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Review of Economic Dynamics 6 (2003) 941–962

Review of
**Economic
Dynamics**

www.elsevier.com/locate/red

The response of term rates to monetary policy uncertainty

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Received 19 July 2001; revised 9 December 2002

Abstract

This paper shows that greater uncertainty about monetary policy can lead to a decline in nominal interest rates. In the context of a limited participation model, monetary policy uncertainty is modeled as a mean preserving spread in the distribution for the money growth process. This increase in uncertainty lowers the yield on short-term maturity bonds because the household sector responds by increasing liquidity in the banking sector. Long-term maturity bonds also have lower yields but this decrease is a result of the effect that greater uncertainty has on the nominal intertemporal rate of substitution—which is a convex function of money growth. We examine the nature of these relations empirically by introducing the GARCH-SVAR model—a multivariate generalization of the GARCH-M model. The predictions of the model are broadly supported by the data: higher uncertainty in the federal funds rate can lower the yields of the three- and six-month treasury bill rates.

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JEL classification: E4; E5; C4

Keywords: Limited participation; Term structure; Mean preserving spread; Multivariate GARCH; GARCH-SVAR

1. Introduction

The current generation of quantitative macroeconomic models, such as those based on the real business cycle paradigm, invariably cast the analysis within a stochastic environment in which the first moments of policy variables constitute the almost exclusive object of interest. In this literature, beginning with the Lucas tradition that emphasized

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the distinction between unanticipated and anticipated monetary policy and continuing with modern extensions that introduce various real and nominal rigidities (sticky prices, sticky wages, and limited participation models, for example), there are few examples that study the impact that the second (and higher) moments of policy variables have on economic activity and welfare. This paper broadens the analysis of macroeconomic policy by investigating how monetary policy uncertainty affects one important aspect of the macroeconomy: nominal yields on risk-free bonds.

We are not the first to point out the paucity of research that examines the consequences of policy uncertainty. Obstfeld and Rogoff (2000) highlight the scant attention that policy uncertainty receives in open economy, macroeconomic policy analysis. While concerns about uncertainty of monetary policy are reflected in popular discussions of *policy transparency* and *policy risk*, the theoretical neglect of these issues is primarily driven by a key technical consideration: the solution of stochastic general equilibrium macroeconomic models typically involves a linear approximation that implies certainty equivalence in equilibrium. Obstfeld and Rogoff (2000) depart from certainty equivalence by assuming that the exogenous variables in the model have lognormal distributions. This particular distributional assumption allows them to obtain closed form solutions. Our analysis also requires that we make distributional assumptions to find exact solutions to the economy but these take the form of a discrete-state Markov process for monetary policy. Moreover, the transition probability matrix of this Markov process is appropriately parameterized to study the effects of *time-varying* uncertainty.¹

Few papers outside the finance literature have successfully explained the variation in the term structure of interest rates with a modern equilibrium macroeconomic model. For example, den Haan's (1995) analysis predicts a yield curve that is essentially flat. A notable exception is that of Evans and Marshall (1998) who find that a limited participation model of monetary non-neutrality is broadly consistent with empirical regularities in the term structure. A limited participation model is an attractive environment for an investigation of policy uncertainty on term-structure relations because of three important properties:²

- (1) the channel of monetary policy transmission is captured through the traditional mechanism of liquidity affecting interest rates which, in turn, affect real activity;
- (2) agent's savings decisions, which in part determine the supply of funds in the loan market, are made before the state of the world is known. Consequently, time-varying uncertainty in monetary policy may create an endogenous response in the loan market which will be reflected in interest rates; and
- (3) nominal interest rates are affected by both Fisherian and liquidity factors.

¹ That is, Obstfeld and Rogoff (2000) focus on the unconditional variance of money growth so that their analysis is one of comparative dynamics. In contrast, the analysis presented here studies the effects of changes in uncertainty within a particular economy.

² This monetary model is also a departure from the Obstfeld and Rogoff (2000) analysis which generates a demand for money by placing real balances in the utility function. Since their focus is on price setting behavior and nominal rigidities, a money-in-the-utility function approach is reasonable. However, since our emphasis is on the term structure, a richer model of interest rates is required.

Subsequently, changes in the second moment of monetary policy (which in our model is described by a simple money growth rule) may affect interest rates through one or both factors. The few previous studies that have examined the effects of time-varying uncertainty (e.g., Lee, 1995; Hodrick, 1989; Dellas and Salyer, forthcoming) used a simple cash-in-advance framework so that nominal interest rates are not affected by liquidity considerations. In addition, the environments investigated in these papers were either exchange economies or they insulated production from monetary uncertainty so that the interaction between uncertainty, output, and interest rates could not be analyzed.

It is important to also note at the outset that we model a very specific type of monetary policy uncertainty. That is, we characterize policy uncertainty as a time-varying conditional variance of the monetary growth rate. This narrow focus, in combination with the economic environment, leads to testable hypotheses. Of course, there are many other interesting types and sources of policy uncertainty, e.g., the nature of the central bank's reaction function (is it a forward- or backward-looking Taylor rule and does it include interest-rate smoothing terms?), time variation in the parameters of the reaction function, uncertainty due to measurement error in real-time data (as stressed by Orphanides, 2001), and uncertainty over the objective function of the monetary authority. Understanding the roles that these and other sources of uncertainty have on economic behavior is a laudable research goal, in our opinion; we view our research as a first step in furthering that goal.

The main results in our paper can be summarized as follows. The model predicts that increases in monetary policy uncertainty will produce a generalized decline in interest rates for all maturities. This prediction has different explanations that depend on the maturity of the bond: at the very short end of the maturity spectrum, the endogenous response of savings (i.e., funds placed in the banking sector) to greater uncertainty results in more liquidity in the lending market, thus lowering the nominal yield. At longer maturities, the decline in rates because of greater uncertainty is due to the fact that the marginal utility of a dollar is a convex function of money growth, which causes a fall in the certainty equivalence of a dollar in the future. The predictions on term premia are indeterminate since they depend on risk aversion and the persistence of monetary policy.

Empirical investigation of these propositions requires that we introduce appropriate econometric methods to measure the effects of uncertainty (which we take to mean volatility for empirical purposes) on the conditional mean of the variables in a VAR. A natural solution to this problem consists of generalizing the GARCH-M model to a multivariate context. The resulting model, which we label GARCH-SVAR and which is similar to the MGARCH-M VAR in Elder (forthcoming), not only allows direct measurement of volatility effects on the impulse response functions but also delivers interesting new properties for them: different shapes as a function of the magnitude of the shock, and asymmetric responses to positive and negative shocks. We apply the GARCH-SVAR model to Evans and Marshall's (1998) monetary VAR to identify the monetary policy innovation series and find broad support for the predictions of the model. In addition, the behavior of output volatility is consistent with the general decline in volatility reported in McConnell and Pérez-Quirós (2000). The remainder of the paper is organized as follows. Section 2 presents the model, whose solution is described in Section 3. Section 4 measures the effect of monetary policy uncertainty empirically and Section 5 presents our conclusions and directions for future research.

2. The model

The model that we employ for our analysis is closely related to that presented in Christiano et al. (1997); hence, expositional comments will be brief.³ The setup is a standard limited participation framework with four sectors: firms, households, financial intermediaries, and the monetary authority. Moreover, the interaction between these sectors is characterized by three factors:

- (1) households determine the fraction of savings placed in the banking sector before they know the current monetary growth rate state;
- (2) firms must borrow funds to pay their labor costs; and
- (3) the monetary transfer is distributed solely to the financial intermediaries.

