus 1.38). The key for this finding is in the behavior of the federal funds rate, which would have increased only by 9 basis points, on average, if Greenspan had been in charge of the Fed instead of Volcker. Given the higher inflation in the counterfactual, the higher nominal interest rates would have meant much lower real rates. The counterfactual of Burns-Miller in Greenspan's and Volcker's time casts doubt on the malignant reputations of these two short-lived chairmen, at least when compared with Greenspan. Burns-Miller would have brought even slightly lower inflation than Greenspan, thanks to a higher real federal funds rate and a bit higher output growth. However, Burns-Miller would have delivered higher inflation than Volcker.

Table 6.1: Switching Chairmen, Data versus Counterfactual Histories

	Means			Standard Deviations		
	Inflation	Output Gr.	FFR	Inflation	Output Gr.	FFR
BM (data)	6.2333	2.0322	6.5764	2.7347	4.7010	2.2720
Greenspan to BM	6.8269	1.8881	6.5046	3.3732	4.6781	2.0103
Volcker to BM	4.3604	1.5010	7.6479	2.4620	4.6219	2.3470
Volcker (data)	5.3584	1.3846	10.3338	3.1811	4.4811	3.4995
BM to Volcker	6.4132	1.3560	10.4126	2.9728	4.4220	3.0648
Greenspan to Volcker	6.7284	1.3423	10.4235	2.9824	4.3730	2.8734
Greenspan (data)	2.9583	1.5177	4.7352	1.2675	2.4567	2.1887
BM to Greenspan	2.3355	1.5277	4.4529	1.5625	2.4684	2.4652
Volcker to Greenspan	-0.4947	1.3751	3.6560	1.7700	2.4705	2.7619

This is an important empirical finding: according to our model, time-varying monetary policy significantly affected average inflation. While Volcker's response to inflation was strong, Greenspan's response was milder and he seems to have behaved quite similarly to how Burns-Miller would have behaved.

Counterfactual Paths An alternative way to analyze our results is to plot the whole counterfactual histories summarized in table 6.1. We find it interesting to plot the whole history because changes in the economy's behavior in one period will propagate over time and we want to understand, for example, how Greenspan's legacy would have molded Volcker's tenure. Also, plotting the whole history allows us to track the counterfactual response of monetary policy to large economic events such as the oil shocks.

In figure 6.3, we move to Burns-Miller being reappointed in Greenspan's time. This plot suggests that the differences in monetary policy under Greenspan and Burns-Miller may have been overstated by the literature.

