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THE CONVENTIONAL MONETARY POLICY AND TERM STRUCTURE OF INTEREST RATES DURING THE FINANCIAL CRISIS

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This paper analyzes whether the Fed had the ability through its conventional monetary policy to affect key economic and financial variables, and, in particular, the term structure of interest rates, during the recent financial crisis. This departs from the empirical literature that focuses mainly on the effectiveness of unconventional monetary policies during this episode, although these policies are appropriate only to the extent that the conventional policy was ineffective in the first place. Our identification strategy based on the conditional heteroskedasticity of the structural innovations allows us to specify a flexible structural vector auto-regressive process that relaxes the identifying assumptions commonly used in earlier studies. Comparing our results obtained from samples excluding and including the financial crisis, we find that the conventional monetary policy has lost its effectiveness shortly after the beginning of the financial turmoil. This result suggests that the Fed's use of unconventional policies was appropriate, at least, with the objective of changing the term structure of interest rates.

Keywords: Conventional Monetary Policy, Term Structure of Interest Rates, Structural Vector Auto-Regression, Conditional Heteroskedasticity, Financial Crisis

1. INTRODUCTION

This paper fills a gap in the empirical literature by investigating whether the Fed had the ability through its conventional monetary policy to affect key economic and financial variables, and, in particular, the term structure of interest rates, during the recent financial crisis. Using a flexible identification strategy that relaxes some commonly used identifying restrictions, we find that such policy has lost most of

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its effectiveness shortly after the beginning of the financial turmoil. This result suggests that the Fed's use of unconventional policies was appropriate, at least, with the objective of changing the term structure of interest rates.

Recently, there has been a debate on whether monetary policies had any significant effect on economic and financial conditions during the latest financial crisis. On the one hand, Mishkin (2009) and Bernanke (2009) argue that monetary policies during the financial crisis have indeed been effective. For example, in his Stamp lecture at the London School of Economics, Bernanke argues: "The Fed's monetary easing has been reflected in significant declines in a number of lending rates, especially shorter-term rates, thus offsetting to some degree the effects of the financial turmoil on financial conditions." On the other hand, Krugman (2008) and some members of the Fed [Board of Governors of the Federal Reserve System (2008)] were concerned that monetary policies lost their effectiveness during the financial crisis. For example, Krugman writes in his column in the New York Times: "... the usual tools of monetary policy - above all the Federal Reserve's ability to pump up the economy by cutting interest rates - have lost all traction."

Although there is a growing number of empirical studies assessing the effectiveness of unconventional monetary policies [see Christensen et al. (2009), Stroebel and Taylor (2009), Taylor and Williams (2009), Cecioni et al. (2011), Thornton (2011), Wu (2011), Duygan-Bump et al. (2013)], the literature is relatively silent on the effects of the conventional monetary policy during the financial crisis.[1] This is surprising given that it is appropriate for the Fed to implement unconventional policies only to the extent that the conventional policy was ineffective in the first place. However, this might be due to the fact that it is not a trivial question given problems associated with existing methods of identifying conventional monetary policy shocks and their effects in the context of the financial crisis.

These methods can be broadly grouped into two categories: event studies, which rely on a narrative approach to isolate exogenous and unanticipated changes in the conventional monetary policy, and those based on estimating structural vector auto-regressions (SVAR). Event studies implicitly assume the existence of a sufficiently large number of policy announcement dates at which the various shocks, other than conventional monetary policy shocks, affecting economic and financial conditions do not occur systematically at the event days. In this context, the conventional monetary policy shocks and their effects can be identified by aggregating over the various event days, even though each event may be individually contaminated by nonpolicy shocks [Cook and Hahn (1989), Roley and Sellon (1995), Kuttner (2001)]. Unfortunately, during the financial crisis, there were only few announcements by the Fed regarding changes in the fund rate, and these changes were systematically in response to market-wide shocks.