The details and implications of this environment are provided below.

2.1. Firms

Firms in the model are identical and produce output via a constant returns to scale technology:

$$y_t = h_t^{1-\alpha}. \quad (1)$$

For expositional simplicity and to concentrate on the liquidity channel, note that we have assumed that capital is fixed at the value of one in all periods.⁴ Consequently, firms purchase labor from households with the nominal wage given by W_t . Firms must pay for labor services in advance of production with the wage bill financed via loans from the financial intermediaries. Therefore, the cost of production is given by $R_t W_t h_t$, where R_t is the (gross) interest rate on loans from the banking sector, which are repaid at the end of the period. The necessary condition associated with the optimal choice for labor is the familiar

$$R_t \frac{W_t}{P_t} = (1 - \alpha) h_t^{-\alpha}. \quad (2)$$

As can be clearly seen in Eq. (2), nominal interest rates will affect labor costs and, therefore, can influence economic activity.

2.2. Households

Households decisions are more complicated and are made sequentially as information becomes available. Specifically, it is assumed that agents must allocate their nominal

³ As stated in the introduction, we use a limited participation model because nominal interest rates are affected by both liquidity and Fisherian factors. However, the particular model we employ does not generate persistent output effects due to a monetary shock because we do not include portfolio adjustment costs as in Christiano et al. (1997). This simplification is justified on the grounds that our primary theoretical interest is in the qualitative effects of policy uncertainty on interest rates.

⁴ The capital stock is owned by the households; hence, firm profits represent the returns to capital. These are distributed to households at the end of the period.

wealth at the beginning of the period between funds to be used for consumption in the goods market, denoted c_t , where agents face a cash-in-advance constraint and savings placed in the banking sector, denoted I_t . This portfolio decision is made before the current state of the world, i.e., the monetary growth rate state, is known. After the funds are allocated to the banking sector, agents learn of the monetary growth rate state and, with this resolution of uncertainty, all prices are known. Consumption and labor decisions are then made. Note that the funds allocated for consumption at the beginning of the period are augmented by current labor income; this total is used to finance consumption (the cash-in-advance constraint is binding). Households then receive profits from firms (denoted ζ_t), the income from deposits made to the banking sector, and bank profits made from lending new money, T_t , received from the monetary authorities (described in detail below).

The households' maximization problem can be written in the form of the following dynamic programming problem:

$$V\left(\frac{M_{t-1}}{P_t}\right) = \max_{I_t} E_{t-1} \left\{ \max_{(c_t, h_t, M_t)} \left[U(c_t, 1 - h_t) + \beta E_t \left(V\left(\frac{M_t}{P_{t+1}}\right) \right) \right] \right\}, \quad (3)$$

$$\text{subject to } P_t c_t \leq M_{t-1} - I_t + W_t h_t, \quad (4)$$

$$M_t = (M_{t-1} - I_t + W_t h_t - P_t c_t) + \zeta_t + R_t (T_t + I_t). \quad (5)$$

The time subscripts on the expectations operators are used to denote the information set relevant at the time of decision. Equation (4) is the cash-in-advance constraint while Eq. (5) is the budget constraint. The necessary conditions associated with this maximization problem are:

$$E_{t-1} \left[\frac{U_{c,t}}{P_t} - R_t \beta E_t \left(\frac{U_{c,t+1}}{P_{t+1}} \right) \right] = 0, \quad (6)$$

$$U_{l,t} = U_{c,t} \frac{W_t}{P_t}, \quad (7)$$

where $U_{c,t}$ and $U_{l,t}$ denote the marginal utilities of consumption and leisure, respectively. Equation (6) is the hallmark of the limited participation model and represents the fact that the one-period nominal interest rate will be, on average, equal to the nominal intertemporal marginal rate of substitution. However, R_t will depart from this term due to unanticipated changes in liquidity. Consequently, the short-term nominal interest rate is affected by Fisherian (i.e., the intertemporal) marginal rate of substitution and liquidity factors. The second equation represents the traditional labor–leisure trade-off.

2.3. Financial intermediaries

Each period, financial intermediaries in the economy issue loans, L_t , in order to maximize profits. It is assumed that there are no costs associated with making loans so that all funds are inelastically supplied. That is,

$$L_t = T_t + I_t. \quad (8)$$

As noted before, T_t denotes the monetary transfer from the central bank. The assumption that the monetary injection enters into the economy via the banking sector is another

distinguishing characteristic of the limited participation model and is an attempt to capture the asymmetric effects that open market operations have on households and financial intermediaries. All profits made from lending activity, $R_t(T_t + I_t)$, are returned to households at the end of the period.

2.4. The monetary authority

The sole purpose of the central bank is to provide money to the economy. Rather than explicitly modeling monetary policy, we assume that the money supply grows exogenously at the rate g_t . That is, the evolution of the money supply, \bar{M}_t , is given by:

$$\bar{M}_t = \bar{M}_{t-1}(1 + g_t). \quad (9)$$

We assume that the growth rate follows a discrete-state Markov process. The parameters of this process are chosen to facilitate the study of time-varying uncertainty.⁵ Specifically, g_t will follow a four-state Markov process with possible realizations,

$$g_t = \begin{cases} g_1 = \bar{g} - \delta, \\ g_2 = \bar{g}, \\ g_3 = \bar{g}, \\ g_4 = \bar{g} + \delta. \end{cases} \quad (10)$$

Since the realization of the monetary growth rate is identical in states 2 and 3, the monetary growth rate state is not determined solely by the value of g_t . Hence, we will describe the current state as s_i , $i = 1, 2, 3, 4$. The transition probability matrix of this Markov process is given by

$$\Pi = \begin{bmatrix} \pi & \frac{1-\pi}{3} & \frac{1-\pi}{3} & \frac{1-\pi}{3} \\ \frac{1-\pi}{3} & \pi & \frac{1-\pi}{3} & \frac{1-\pi}{3} \\ \frac{1-\pi}{2} & 0 & \pi & \frac{1-\pi}{2} \\ \frac{1-\pi}{3} & \frac{1-\pi}{3} & \frac{1-\pi}{3} & \pi \end{bmatrix}. \quad (11)$$

The limiting or unconditional distribution of this process (given by the eigenvector of Π associated with the eigenvalue of 1) is uniform so that the unconditional probability of state i is $p_i = 1/4$. It is obvious from Eq. (10) that this implies that the unconditional first and second moments of money growth are $E(g_t) = \bar{g}$ and $\text{Var}(g_t) = \delta^2/2$. Also, the first-order autocorrelation of money growth is given by $\text{Corr}(g_t, g_{t-1}) = (4\pi - 1)/3$. Hence, whether $\pi (>, =, <) 1/4$ implies whether $\text{Corr}(g_t, g_{t-1}) (>, =, <) 0$.