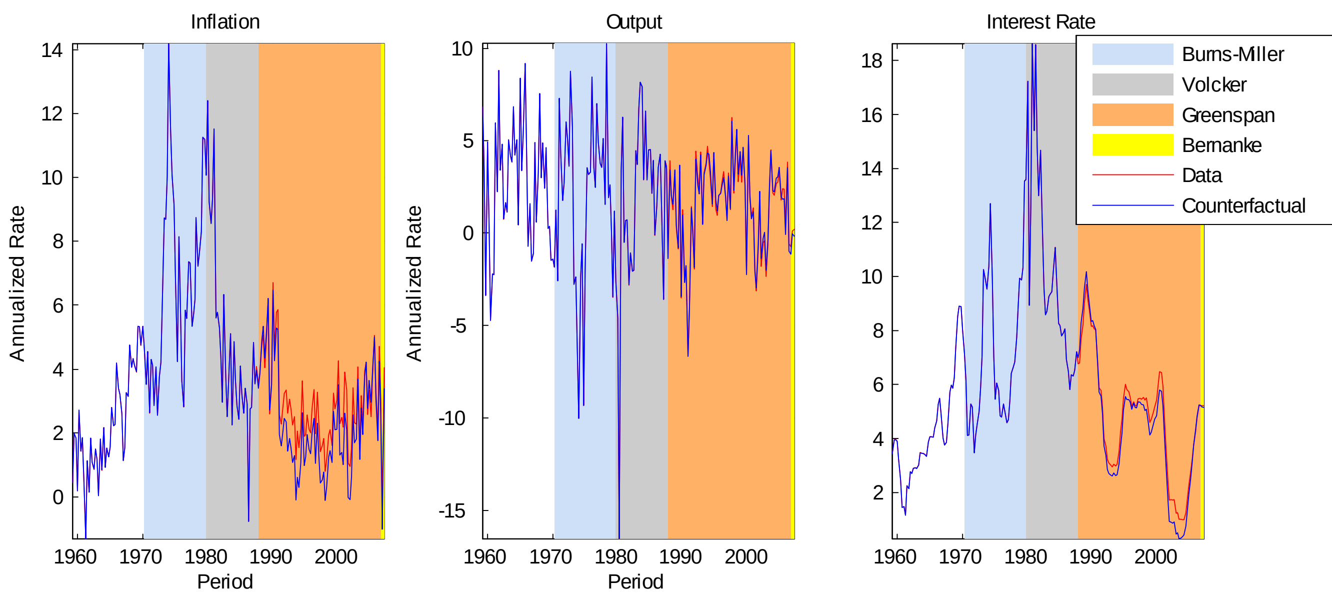

Figure 6.3: Burns-Miller during the Greenspan years

In figure 6.4, we plot the counterfactual of Burns-Miller extending their tenure to 1987. The results are very similar to the case in which we move Greenspan to the same period: slower disinflation and no improvement in output growth.

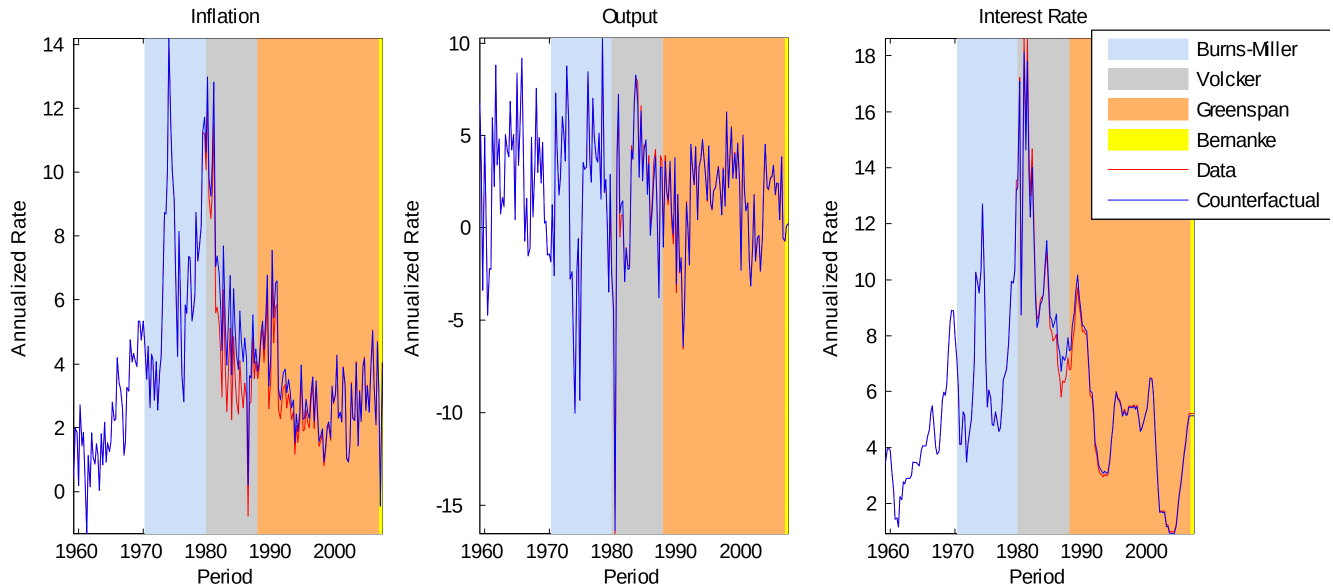

Figure 6.4: Burns-Miller during the Volcker years

A particularly interesting exercise is to check what would have happened if Reagan had decided to reappoint Volcker and not appoint Greenspan. We plot these results in figure 6.5. The quick answer is: lower inflation and interest rates. Our estimates also suggest that Volcker would have reduced price increases with little cost to output.