SVAR-based studies, on the other hand, impose some restrictions on the contemporaneous interactions among variables. These restrictions can take the form of short-run exclusions [Evans and Marshall (1998)], long-run restrictions [Evans and Marshall (1998)], sign restrictions [Roush (2007)], or nonlinear restrictions reflecting no arbitrage conditions [Smith and Taylor (2010), Ang et al. (2011), Ang and Piazzesi (2003)]. Unfortunately, all these identification schemes involve restrictions that are not dictated by the data, but rather reflect the econometrician's judgement, among others, about the specification of the monetary authority's feedback rule. For example, the short-run exclusions invoked in Evans and Marshall (1998) imply that the Fed, when making its policy, completely ignores current values of the reserve variables. Also, none of the identification schemes mentioned above is testable, under the usually maintained assumption that the structural shocks are conditionally homoskedastic.

Our analysis relies on a methodology that relaxes some identifying assumptions commonly used in earlier studies. Instead, conventional monetary policy shocks and their effects are identified by exploiting the conditional heteroskedasticity of the innovations to the variables included in the SVAR, as in Normandin and Phaneuf (2004) and Bouakez and Normandin (2010). The idea behind this approach is that time variation in the conditional volatilities of the structural innovations provides additional information that allows us to identify more parameters (relative to the usual conditionally homoskedastic case). As a result, some arbitrary restrictions can be relaxed on the contemporaneous interactions between the variables of interest, thus leading to a rich specification of the Fed's feedback rule.

Empirically, we estimate the flexible system over two samples. The first one covers the period between November 1982 and March 2007, so that it excludes the latest financial crisis. The second sample covers the period between November 1982 and August 2008, and as such it includes the part of the financial crisis where the Fed had the ability to implement the conventional monetary policy, but excludes the portion of the crisis where unconventional monetary policies became dominant. For both samples, we obtain parameter estimates indicating that all structural innovations display conditional heteroskedasticity, which is crucial for our identification strategy.

Using the parameter estimates obtained for each sample, we compute the dynamic responses in order to compare the effects of positive conventional monetary policy shocks occurring before and during the financial crisis. For the precrisis sample, we find that the response of output is positive and hump shaped, the price level gradually increases to reach a plateau, and the Fed funds rate displays a sharp, but short lived, decline. For the factors underlying the term structure of interest rates, the level of the yield curve decreases persistently, the response of the slope is negative and hump shaped, whereas the curvature does not respond. Finally, the yields of government bonds for all selected maturities decrease following the policy, although they return fairly rapidly to their preshock levels. In sum, these responses are consistent with well-accepted beliefs about the dynamic effects of the conventional monetary policy. Turning to the sample that includes the financial crisis, we observe that the responses of key macroeconomic aggregates, term structure factors, and yields are always negligible.[2] Comparing the results obtained for the two samples suggests that the conventional monetary policy during the financial crisis was not as effective in influencing economic and financial conditions. This conclusion is striking given that the financial crisis period represents only a small part of the whole sample period.

We next undertake a variance decomposition analysis to assess the contributions of conventional monetary policy shocks to the forecast error variances of selected variables. For the precrisis period, we find that the policy shock explains a sizeable portion of the fluctuations of the variables of interest. In contrast, for the sample including the financial crisis, the contributions of the conventional monetary policy shock become negligible for all variables. In sum, the variance decomposition analysis accords with the conclusion reached from the dynamic responses discussed above. We further perform a response decomposition analysis to document which are the fundamental elements underlying the change in the effects of conventional monetary policy shocks on the yield curve following the financial crisis. To this end, we extend the development of Campbell and Ammer (1993) to disentangle the impact response of yields in terms of the responses of revisions in investors' expectations of three components: inflation rate, real rate of return, and excess return (risk premium). This exercise reveals that, for the precrisis period, the impact responses of yields are mainly explained by downward revisions in expectations of future real rate of return for the short end of the yield curve, and by downward revisions in expectations of future excess return for the long end. However, for the sample including the financial crisis, the muted initial responses of yields reflect insubstantial revisions in expectations of all components. These findings suggest that the revisions of investors' expectations, especially for the real rate of return and excess return, have changed during the financial crisis.