While the unconditional probabilities are necessary for characterizing the stationary distribution of the equilibrium in the economy, it is the conditional distribution of money growth that determines equilibrium behavior. In particular, as can be seen in Eq. (6), changes in the first and second moments of money growth will affect the conditional expectations that determine investment decisions (the funds deposited in the banking sector) and nominal interest rates. The first and second moments conditional on the state s_t at time t are easily characterized by

⁵ This Markov process was used previously by Salyer and Slotsve (1993) to study the effects that time-varying uncertainty of technology shocks have on equity prices and interest rates.

s_i	$E(g_{t+1} s_t = s_i)$	$Var(g_{t+1} s_t = s_i)$
1	$\bar{g} - \delta \frac{(4\pi-1)}{3}$	$\frac{2}{9}(1 + 7\pi + 8\pi^2)\delta^2$
2	\bar{g}	$\frac{2}{3}(1 - \pi)\delta^2$
3	\bar{g}	$(1 - \pi)\delta^2$
4	$\bar{g} + \delta \frac{(4\pi-1)}{3}$	$\frac{2}{9}(1 + 7\pi + 8\pi^2)\delta^2$.

Consequently, the effects of the first moments of money growth on equilibrium can be studied by comparing the equilibrium properties between states s_1 and s_4 . However, more important for our purposes, equilibrium behavior between states s_2 and s_3 reflects the impact of changes in the second moment of money growth since the conditional distribution in state s_3 represents a mean preserving spread in the distribution relative to that in state s_2 . Since our interest lies in studying the effects of time-varying uncertainty of monetary policy, we will focus exclusively on equilibrium in these two states.

3. Equilibrium

Equilibrium in the economy is characterized by the sequence of consumption, labor, and interest rates that satisfy the necessary conditions given in the previous section and are consistent with market clearing. Market clearing in the goods market requires

$$c_t = h_t^{1-\alpha}. \tag{12}$$

Equilibrium in the lending market, the assumption that the cash-in-advance constraint is binding, and the equilibrium condition $M_t = \bar{M}_t$ imply

$$T_t + I_t = L_t = W_t h_t, \tag{13}$$

$$P_t c_t = M_{t-1} + W_t h_t - I_t = M_{t-1} + T_t = M_{t-1}(1 + g_t) = M_t. \tag{14}$$

To compute equilibrium, the following functional form for preferences is used:⁶

$$U(c_t, 1 - h_t) = \frac{c_t^{1-\gamma}}{1-\gamma} + A(1 - h_t),$$

where it is assumed that $\gamma \geq 1$ and $A > 0$. Using this functional form, equilibrium in the labor market implies

$$A c_t^\gamma = \frac{W_t}{P_t} = (1 - \alpha) \frac{h_t^{-\alpha}}{R_t}. \tag{15}$$

Finally, the intertemporal necessary condition is

$$E_{t-1} \left[\frac{1}{c_t^{-\gamma} P_t} - R_t \beta E_t \left(\frac{1}{c_{t+1}^{-\gamma} P_{t+1}} \right) \right] = 0. \tag{16}$$

⁶ These preferences are a departure from those studied in Christiano et al. (1997), who use preferences that are logarithmic in a composite good represented as a nonlinear function of consumption and leisure. Their functional form highlights agents' labor supply elasticity. Since our interest is in time-varying changes in risk, we impose constant relative risk aversion on consumption so that we can examine the effects of risk aversion on equilibrium behavior.

Due to the sequential revelation of information, consumption, labor and interest rates will, in a stationary equilibrium, be a function of both the current and the previous realization of the monetary growth rate. The investment decision, in contrast, will only be a function of the monetary growth rate at time $t - 1$ since this determines the relevant information set. We define a stationary monetary equilibrium in terms of the beginning of period money stock, M_{t-1} . That is, the investment decision is

$$i_t = i_i = \frac{I_t}{M_{t-1}}, \quad (17)$$

where $i = 1, 2, 3, 4$ denotes the state (i.e., the realization of the monetary growth rate state) in period $t - 1$.

Note that the ratio of funds in the labor and goods market can be expressed as

$$\frac{W_t h_t}{P_t c_t} = \frac{T_t + I_t}{M_{t-1}(1 + g_j)} = \frac{M_{t-1}(g_j + i_i)}{M_{t-1}(1 + g_j)} = \frac{(g_j + i_i)}{(1 + g_j)}, \quad (18)$$

where $j = 1, 2, 3, 4$ denotes the state of the monetary growth rate state at time t . Using the labor–leisure necessary condition in the left-hand side of Eq. (15) and given the production function in (1), the left-hand side term can be written as

$$A c_{ij}^{\gamma-1} h_{ij} = A h_{ij}^{\gamma(1-\alpha)+\alpha},$$

so that, in equilibrium, the ratio of funds in the lending and goods market implies the following 16 equations:

$$A h_{ij}^{\gamma(1-\alpha)+\alpha} = \frac{(g_j + i_i)}{(1 + g_j)}, \quad i, j = 1, 2, 3, 4. \quad (19)$$

By using the cash-in-advance constraint and the production function, the intertemporal necessary condition (6) can be written as

$$E_i \left[\frac{h_{ij}^{(1-\alpha)(1-\gamma)}}{1 + g_j} - \frac{R_{ij}}{(1 + g_j)} \beta E_j \left(\frac{h_{jk}^{(1-\alpha)(1-\gamma)}}{1 + g_k} \right) \right] = 0, \quad (20)$$

where $k = 1, 2, 3, 4$ is used to denote the state in period $t + 1$. Equation (20) implies an additional 4 equations that must be satisfied in equilibrium.

Equilibrium in the labor market, given by Eq. (15), generates the final 16 equations defining equilibrium:

$$R_{ij} = \frac{(1 - \alpha)}{T} h_{ij}^{-[\gamma(1-\alpha)+\alpha]}, \quad i, j = 1, 2, 3, 4. \quad (21)$$

Equilibrium is thus characterized by the 36 values (h_{ij}, R_{ij}, i_i) that solve the 36 equations represented by expressions (19)–(21).

To explore the implications that time-varying monetary uncertainty has on interest rates, we introduce three other bonds into this economy—a one-period real bond (denominated in units of consumption), and a one- and two-period nominal bonds. The (gross) yields on these bonds are, respectively, ρ_t , R_t^I , and R_t^{II} . These bonds trade in an asset market that is assumed to open after the current monetary growth rate is known. Consequently, the yield on the one-period nominal bond is differentiated from R_t (the one-period yield on funds

placed in the banking sector) because all uncertainty about liquidity has been resolved. By comparing the equilibrium behavior of these one-period yields, the effects of liquidity and uncertainty can be studied. The pricing formulas for the three bonds are determined by the associated necessary conditions:

$$U_{c,t} = \rho_t \beta E_t[U_{c,t+1}], \tag{22}$$

$$\frac{U_{c,t}}{P_t} = R_t^I \beta E_t \left(\frac{U_{c,t+1}}{P_{t+1}} \right), \tag{23}$$

$$\frac{U_{c,t}}{P_t} = (R_t^{\text{II}})^2 \beta E_t \left(\frac{U_{c,t+1}}{P_{t+1}} \frac{1}{R_{t+1}^I} \right). \tag{24}$$

Finally, we compute the holding premia to study the implications for term premia, i.e., the difference between the expected return from selling a two-period bond after one-period and the current one-period yield. Since there are two one-period yields in this economy, there will be two associated term premia. These are calculated as follows:

$$T P_t = E_t \left[\frac{(R_t^{\text{II}})^2}{R_{t+1}} \right] - R_t, \tag{25}$$

$$T P_t^I = E_t \left[\frac{(R_t^{\text{II}})^2}{R_t^I} \right] - R_t^I. \tag{26}$$

We now describe the equilibrium behavior of these yields and yield differentials.