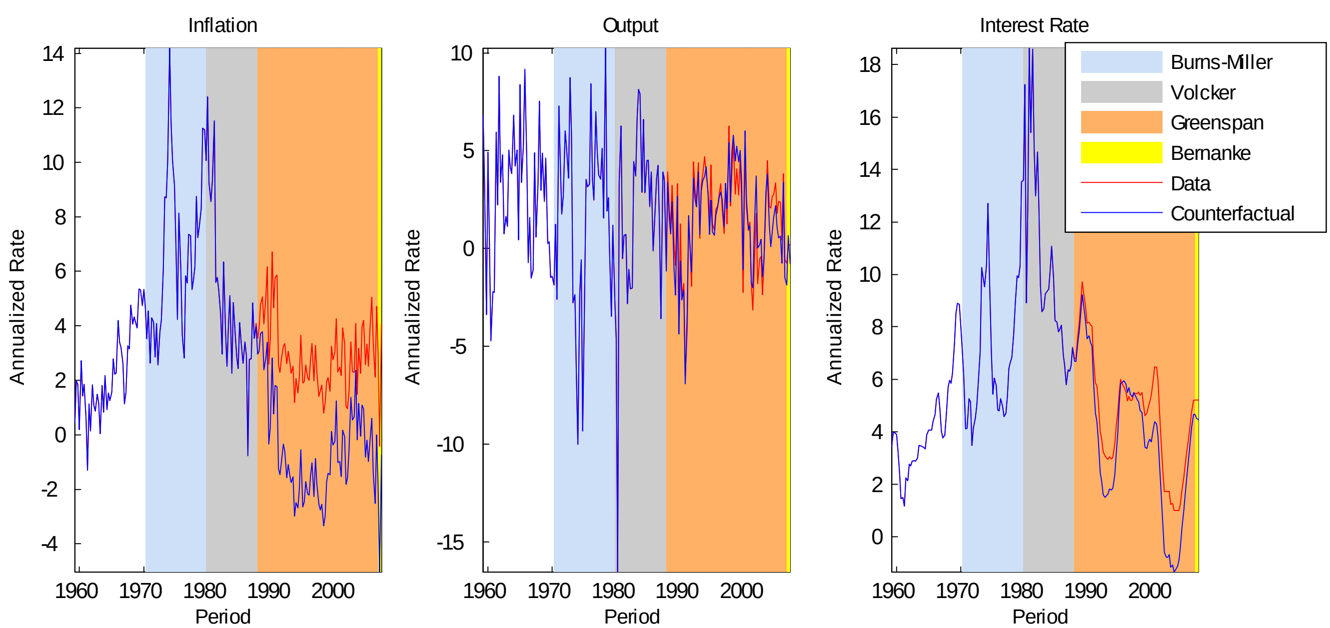

Figure 6.5: Volcker during the Greenspan years

Our final exercise is to plot, in figure 6.6, the counterfactual in which we move Volcker to the time of Burns-Miller. The main finding is that inflation would have been rather lower, especially because the effects of the second oil shock would have been much more muted. This counterfactual is plausible: other countries, such as Germany, Switzerland, and Japan, that undertook a more aggressive monetary policy during the late 1970s were able to keep inflation under control at levels below 5 percent at an annual rate, while the U.S. had peaks of price increases over 10 percent.