Finally, we analyze the robustness of our results in three dimensions. First, we use total balances at the Fed instead of total reserves following Carpenter and Demiralp (2008), who argue that total balances are a better measure to describe the Fed funds market. Second, following the argument in Vilasuso (1999) that the effects of conventional monetary policy shocks depend on the Fed's operating procedures, we use February 1994 as an alternative starting date for both of our samples. This is when the Fed adopted the current practice of announcing its target for the Fed funds rate. Third, we amend the specification of the SVAR to account for richer interactions between the factors of the term structure of interest rates. The empirical results suggest that our conclusion on the ineffectiveness of the conventional monetary policy in changing key macroeconomic aggregates and the term structure of interest rates is robust to alternative measures of total reserves, other sample periods, and different specifications.

For the rest of the paper, we refer to the conventional monetary policy simply as monetary policy, unless otherwise stated. Section 2 presents the methodology underlying the flexible system used to identify monetary policy shocks and their effects. Section 3 reports the empirical results suggesting that the monetary policy during the financial crisis was not as effective in influencing key economic and financial variables. Section 4 concludes.

2. METHODOLOGY

In this section, we present the flexible system used to compare the effects of monetary policy shocks before and during the financial crisis. We then discuss the identification strategy, estimation method, and sample selection.

2.1. Specification

Our objective is to evaluate the responses of key macroeconomic aggregates and several yields of government bonds for different maturities, following monetary policy shocks occurring before and during the recent financial crisis. In practice, it would be untractable to perform the analysis from a large, single, SVAR that includes all these variables. For this reason, we follow the strategy popularized by Evans and Marshall (1998), which consists in specifying small-scale SVARs, where each of these systems involves all macroeconomic aggregates, but only one of the factors underlying the term structure of interest rates. Also, the responses of yields for different maturities are constructed from the responses of term structure factors, obtained from the various systems. Admittedly, a drawback of this modeling strategy is that it implicitly assumes that the term structure factors have no influence on each other. However, the advantages of this approach are the following: (i) the assumption that the term structure factors are not mutually related implies that the response of each factor is not affected by the way the other factors are extracted, (ii) each small-scale SVAR is parsimonious given that it involves a relatively small number of parameters, and (iii) the small-scale systems are often used in the empirical literature, which allows us to compare our results to those reported in previous studies.

It is worth stressing that, in other dimensions, our specification strategy departs from the empirical literature. Namely, we relax some restrictions commonly imposed to identify monetary policy shocks and their effects. As a result, our approach yields a more flexible description of the monetary authority's feedback rule.

Specifically, for a given term structure factor, we start with the following κ-order SVAR:

$$A_i z_{i,t} = \sum_{j=1}^{\kappa} B_{i,j} z_{i,t-j} + \varepsilon_{i,t}, \tag{1}$$

which is partitioned as

$$\begin{pmatrix} A_{gg} & A_{gr} & A_{gi} \\ A_{rg} & A_{rr} & A_{ri} \\ A_{ig} & A_{ir} & A_{ii} \end{pmatrix} \begin{pmatrix} g_t \\ r_t \\ f_{i,t} \end{pmatrix} = \sum_{j=1}^{\kappa} \begin{pmatrix} B_{gg,j} & B_{gr,j} & B_{gi,j} \\ B_{rg,j} & B_{rr,j} & B_{ri,j} \\ B_{ig,j} & B_{ir,j} & B_{ii,j} \end{pmatrix} \begin{pmatrix} g_{t-j} \\ r_{t-j} \\ f_{i,t-j} \end{pmatrix} + \begin{pmatrix} \varepsilon_{g,t} \\ \varepsilon_{r,t} \\ \varepsilon_{f_i,t} \end{pmatrix}. \tag{2}$$