3.1. Characterizing equilibrium

In order to study the equilibrium characteristics of the economy, the parameter values describing tastes (β, γ, A), technology (α), and monetary policy (π, \bar{g}, δ) must be specified. The parameter values were calibrated to produce reasonable outcomes that would highlight the qualitative characteristics of equilibrium. Specifically, agents' discount factor was set to $\beta = 0.95$ while the labor's share was held constant at 64% ($\alpha = 0.36$). In addition, the unconditional mean and standard deviations of monetary growth were set at $E(g_t) = \bar{g} = 0.04$ and $\sigma_g = \delta = 0.12$. These parameter values imply that the steady-state (i.e., no-uncertainty) nominal interest rate is roughly 9%.

We conducted four experiments that differed by the degree of persistence in money growth and by the degree of relative risk aversion. Specifically, we computed the equilibrium for $\pi = 0.25, 0.81$ which, given the Markov process specified in (11), implies that $\text{Corr}(g_t, g_{t+1}) = 0, 0.75$, and for values of the risk aversion parameter $\gamma = 1, 5$. Finally, the parameter A was adjusted so that, for all experiments, 40% of time was spent in work activity in steady state.

Before examining the effects of time-varying uncertainty in the monetary growth rate, it is important to first note that equilibrium is indeed influenced by changes in liquidity. This can be seen in Eq. (19) in which the right-hand side is an increasing function in both i_i and g_j ; given that $\alpha < 1$, this implies that labor will be positively related to both terms. The effect on interest rates can be seen by noting that

$$\frac{(W_t/P_t)h_t}{c_t} = \frac{(1-\alpha)h_t^{1-\alpha}}{R_t c_t} = \frac{(1-\alpha)}{R_{ij}} = \frac{g_j + i_i}{1 + g_j}.$$

Consequently, greater liquidity will cause the short-term nominal interest rate to fall.

The effects of time-varying uncertainty in money growth are now examined in the four economies by comparing equilibrium values in states s_2 and s_3 . Since equilibrium interest rates and labor are determined by both the current and previous monetary growth rate states, we assume that these states are constant. That is, the low uncertainty state is represented by the values $(i_2, h_{22}, R_{22}, \rho_{22}, R_{22}^I, R_{22}^{II})$, while the effects of greater uncertainty of future money growth are reflected in the values $(i_3, h_{33}, R_{33}, \rho_{33}, R_{33}^I, R_{33}^{II})$. These values are reported in Table 1.

Consider first the case where there is no serial correlation in money growth, $\pi = 0.25$. Note that increases in uncertainty (corresponding to $s_t = s_3$) result in an increase in the amount of funds placed in the banking sector. This increase in liquidity results in a fall in the short-term nominal interest ($R_{33} < R_{22}$) which, in turn, produces a (small) increase in labor. While relative risk aversion affects the level of interest rates, it does not affect the qualitative effects of uncertainty.⁷

Like the short-term interest rate, all other yields (both nominal and real) fall with increases in uncertainty. This effect, however, is not due to increased liquidity but to the fact that both the agent's marginal utility and the inverse of the inflation rate (which determines the real return on nominal bonds) are convex functions. A mean preserving spread in the distribution causes the expected value of these functions to increase, which results in lower yields.

The intuition behind these results is clear. Consider the real interest rate, ρ_t . Greater uncertainty of future consumption lowers the certainty equivalent level of next period's consumption implying an increase in the relative amount of current consumption. The price of current consumption relative to future consumption, the real interest rate, therefore falls. Again, relative risk aversion does not affect this qualitative response. With serial correlation in money growth, these qualitative effects are still present but are smaller in magnitude.

Turning to the predictions for the term premia, note that the term premium defined in terms of R_t (i.e., TP_t) always increases with greater uncertainty. However, the term premium TP_t^I does not exhibit such monotonic behavior—with low risk aversion, this term premium stays relatively constant when there is no serial correlation in the growth rate (namely $\pi = 0.25$) or falls when the money growth rate is serially correlated ($\pi = 0.81$). However, with high risk aversion, the relationship is reversed: this term premium increases when money growth is serially uncorrelated (and also when uncertainty increases) but remains relatively constant when money growth is serially correlated, irrespective of the level of uncertainty.

These results can be summarized as follows: greater monetary uncertainty leads to lower interest rates. The effect on the term premia depends on whether the short-term interest rate is affected primarily by liquidity or expected inflation. If liquidity factors

⁷ The question arises whether this endogenous response would exist in a model in which agents had access to a richer menu of assets. Here an increase in uncertainty increases the demand for savings; hence, even if assets other than banking deposits were available, we conjecture that this would not eliminate entirely the increase in banking deposits observed in our model. That is, it is rare for an increase in savings to result in a portfolio allocation that eliminates entirely the demand for one asset. (Note that the household's response is one of savings not simply portfolio reallocation.) The qualitative response of interest rates would, as a consequence, be maintained.

Table 1
The effects of monetary policy uncertainty in a limited participation model

variable	Low relative risk aversion: $\gamma = 1$				High relative risk aversion: $\gamma = 5$			
	Corr(g_t, g_{t-1}) = 0		Corr(g_t, g_{t-1}) = 0.75		Corr(g_t, g_{t-1}) = 0		Corr(g_t, g_{t-1}) = 0.75	
	low variance ($s_t = s_{t-1} = s_2$)	high variance ($s_t = s_{t-1} = s_3$)	low variance ($s_t = s_{t-1} = s_2$)	high variance ($s_t = s_{t-1} = s_3$)	low variance ($s_t = s_{t-1} = s_2$)	high variance ($s_t = s_{t-1} = s_3$)	low variance ($s_t = s_{t-1} = s_2$)	high variance ($s_t = s_{t-1} = s_3$)
i_{t-1}	58.0	58.4	57.3	57.5	58.0	58.4	57.1	57.3
$h_{t t-1}$	40.8	41.1	40.4	40.5	40.2	40.3	40.0	40.1
$R_{t t-1} - 1$	7.3	6.7	8.5	8.1	7.3	6.6	8.8	8.5
$R_{t t-1}^I - 1$	8.7	8.4	9.3	9.2	7.8	7.0	9.0	8.8
$R_{t t-1}^{II} - 1$	8.7	8.5	9.1	9.0	8.2	7.8	9.1	8.9
$\rho_{t t-1} - 1$	4.8	4.5	5.1	5.1	4.5	4.2	5.1	5.0
$TP_{t t-1}$	2.3	2.9	1.1	1.6	1.3	1.6	0.50	0.70
$TP_{t t-1}^I$	0	0	-0.10	-0.20	0.50	0.80	0.10	0.10

Note. All variables expressed in percentages.

are dominant (TP_t), then the term premia should increase with greater uncertainty. If inflationary expectations are the primary factor affecting nominal interest rates, then the model's predictions are less clear: greater uncertainty should lower term premia if agents have low risk aversion; if risk aversion is high, term premia should increase instead.

4. Measuring the effects of time-varying uncertainty

4.1. The GARCH-SVAR

The theoretical model described in the previous sections requires an empirical counterpart capable of capturing the effects of time-varying uncertainty on the conditional mean of the variables in the system. However, there are few models designed in this manner, and while time-varying uncertainty is commonly modeled with a GARCH or a stochastic volatility (SV) model, we are only aware of the GARCH-M as an alternative that relates volatility with the conditional mean. At the same time, empirical macroeconomic research requires methods that allow investigators to describe the dynamic intercorrelations that exist among the economic variables of the model. The vector autoregression (VAR) is the most commonly used tool for this purpose.