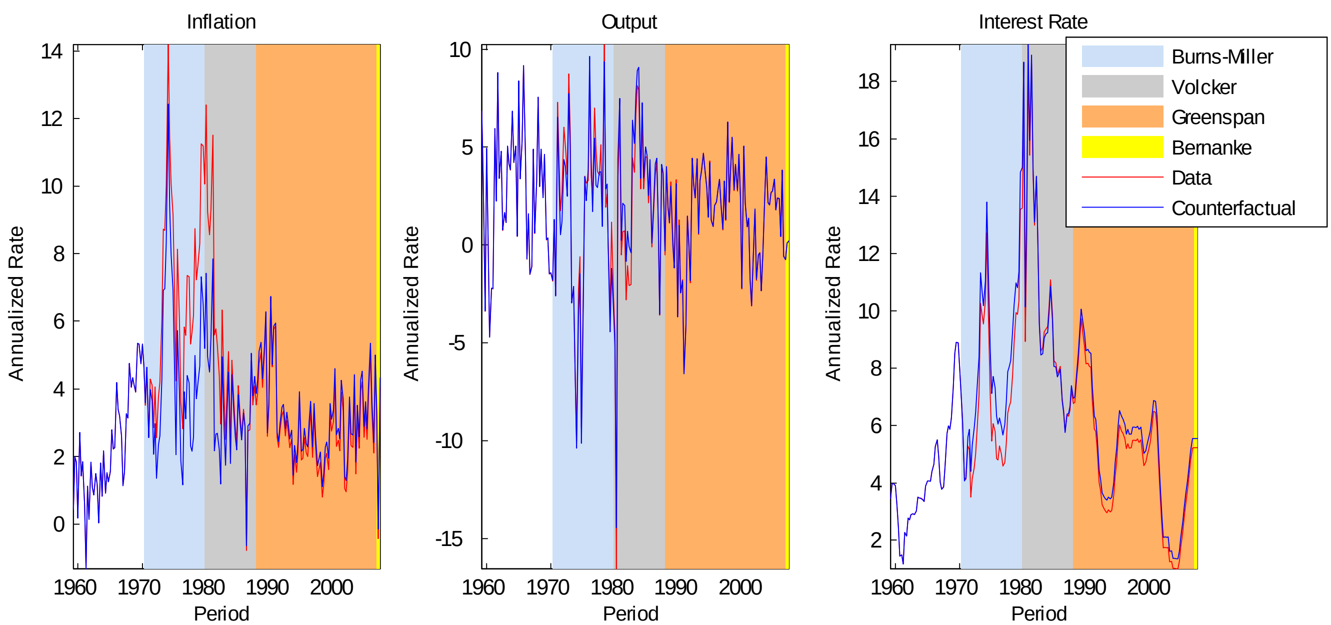

Figure 6.6: Volcker during the Burns-Miller years

6.4.2. Counterfactual II: No Volatility Changes

In our second historical counterfactual, we compute how the economy would have performed in the absence of changes in the volatility of the shocks, that is, if the volatility of the innovation of the structural shocks had been fixed at its historical mean. To do so, we back out the smoothed structural shocks as we did in section 5.8 and we feed them to the model, given our parameter point estimates and the historical mean of volatility, to generate series for inflation, output, and the federal funds rate.

Moments Table 6.2 reports the moments of the data (in annualized terms) and the moments from the counterfactual history (*no s.v.* in the table stands for "no stochastic volatility"). In both cases, we include the moments for the whole sample and for the sample divided before and after

1984.Q1, a conventional date for the start of the great moderation (McConnell and Pérez-Quirós, 2000). In the last two rows of the table, we compute the ratio of the moments after 1984.Q1 over the moments before 1984.Q1. The benchmark model with stochastic volatility plus parameter drifting replicates the data exactly.

Some of the numbers in table 6.2 are well known. For instance, after 1984, the standard deviation of inflation falls by nearly 60 percent, the standard deviation of output growth falls by 44 percent, and the standard deviation of the federal funds rate falls by 39 percent. In terms of means, after 1984, there is less inflation and the federal funds rate is lower, but output growth is also 15 percent lower.

Table 6.2: No Volatility Changes, Data versus Counterfactual History

	Means			Standard Deviations		
	Inflation	Output Growth	FFR	Inflation	Output Growth	FFR
Data	3.8170	1.8475	6.0021	2.6181	3.5879	3.3004
Data, pre 1984.1	4.6180	1.9943	6.7179	3.2260	4.3995	3.8665
Data, after 1984.1	2.9644	1.6911	5.2401	1.3113	2.4616	2.3560
No s.v.	2.5995	0.7169	6.9388	3.5534	3.1735	2.4128
No s.v., pre-1984.1	2.0515	0.9539	6.3076	3.7365	3.4120	2.7538
No s.v., after-1984.1	3.1828	0.4647	7.6106	3.2672	2.8954	1.7673
Data, post-1984.1/pre-1984.1	0.6419	0.8480	0.7800	0.4065	0.5595	0.6093
No s.v., post-1984.1/pre-1984.1	1.5515	0.4871	1.2066	0.8744	0.8486	0.6418

The table also reflects the fact that without volatility shocks, the reduction in volatility observed after 1984 would have been noticeably smaller. The standard deviation of inflation would have fallen by only 13 percent, the standard deviation of output growth would have fallen by 16 percent, and the standard deviation of the federal funds rate would have fallen by 35 percent, that is, only 33, 20, and 87 percent, respectively, of how much they would have fallen otherwise. We must resist here the temptation to undertake a standard variance decomposition exercise. Since we have a second-order approximation to the policy function and its associated cross-product terms, we cannot neatly divide total variance among the different shocks as we could do in the linear case.