The vectors g_t and r_t include the macroeconomic aggregates belonging to the goods and reserve markets, respectively, that are traditionally considered in previous empirical studies seeking to identify monetary policy shocks and their effects [such as Sims (1992), Bernanke and Mihov (1998), Evans and Marshall (1998), Normandin and Phaneuf (2004), Lanne and Lutkepohl (2008), Lutkepohl (2012)]. The goods market variables are an index of production (ip_t), the price level (p_t), and commodity prices (cp_t), whereas the reserve market variables are the nonborrowed reserves (nbr_t), total reserves (tr_t), and the Fed funds rate (ff_t). The variable $f_{i,t}$ corresponds to the ith factor of the term structure of interest rates. As will be clear below, we consider three factors, corresponding to the level, slope, and curvature of the yield curve. The vector $\varepsilon_{i,t}$ incorporates mutually uncorrelated structural innovations and, in particular, the monetary policy shock. The matrix A_i contains the parameters capturing the contemporaneous interactions among variables. The matrices $B_{i,j}$ reflect the dynamic feedbacks between these variables.

Denote $\nu_{i,t}$ as the vector of residuals (or statistical innovations) obtained from the reduced form associated with (1). These residuals are linked to the structural innovations through

$$A_i \nu_{i,t} = \varepsilon_{i,t}. \tag{3}$$

As is well known, under the usual assumption of conditional homoskedasticity, the extraction of the structural innovations from the residuals requires identifying restrictions on some elements of A_i. As discussed below, our empirical methodology relaxes this assumption, so that monetary policy shocks and their effects can be identified even when some restrictions commonly imposed in the literature are relaxed.

From a statistical perspective, the identification may be achieved even when A_i is left completely unrestricted, given that it is unique apart from changes in the signs and permutations of its rows [e.g., Sentana and Fiorentini (2001), Waggoner and Zha (2003), Ehrmann et al. (2011), Lutkepohl (2012)]. In this context, however, the structural innovations cannot be interpreted economically. To circumvent this difficulty, we normalize the sign of the diagonal elements of A_i to be positive and invoke a minimum set of restrictions on the submatrices A_{gr}, A_{gi}, A_{rr}, and A_{ri} to ensure that one specific structural innovation represents the monetary policy shock. In particular, we depart from most empirical studies by deriving the restrictions on A_{rr} from the equilibrium solution of the following formulation of the reserve market[3]:

$$\nu_{tr,t} = -\alpha \nu_{ff,t} + \sigma_d \varepsilon_{d,t}, \tag{4a}$$

$$\nu_{nbr,t} = \phi_d \sigma_d \varepsilon_{d,t} - \phi_b \sigma_b \varepsilon_{b,t} + \sigma_s \varepsilon_{s,t}, \tag{4b}$$

$$(\nu_{tr,t} - \nu_{nbr,t}) = \beta \nu_{ff,t} - \sigma_b \varepsilon_{b,t}, \tag{4c}$$

where $\nu_{.,t}$ and $\varepsilon_{.,t}$ denote, as before, statistical and structural innovations. The structural innovation $\varepsilon_{s,t}$ is interpreted as the monetary policy shock, representing an unexpected exogenous policy action taken by the Fed. Furthermore, the terms $\varepsilon_{d,t}$ and $\varepsilon_{b,t}$ denote, respectively, the shocks of demand for total reserves and supply of borrowed reserves by commercial banks. The positive parameters σ_s, σ_d, and σ_b scale the structural innovations of interest, the positive terms α and β are slope parameters, and the unrestricted coefficients ϕ_d and ϕ_b measure the strength of the Fed's responses to certain shocks. The formulation (4) specifies, in innovation form, the banks' demand for total reserves (4a) and a kinked supply of reserves, reflecting the injections of reserves by the Fed through conventional open market operations (4b) and banks' supply of borrowed reserves (4c).