The demands of our theoretical model and its implications force us to combine these alternatives into new methods. In particular, we are interested in examining how shocks to monetary policy affect economic activity, prices, and the term structure by way of a direct effect on their conditional means and by way of an indirect effect due to changes in the conditional variance. Thus, consider a typical, reduced-form VAR

$$Y = X\pi + u, \quad E(u'u) = \Omega, \quad (27)$$

where Y is a $(T \times n)$ matrix whose rows contain the observations of the $(n \times 1)$ vector y_t ; X is a $(T \times (np + 1))$ matrix that contains the constants and up to p lags of Y ; and u are the $(T \times n)$ reduced-form residuals with variance–covariance matrix Ω . Identification of the structural form from (27) requires an assumption that ensures that the transformed model has orthogonal residuals ε (that is, $E(\varepsilon'\varepsilon) = D$, where D is a diagonal matrix) in a manner that guarantees that the contemporaneous correlations between the elements in Y reflect the true structure of the economy.

A common assumption in the literature consists in decomposing the reduced-form, variance–covariance matrix into its Cholesky factors, $\Omega = A'DA$. Given an assumption about the Wold-causal order of the variables in Y , this decomposition delivers the unique structural-form counterpart to (27) as

$$YA^{-1} = X\pi A^{-1} + \varepsilon, \quad \varepsilon = uA^{-1}. \quad (28)$$

There are, of course, other ways of orthogonalizing Ω (different Wold-causal orderings, non-Cholesky factorizations, and so on); however, for the purposes of presentation we ignore these momentarily. Consider now expanding (28) in two ways. First, allow the structural residuals ε to follow a general GARCH process. Although theoretically

this translates into a multivariate GARCH specification, notice that because the ε are orthogonalized by construction, their multivariate structure can be simplified into

$$H_t i = W + \Gamma_1 H_{t-1} i + \dots + \Gamma_r H_{t-r} i + \dots + \Phi_1 \varepsilon_{t-1}^2 + \dots + \Phi_m \varepsilon_{t-m}^2, \tag{29}$$

where H_t is an $(n \times n)$ diagonal matrix whose elements are the conditional variances of the ε ; i is an $(n \times 1)$ vector of ones that vectorizes the matrix H_t into an $(n \times 1)$ vector; W is an $(n \times 1)$ vector of constants; and the Γ_i and Φ_j are diagonal $(n \times n)$ coefficient matrices. Expression (29) therefore corresponds to the restricted version of a multivariate GARCH(r, m) model in which each of the diagonal elements of H_t follows a univariate GARCH(r, m) process.

The second extension we consider is to allow the conditional variance to enter directly into the specification of the conditional mean of the VAR. Therefore, (28) becomes

$$Y A^{-1} = X \pi A^{-1} + G \beta A^{-1} + \varepsilon, \tag{30}$$

where $G'_i = (H_t i, \dots, H_{t-p+1} i)$. We refer to this model as a GARCH-SVAR, following the original nomenclature for its univariate counterpart. Although developed independently, the GARCH-SVAR is very similar to the MGARCH-M VAR model in Elder (forthcoming) and shares many of its properties. This precedent gives us confidence on the merits of the modeling strategy that we propose.

Estimation of our model can be done by maximum likelihood by further assuming that the ε are multivariate normally distributed so that the likelihood can be expressed as

$$L(\theta) = -\frac{n(T-p)}{2} \log(2\pi) - \frac{1}{2} \sum_{t=p}^T (\log |H_t| + \varepsilon'_t H_t^{-1} \varepsilon_t), \tag{31}$$

and by conditioning on the first p observations and using conventional numerical techniques (see Bollerslev, 1990). In practice, due to the high dimensionality and nonlinearity of the problem, it is more efficient to concentrate on the likelihood around H_t and follow a two-step iterative procedure. For example, conditional on preliminary estimates of H_t (say, the univariate GARCH(r, m) estimates from the usual SVAR), estimate the conditional mean system and then concentrate the likelihood on the conditional mean parameters to estimate H_t from its GARCH specification—iterate until there is no improvement in the parameter estimates.

Given the estimates of (30), the impulse response functions for the system can be calculated as suggested in Hamilton (1994), namely

$$\begin{aligned} \frac{\partial y_{j,t+s}}{\partial \varepsilon_{it}} &= E(y_{j,t+s} \mid \varepsilon_{i,t} = \varepsilon_i^*; y_{t-1}, H_t, \dots, y_{t-p}, H_{t-p+1}) \\ &\quad - E(y_{j,t+s} \mid y_{t-1}, H_t, \dots, y_{t-p}, H_{t-p+1}), \end{aligned} \tag{32}$$

where ε_i^* denotes the magnitude of the shock to the i th structural shock being considered in the specific impulse response. The impulse responses from (32) have several notable features that are not found in usual impulse responses from SVARs. First, notice that a shock to the i th variable has the usual effect on the conditional mean of the system but it simultaneously affects the conditional variance (through the lags ε_{t-i}^2), thus having an additional effect on the conditional mean via the lags H_{t-i} . This feature provides a direct

measure of the effects of time-varying uncertainty (or more generically, of second-moment effects): the difference between the impulse response given in expression (32) and the impulse response resulting from setting the coefficients β in (30) to zero.

Secondly, in conventional impulse responses, the magnitude of the shock with which one experiments has no other consequence than changing the scale of the responses, leaving their shapes unaltered. However, the GARCH-SVAR is a nonlinear model and the size of the shock impacts the shape of the response. The larger the shock, the larger its effect on the conditional variance (through ε_{t-i}^2) and the larger the effect on the conditional means of y_{t+s} . This is a natural consequence: larger shocks cause a higher revision of the conditional variance. Lastly, the sign of the shock is also important. In a typical SVAR, the linearity of the model imparts symmetry between positive and negative shocks: by flipping the sign of the original shock, one merely obtains the mirror image of the original response. In the GARCH-SVAR this is no longer true since the sign of the shock does not change the sign of the response of the conditional variance H_t and therefore the conditional variance has the same effect on the conditional mean as if the shock had been positive. The total effect on the conditional mean is therefore asymmetric. The next sections investigate a particular application of the GARCH-SVAR designed to illustrate some of the features of the theoretical model in Section 3.

4.2. Identifying shocks to policy and policy uncertainty in practice

In a related paper, Evans and Marshall (1998) analyze how monetary impulses affect the shape of the yield curve for nominally risk-free bonds. In particular, they find that a contractionary shock causes a substantial increase in short-term nominal yields, with a progressively smaller response as the maturity of the bond is lengthened. This in turn flattens the slope and the curvature of the yield curve. These observations are broadly consistent with the predictions of a limited participation model that is closely related to the model presented in Section 2. Although we investigate a different effect—that of time-varying uncertainty in monetary policy on risk-free interest rates and term premia—it will be advantageous to examine these issues with an empirical framework similar to that in Evans and Marshall (1998). In addition, the specification in Evans and Marshall (1998), originally proposed by Christiano et al. (1996), has been used in other contexts as well (e.g., see Hamilton and Jordà, 2002; Hoover and Jordà, 2001).