Table 6.2 documents that, while time-varying policy is reflected in changes of average inflation, volatility shocks affect the standard deviation of the observed series. Without time-varying volatility the decrease in observed volatility would not have been nearly as big as we observed in the data. Hence, while changes in the systematic component of monetary policy account for changes in average inflation, volatility shocks account for changes in the standard deviation of inflation, output growth and interest rates observed after 1984. Also, without stochastic volatility, output growth would have been quite lower on average.

Counterfactual Paths Figure 6.7 compares the whole path of the counterfactual history (blue line) with the observed one (red line). Figure 6.7 tells us that volatility shocks mattered throughout the sample. The run-up in inflation would have been much slower in the late 1960s (inflation would have actually been negative during the last years of Martin's tenure) with small effects on output growth or the federal funds rate (except at the very end of the sample). Inflation would not have picked up nearly as much during the first oil shock, but output growth would have suffered. During Volcker's time, inflation would also have fallen faster with little cost to output growth. These are indications that both Burns-Miller and Volcker suffered from large and volatile shocks to the economy. In comparison, during the 1990s, inflation would have been more volatile, with a big increase in the middle of the decade. Similarly, during those years, output growth would have been much lower, with a long recession between 1994 and 1998, and the federal funds rate would have been prominently higher. Confirming the results presented in the paper, this is another manifestation of how placid the 1990s were for policy makers.

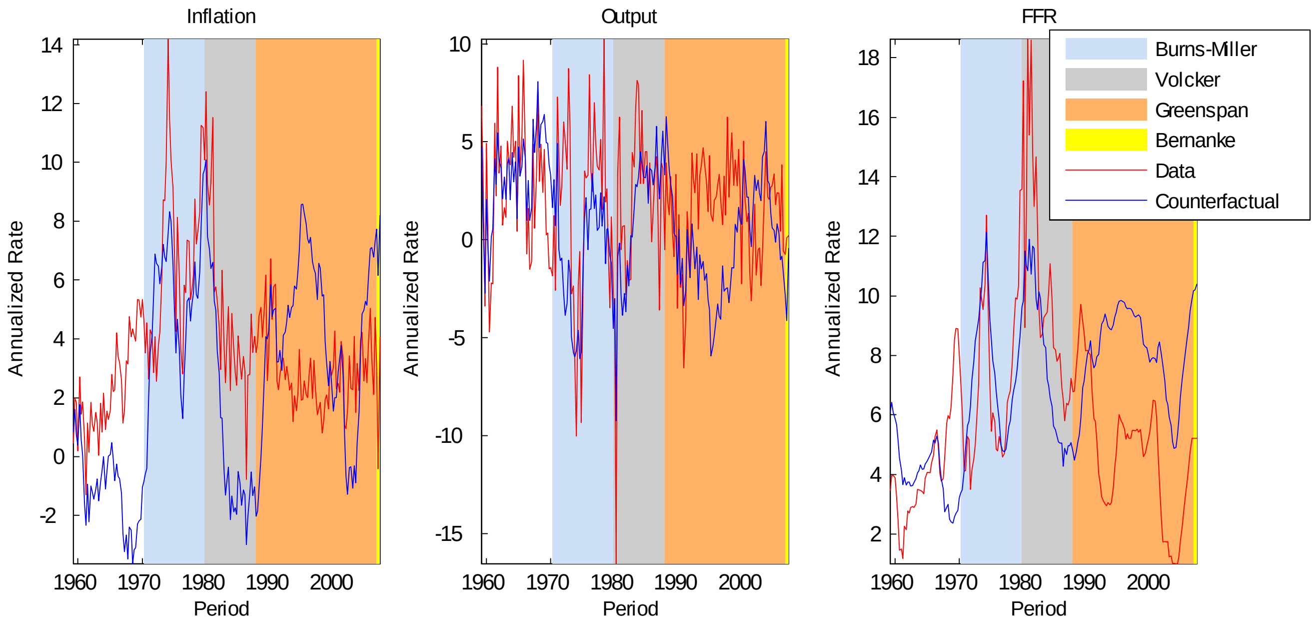

Figure 6.7: Counterfactual “No Changes in Volatility”.

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Contact Details:
BBVA Research
Paseo Castellana, 81 – 7º floor
28046 Madrid (Spain)
Tel.: +34 91 374 60 00 y +34 91 537 70 00
Fax: +34 91 374 30 25
bbvaresearch@bbva.com
www.bbvaresearch.com