For completeness, we follow the literature by assuming $A_{gr} = 0$ so that the goods market variables ip_t, p_t, and cp_t are not influenced contemporaneously by the reserve market variables nbr_t, tr_t, and ff_t, and by setting $A_{gi} = A_{ri} = 0$ such that the goods and reserve markets variables are not affected instantaneously by the term structure factor $f_{i,t}$ [e.g., Strongin (1995), Eichenbaum and Evans (1995), Bernanke and Mihov (1998), Evans and Marshall (1998), Kim and Roubini (2000), Carpenter and Demiralp (2008)]. Although it is not required for the identification of system (3), we also fix $B_{gi,j} = B_{ri,j} = 0$ in the SVAR (2) to compare our results to those reported in existing studies [e.g., Evans and Marshall (1998)]. Note that $A_{gi} = A_{ri} = B_{gi,j} = B_{ri,j} = 0$ imply that neither contemporaneous nor lagged values of term structure factors influence the macroeconomic aggregates. As such, the structural innovations associated with the aggregates, including the monetary policy shock, are not altered by the exclusion of some term structure factors in the system and by the method used to extract these factors.

Inserting the restrictions in system (3) yields

$$\begin{pmatrix} a_{11} & a_{12} & a_{13} & 0 & 0 & 0 & 0 \\ a_{21} & a_{22} & a_{23} & 0 & 0 & 0 & 0 \\ a_{31} & a_{32} & a_{33} & 0 & 0 & 0 & 0 \\ a_{41} & a_{42} & a_{43} & \frac{1+\phi_b}{\sigma_s} & -\frac{\phi_d+\phi_b}{\sigma_s} & \frac{\beta\phi_b-\alpha\phi_d}{\sigma_s} & 0 \\ a_{51} & a_{52} & a_{53} & 0 & \frac{1}{\sigma_d} & \frac{\alpha}{\sigma_d} & 0 \\ a_{61} & a_{62} & a_{63} & \frac{1}{\sigma_b} & -\frac{1}{\sigma_b} & \frac{\beta}{\sigma_b} & 0 \\ a_{i,71} & a_{i,72} & a_{i,73} & a_{i,74} & a_{i,75} & a_{i,76} & a_{i,77} \end{pmatrix} \begin{pmatrix} \nu_{ip,t} \\ \nu_{p,t} \\ \nu_{cp,t} \\ \nu_{nbr,t} \\ \nu_{tr,t} \\ \nu_{ff,t} \\ \nu_{f_i,t} \end{pmatrix}$$

$$= \begin{pmatrix} \varepsilon_{1,t} \\ \varepsilon_{2,t} \\ \varepsilon_{3,t} \\ \varepsilon_{s,t} \\ \varepsilon_{d,t} \\ \varepsilon_{b,t} \\ \varepsilon_{f_i,t} \end{pmatrix}, \qquad \textbf{(5)}$$

where the elements a_{ij} are unconstrained parameters. This system involves 32 unknown parameters to estimate and 17 restrictions, that is 16 exclusion restrictions and the cross-equation restriction $a_{63} = -a_{64}$. Importantly, the monetary policy shock is uniquely identified. This is because the fourth equation is distinct from all the other equations of system (5), and as such it cannot be the result of any permutation of the rows of A_i.

System (5) is useful to compute the responses of macroeconomic aggregates and the term structure factors, following a monetary policy shock. To complete the analysis, we construct the responses of yields for different maturities by using the responses of term structure factors and the three-factor Nelson–Siegel yield curve:

$$y_t(\tau) = f_{1,t}\alpha_{\tau,1} + f_{2,t}\alpha_{\tau,2} + f_{3,t}\alpha_{\tau,3}, \tag{6}$$