The overall empirical strategy that we pursue consists of identifying a monetary shock series based on Evans and Marshall's (1998) monetary VAR, augmented by the three- and six-month Treasury Bill rates. Specifically, the system contains the following variables: the logarithm of non-agricultural employment, EM ; the logarithm of personal consumption expenditures deflator (1996 = 100), P ; the annual growth rate of the index of sensitive commodities price index, $PCOM$; the federal funds rate, FF ; the ratio of non-borrowed reserves plus extended credit to total reserves, $NBRX$; the annual growth rate of M2, $\Delta M2$; the three-month T-Bill rate, $TB3$; and the six-month T-Bill rate, $TB6$. Given this eight-variable system, we follow Evans and Marshall (1998) in taking FF as the monetary policy

indicator.⁸ Therefore, we can interpret the equation for FF as a reduced form for the policy reaction function.

Identification of the monetary policy shock from the policy reaction function further requires that we make an assumption that renders the residuals of the eight variable VAR orthogonal to each other in a manner that also delivers a structural interpretation of such shocks, as proposed in expression (28). The standard assumption in the literature is to assume a Wold-causal order and use the Cholesky decomposition to obtain the appropriate orthogonalization. The ordering used in Evans and Marshall (1998), augmented to our specification, is $EM_t, P_t, PCOM_t, FF_t, NBRX_t, \Delta M2_t, TB3_t, TB6_t$. In addition, Evans and Marshall (1998) experiment with two alternative identification schemes: a nonrecursive identification strategy due to Sims and Zha (1998), and an identification strategy based on long-run restrictions due to Galí (1992). Each of these variants does not deliver significantly different responses to the orthogonalized monetary shock and thus, for the sake of brevity, will not be explored here.

Thus, the GARCH-SVAR is estimated with monthly data for the period 1965:1 to 1999:4 and contains two lags. Although it may appear that two lags are insufficient, consider that the final specification of the GARCH-SVAR contains 259 coefficients and therefore does not allow much latitude to consider richer specifications. We will also experiment with subsamples of the original period, which further restricts available degrees of freedom. Experiments with more lags did not deliver noticeably different impulse responses and furthermore, when we compared our responses to those in Evans and Marshall (1998, Fig. 1, p. 59), there are no appreciable differences (except for the response of prices in the very short run but not in the long run). Before discussing further estimation details, it is instructive to give a general overview of the performance of the GARCH-SVAR model.

Figure 1 compares the responses to a positive shock in the federal funds rate that one obtains from a conventional VAR with those from the GARCH-SVAR. Thus, the thin solid line corresponds to the responses from the conventional VAR, the thick solid line to the responses from the GARCH-SVAR, and the dotted lines to the error bands from the conventional VAR (one-standard deviation in size). The size of the shock is normalized to be of one-standard deviation (which turns out to be about a 0.5% shock, a very reasonable magnitude for the federal funds rate). The units of measurement in all plots are in percentage terms. Generally speaking, we find there are a few moderately significant differences between the models. Employment declines by a lower amount in the GARCH-SVAR model in response to a contractionary shock in FF , with prices responding more in line with traditional views of monetary policy. Thus, tightening interest rates (FF in the model) reduces employment significantly, causes the response of $NBRX$ to be consistent with a liquidity effect, $\Delta M2$ declines accordingly (more strongly in the GARCH-SVAR), and the response of the 3- and 6-month T-Bills is consistent with conventional views of the term structure—the initial impact of the increase in FF causes about a $2/3$ increase in both T-Bill rates. The GARCH-SVAR responses of the T-Bill rates are also lower (although

⁸ The VAR literature contains numerous specifications in which the federal funds rate is chosen as the monetary policy indicator. For an extensive survey, see Christiano et al. (1999).

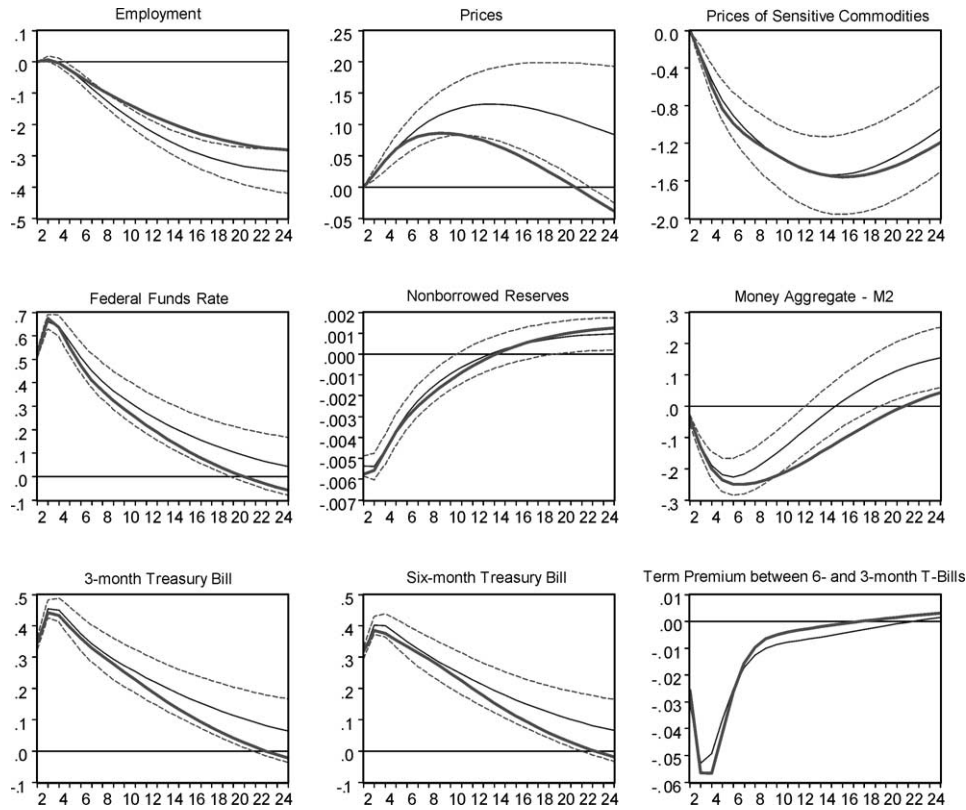


Fig. 1. Comparing a typical SVAR with the GARCH-SVAR. Responses to a 0.5% shock in the federal funds rate equation. All plots measured in percentages. Thick solid lines are the responses from the GARCH-SVAR, thin solid lines are the responses from a typical SVAR, and dotted lines are the one-standard deviation error bands obtained by Monte Carlo simulation.

not significantly) than they are in the usual SVAR, seemingly supporting the model in Section 3.

Despite the apparent merits of the GARCH-SVAR, we were unable to find a measurable effect of volatility on these responses. When we experimented by setting the conditional mean response to volatility to be zero in the GARCH-SVAR, the responses literally lied on top of each other, making them indistinguishable. However, recall that the size of the shock is one standard deviation and thus, it can hardly be expected to cause any revisions in uncertainty. In addition, the next section describes some interesting volatility patterns that may explain this lack of influence. Thus, the next section experiments with bigger shocks, structural breaks in volatility, and exploits some of the new features of the responses in the GARCH-SVAR model.

4.3. Measuring policy uncertainty effects

Before further experimenting with the GARCH-SVAR model, we discuss some of the finer points of the estimation. In particular, the two-step iterative procedure starts by testing the structural residuals of the conventional SVAR for evidence of ARCH effects with a conventional ARCH-LM test (see Hamilton, 1994, p. 664). At this stage, we found no evidence of ARCH for both *PCOM* and $\Delta M2$. Next, we constructed initial GARCH(1,1) models for the remaining series in the system. We had problems getting the GARCH model for *NBRX* to converge (estimates of the GARCH parameters appeared to approach zero simultaneously) and hence we constrained its variance to be constant, as we did with *PCOM* and $\Delta M2$. For the remaining series, the two-step algorithm had no further problems and converged rather smoothly.