where $y_t(\tau)$ is the yield on a zero-coupon government bond with a maturity of τ periods. Following Diebold and Li (2006), the factor loadings are defined as $\alpha_{\tau,1} = 1$, $\alpha_{\tau,2} = (\frac{1-e^{-\lambda\tau}}{\lambda\tau})$, and $\alpha_{\tau,3} = (\frac{1-e^{-\lambda\tau}}{\lambda\tau} - e^{-\lambda\tau})$, where λ governs the exponential decay rate and is set to 0.0609.[4] In this context, the factor $f_{1,t}$ captures the level of the yield curve: An increase in $f_{1,t}$ raises equally the yields of all maturities. The factor $f_{2,t}$ corresponds to the negative of the slope of yield curve: An increase in $f_{2,t}$ raises short yields more than long ones. The factor $f_{3,t}$ is related to the curvature of the yield curve: An increase in $f_{3,t}$ has little effects on very short and very long yields, but raises medium-term yields.

At this point, it is important to notice that system (5) is flexible in the sense that it allows for a rich specification of the monetary authority's feedback rule. This can be seen by rewriting the fourth equation of the system as

$$v_{ff,t} = (\rho_{41}v_{ip,t} + \rho_{42}v_{p,t} + \rho_{43}v_{cp,t} + \rho_{44}v_{nbr,t} + \rho_{45}v_{tr,t}) + \omega_s\varepsilon_{s,t}, \tag{7}$$

where $\rho_{4j} = -[a_{4j}\sigma_s/(\beta\phi_b - \alpha\phi_d)]$ (for $j = 1, 2, 3$), $\rho_{44} = -[(1+\phi_b)/(\beta\phi_b - \alpha\phi_d)]$, $\rho_{45} = [(\phi_b + \phi_d)/(\beta\phi_b - \alpha\phi_d)]$, and $\omega_s = [\sigma_s/(\beta\phi_b - \alpha\phi_d)]$. The rule (7) implies that changes of the Fed funds rate can be decomposed into a systematic response of the Fed and a structural innovation in monetary policy. In particular, the systematic response (the expression in brackets) implies that the Fed may design its policy by taking into account the current values of several variables, namely, output, the price level, commodity prices, nonborrowed reserves, and total reserves. The term $\omega_s\varepsilon_{s,t}$ is the scaled monetary policy shock.

Finally, it is worth stressing that (5) relaxes some restrictions commonly imposed to identify monetary policy shocks and their effects. These restrictions can take various forms, such as short-run exclusions [Evans and Marshall (1998)], long-run restrictions [Evans and Marshall (1998)], sign restrictions [Roush (2007)], or nonlinear restrictions reflecting no arbitrage conditions [Smith and Taylor (2010), Ang et al. (2011), Ang and Piazzesi (2003)]. In all cases, these restrictions are not dictated by the data, but rather reflect the econometrician's judgement, among others, about the specification of the monetary authority's feedback rule. To illustrate this, consider the recursive system specified in Evans and Marshall (1998):

$$\begin{pmatrix} \tilde{a}_{11} & 0 & 0 & 0 & 0 & 0 & 0 \\ \tilde{a}_{21} & \tilde{a}_{22} & 0 & 0 & 0 & 0 & 0 \\ \tilde{a}_{31} & \tilde{a}_{32} & \tilde{a}_{33} & 0 & 0 & 0 & 0 \\ \tilde{a}_{41} & \tilde{a}_{42} & \tilde{a}_{43} & \tilde{a}_{44} & 0 & 0 & 0 \\ \tilde{a}_{51} & \tilde{a}_{52} & \tilde{a}_{53} & \tilde{a}_{54} & \tilde{a}_{55} & 0 & 0 \\ \tilde{a}_{61} & \tilde{a}_{62} & \tilde{a}_{63} & \tilde{a}_{64} & \tilde{a}_{65} & \tilde{a}_{66} & 0 \\ \tilde{a}_{i,71} & \tilde{a}_{i,72} & \tilde{a}_{i,73} & \tilde{a}_{i,74} & \tilde{a}_{i,75} & \tilde{a}_{i,76} & \tilde{a}_{i,77} \end{pmatrix} \begin{pmatrix} \nu_{ip,t} \\ \nu_{p,t} \\ \nu_{cp,t} \\ \nu_{ff,t} \\ \nu_{nbr,t} \\ \nu_{tr,t} \\ \nu_{f_i,t} \end{pmatrix} = \begin{pmatrix} \tilde{\varepsilon}_{1,t} \\ \tilde{\varepsilon}_{2,t} \\ \tilde{\varepsilon}_{3,t} \\ \tilde{\varepsilon}_{s,t} \\ \tilde{\varepsilon}_{5,t} \\ \tilde{\varepsilon}_{6,t} \\ \tilde{\varepsilon}_{f_i,t} \end{pmatrix}. \quad \textbf{(8)}$$