Figure 2 displays plots of the conditional variances for *EM*, *P*, *FF*, *TB3*, and *TB6*, which are interesting in their own right. For instance, the upper left panel in Fig. 2 displays the conditional volatility in employment. This volatility decreases significantly for the latter part of the sample (starting in the mid-eighties), and is consistent with the findings of a number of recent papers (see Blanchard and Simon, 2001; Kahn et al., 2002; McConnell and Pérez-Quirós, 2000). The top right panel shows that prices display a different pattern of volatility, which is much more stable and consistently higher from the mid-seventies to the early nineties and lower in the early and latter parts of the sample—a result that is also broadly consistent with what is reported in Blanchard and Simon (2001), for example. The remaining panels in Fig. 2 display the conditional variances for the three interest rate variables in our study and display well known patterns, with spikes in volatility that coincide with the Volcker disinflation and a gradual decline since then.

One concern that we had was to allow for the breaks in volatility that have been reported in the literature. Thus, McConnell and Pérez-Quirós (2000) report a break in the volatility of output in the first quarter of 1984 (similar breaks in volatility for this specific date have been found by others, for example, Chauvet and Popli (2002)). Similarly, there are clear spikes in the volatility of the interest rate data that correspond to the initial part of Volcker's tenure and are closely related to the non-borrowed reserves targeting period followed at the federal funds. As a consequence, we experimented by re-estimating the GARCH-SVAR over two subsamples. The first ran from 1965:1 to 1979:10 and the second from 1984:1 to 1999:4, therefore purposely excluding the turbulent 1979:10–1983:12 period, for which there is not enough data. The first subsample did not display evidence of ARCH effects for the residuals of the *FF* variable (measured by the corresponding ARCH-LM test) and, therefore, we did not investigate it any further since its response would not differ from that in a typical SVAR. However, the second subsample did display strong evidence of ARCH effects in the *FF* residuals and is the one for which subsequent experiments are reported.

We are now in a position to conduct our final two experiments. First, we will shock the federal funds rate by +3% (instead of +0.5%), since this shock is more likely to cause revisions in volatility and allows us to exploit the dependency of the GARCH-SVAR responses on the size of the shock. We will then compare these responses with the responses one would obtain by shutting down the β coefficients in expression (30). This experiment delivers a direct measure of the relative importance of monetary policy volatility on the conditional mean of term-structure responses (as well as the remaining

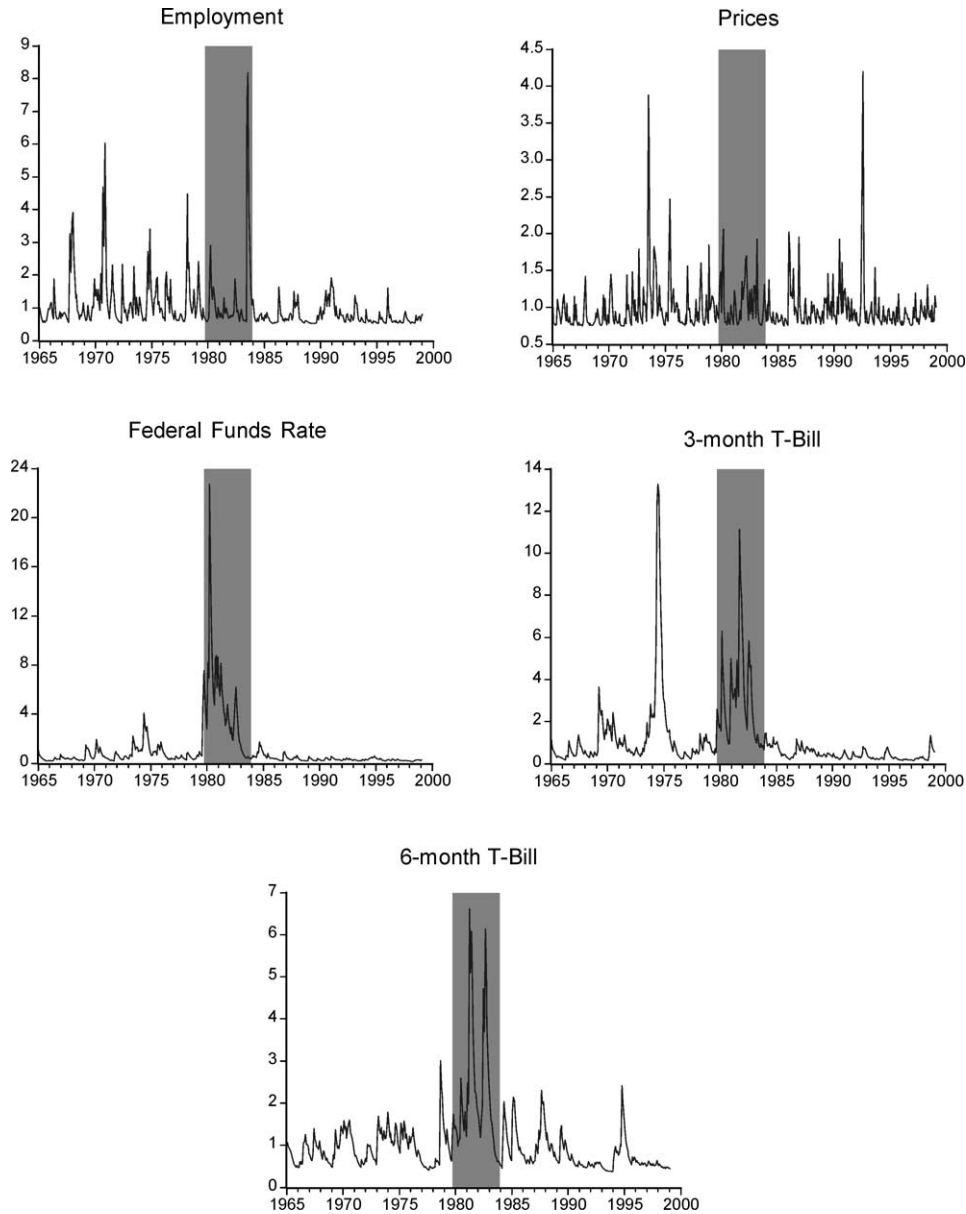


Fig. 2. Conditional variance estimates from GARCH-SVAR model. Conditional variances calculated from the GARCH-SVAR model. Shaded area denotes the period October, 1979 to December, 1983.

variables in the system). The second experiment we conduct consists of examining the asymmetry of the responses to negative and positive shocks. Therefore, we shock the federal funds equation by -3% instead and then take the negative of these responses so as

to provide visual comparisons of the asymmetric property of the impulse responses. If the responses are symmetric, then they will lie exactly on top of each other. These experiments are contained in Fig. 3.

Each panel in Fig. 3 displays three lines. The thick, solid line corresponds to the GARCH-SVAR response of the variable to a +3% shock in the federal funds rate equation; the thin solid line corresponds to the negative of the response to a –3% shock instead; and the dotted line corresponds to the responses to a +3% to the federal funds rate when the coefficients on the volatility terms in the conditional mean equations have been set to zero.

Several results deserve comment. One of the main conclusions of the model in Section 3 is that greater monetary policy uncertainty leads to lower interest rates. Judging from the responses of the 3- and 6-month T-Bill rates in Fig. 3, we find this to be true: both of these rates attain lower values when the volatility terms enter the conditional mean (solid thick line) than when they are constrained to be zero (dotted line). Similarly, notice that the responses can be highly asymmetric to the sign of the shock (particularly for the variables P , $PCOM$, and $\Delta M2$). Unfortunately, this asymmetric behavior also suggests that interest

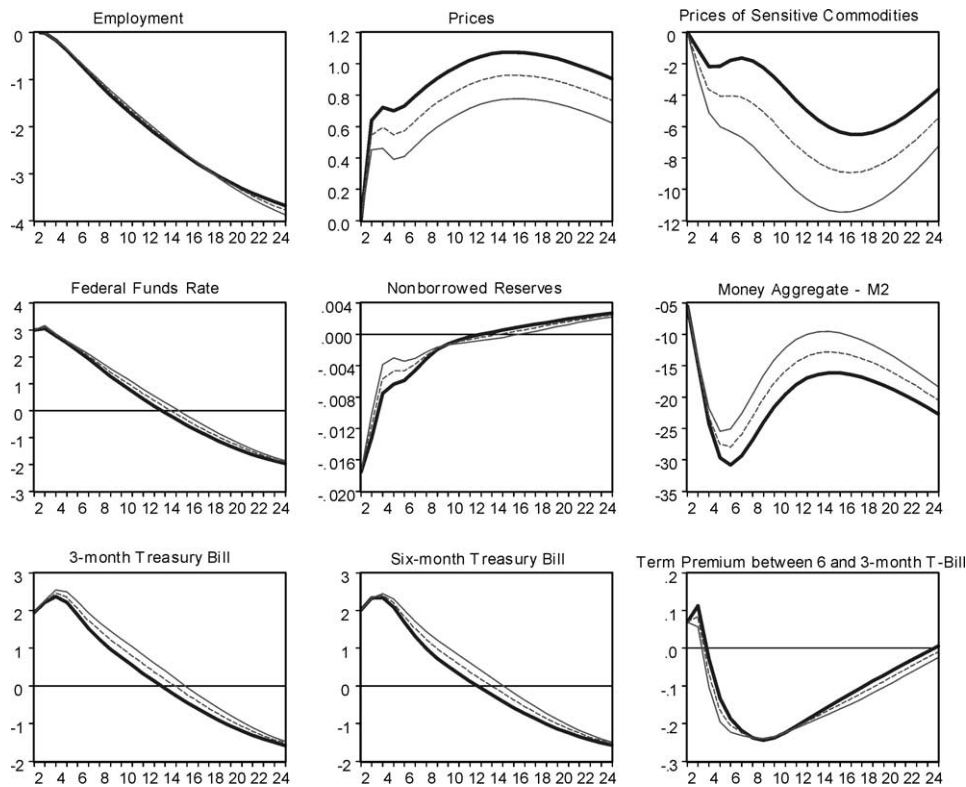


Fig. 3. Measuring volatility and asymmetry in the GARCH-SVAR. Thick solid line represents responses to a 3% shock in the federal funds rate equation; thin solid line represents the negative of the responses to a –3% shock instead; and the dotted line represents the responses to a 3% shock when the volatility effects on the conditional mean are set to zero.

rates are *lower* in response to a monetary easing when volatility effects are excluded instead. The way to see this effect is by noticing that the thin line would lie below the dotted line if one were to invert the impulse responses around the zero axis.

How important is the effect of monetary policy volatility on interest rates? It is difficult to give a statistical answer because the magnitude of the volatility effect depends on the size of the shock and therefore, by varying its magnitude, the difference can be increased or decreased (recall that the difference is negligible when the shock is 0.5% in size). In our example, the effect of the conditional volatility of *FF* shocks on interest rates is approximately 15 basis points on average (for a 3% shock), and while it is visually small, this value is close to that obtained in the simulations reported in Table 1.

The response of the term premium between the six- and the three-month T-Bill rates is reported in the bottom right panel of Fig. 3. In response to a monetary tightening, the term premium initially increases and then rapidly decreases over the next two years. The effect of volatility is to lower this premium by less than 5 basis points, a rather small amount, but this is over a term premium that ranges from a maximum of 10 basis points to a minimum of –20 basis points. The effect of monetary policy volatility on the remaining variables in the system is rather small with the notable exception of the price levels and *M2*.

5. Conclusion

Limited participation models are perhaps the only class of dynamic equilibrium models of monetary economies whose predictions of term-structure relations match the data reasonably well. Because they are capable of generating a liquidity effect, these models are particularly well suited to investigate the transmission of monetary policy on the term structure. The modeling tradition that characterizes these models (as well as most dynamic equilibrium models) essentially devotes undivided attention to the analysis of relations based on first moments of the stochastic processes that characterize the behavior of policy variables. As we discuss, this restrictive analysis is largely motivated by the technical difficulties entailed in solving these models rather than by an intrinsic disinterest in higher moment effects.

One contribution of this paper is to open new ground in this modeling tradition by exploring the effects of a particularly relevant second moment effect: that of time-varying monetary policy uncertainty on term rates. Contrary to cursory intuition, we show that term rates tend to decline when monetary policy becomes more uncertain. At the short end, this increase in uncertainty results in increased liquidity in the lending market whereas at the long end, the convexity of consumption to money growth modifies the certainty equivalence of a dollar in the future.

Another contribution of this paper is to introduce new empirical methods designed to measure second moment effects on the conditional mean of a dynamic system. The GARCH-SVAR delivers broad empirical validation to the predictions of the theoretical model but we expect that its interest widely transcends the application in this paper. For example, the GARCH-SVAR can be used to obtain direct measures of the effects of output and inflation volatility on the response of monetary policy and term rates. Generalizations of the GARCH-SVAR are immediately apparent and we reserve for future research the

investigation of these issues. One specific advantage of the GARCH-SVAR that we want to consider is the possibility of identifying the structure of reduced form VARs by finding the space of linear combinations that will insure GARCH effects are restricted to the diagonal terms of the variance covariance matrix.

The analysis in this paper adds to a growing literature that examines the effects that second moments have on the conduct of monetary policy. For instance, Dupor (forthcoming), shows that randomizing the monetary growth rate can increase utility in an economy with nominal price rigidities (due to monopolistic competition) since money growth surprises can help to eliminate welfare losses due to monopoly. In our model, greater uncertainty results in a more elastic response of labor due to a given monetary shock because of the greater fall in interest rates—hence it is possible that greater uncertainty in monetary policy is welfare improving. However, the simple environment studied here (in particular, the assumption of no-productive assets) makes any welfare claims tentative at best. In another related paper, Dotsey and Sarte (2000) demonstrate in a cash-in-advance economy that increased variability in money growth can increase the economy's growth rate. Like the results in our paper, the mechanism is that increased uncertainty results in a greater precautionary savings which, in turn, leads to greater capital and growth. While these results improve our understanding of the impact of uncertainty, clearly, more research is needed—critically, the role of money and liquidity needs to be given greater attention, we believe, if these efforts are to be successful.

Acknowledgments

We thank Tom Mayer for his encouragement and suggestions, and two anonymous referees for recommending changes that helped improve the paper significantly.

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