The recursive system (8) involves 28 unknown parameters to estimate and places 21 short-run exclusion restrictions to achieve identification, under the usual assumption stipulating that the structural innovations are conditionally homoskedastic. Some of these restrictions imply that the monetary authority's feedback rule is such that, in making its policy, the Fed completely ignores current values of nonborrowed reserves and total reserves ($\tilde{a}_{45} = \tilde{a}_{46} = 0$). In practice, such a behavior is unlikely, given that it would require that the Fed always fully offset shocks to demand for total reserves and to supply of borrowed reserves ($\phi_d = 1$ and $\phi_b = -1$). In this context, the monetary authority's feedback rule is possibly misspecified, so that the resulting nonsystematic component may mismeasure monetary policy shocks.

2.2. Identification

Our strategy to identify system (5) and, in particular, monetary policy shocks and their effects, exploits the conditional heteroskedasticity of the structural innovations. To understand how time-varying conditional volatility helps with identification, first note that the unconditional scedastic structures of the statistical and structural innovations, associated with the system involving the ith term structure factor, are related through

$$\Sigma_i = A_i^{-1} A_i^{-1\prime}, \quad \textbf{(9)}$$

where $\Sigma_i = E(\nu_{i,t}\nu_{i,t}')$ denotes the unconditional nondiagonal covariance matrix of the nonorthogonal statistical innovations, and $I = E(\varepsilon_{i,t}\varepsilon_{i,t}')$ normalizes (without loss of generality) the unconditional diagonal covariance matrix of the orthogonal structural innovations. In the context of an n-variable system, the distinct elements of Σ_i allows us to identify $\frac{n(n+1)}{2}$ of the n^2 elements of A_i, leaving $\frac{n(n-1)}{2}$ elements to be identified. Note also that the conditional scedastic structures are given by

$$\Sigma_{i,t} = A_i^{-1} \Gamma_{i,t} A_i^{-1\prime}, \quad \textbf{(10)}$$

where $\Sigma_{i,t} = E_{t-1}(\nu_{i,t}\nu_{i,t}')$ is the conditional nondiagonal covariance matrix of the statistical innovations, and $\Gamma_{i,t} = E_{t-1}(\varepsilon_{i,t}\varepsilon_{i,t}')$ corresponds to the conditional diagonal covariance matrix of the structural innovations. Importantly, the presence of conditional heteroskedasticity ($\Gamma_{i,t} \neq I$) implies that the scedastic structures

(9) and (10) are distinct, such that the relation (10) provides additional equations allowing to potentially identify the extra $\frac{n(n-1)}{2}$ elements of A_i. In particular, Milunovich and Yang (2013) demonstrate that using the scedastic structures (9) and (10) where $\Gamma_{i,t}$ is specified by univariate GARCH processes for, at least, $(n-1)$ structural innovations permits to statistically identify all n^2 elements of A_i, without having to impose any restrictions, as well as all GARCH coefficients.[5] Recall, however, that when A_i is left completely unrestricted then the structural innovations cannot be interpreted economically (see Section 2.1).

In contrast, under the usual assumption that the structural innovations are conditionally homoskedastic ($\Gamma_{i,t} = I$), equations (9) and (10) coincide. In this case, $\frac{n(n-1)}{2}$ restrictions need to be imposed on the elements of A_i in order to achieve identification. This is why the recursive system (8), for example, places a total of 21 restrictions, given that for this specification the assumption of conditional homoskedasticity is systematically invoked. As stated above, these restrictions are not dictated by the data, but rather reflect the econometrician's judgement.

2.3. Estimation

For expositional purposes, the specification relying on the three SVARs, associated with the different term structure factors, was useful to compare our approach to that found in the empirical literature. In our empirical analysis, however, it will prove convenient to stack the three separate flexible systems described by (5) into the following single SVAR:

$$AZ_t = \sum_{j=1}^{\kappa} B_j Z_{t-j} + \varepsilon_t, \tag{11}$$

where $Z_t = \left(ip_t \;\; p_t \;\; cp_t \;\; nbr_t \;\; tr_t \;\; ff_t \;\; f_{1,t} \;\; f_{2,t} \;\; f_{3,t}\right)'$ includes all the macroeconomic aggregates as well as the three-term structure factors, while $\varepsilon_t = \left(\varepsilon_{1,t} \;\; \varepsilon_{2,t} \;\; \varepsilon_{3,t} \;\; \varepsilon_{s,t} \;\; \varepsilon_{d,t} \;\; \varepsilon_{b,t} \;\; \varepsilon_{f_1,t} \;\; \varepsilon_{f_2,t} \;\; \varepsilon_{f_3,t}\right)'$ incorporates all the structural innovations.[6]

Furthermore, the dynamics of the conditional variances of the structural innovations is specified as

$$\Gamma_t = (I - \Theta_1 - \Theta_2) + \Theta_1 \odot \varepsilon_{t-1}\varepsilon_{t-1}' + \Theta_2 \odot \Gamma_{t-1}, \tag{12}$$

where $\Gamma_t = E_{t-1}(\varepsilon_t \varepsilon_t')$, $\odot$ denotes element-by-element multiplications, and Θ_1 and Θ_2 are diagonal matrices. Equation (12) involves intercepts that are consistent with the normalization $I = E(\varepsilon_t \varepsilon_t')$. It also implies a univariate GARCH(1,1) process for some (all) structural innovations if Θ_1 and Θ_2 are positive semidefinite (positive definite) and $(I - \Theta_1 - \Theta_2)$ is positive definite.

To estimate the parameters in (11) and (12), we perform a two-step procedure. The first step consists of estimating, by ordinary least square (OLS), the reduced form associated with (11). This reduced form corresponds to a restricted κ-order vector autoregression (VAR), in which the coefficients relating the macroeconomic aggregates to lagged values of the term structure factors are fixed to zero. From the regressions, we extract the estimates of the statistical innovations ν_t for $t = (\kappa + 1), \ldots, T$.

The second step consists of estimating, by maximum likelihood (ML), the (nonzero) elements of the matrices A, Θ_1, and Θ_2. To do so, we assume that the statistical innovations are conditionally normally distributed, and we construct the likelihood function from the estimated statistical innovations ν_t (obtained in the first step) and the estimated conditional covariance matrix Σ_t. This matrix is computed recursively for $t = (\kappa + 1), \ldots, T$, by evaluating the relation $\Sigma_t = A^{-1}\Gamma_t A^{-1\prime}$ and equation (12) for given values of A, Θ_1, and Θ_2 and the initial conditions $\Gamma_\kappa = \varepsilon_\kappa \varepsilon_\kappa' = I$.[7]

Admittedly, the procedure just described involves the estimation of a large number of parameters given the sample sizes. As will be explained below, the samples that we consider include between 293 and 310 observations per variable, which lead to a total of between 2,637 and 2,790 observations over the nine variables involved in the SVAR (11). Also, the numbers of parameters are $63 \times \kappa$ in the first step of the estimation procedure and 64 in the second step, for a total of 442 parameters when $\kappa = 6$ (as will be used below). Fortunately, this large number of parameters does not empirically cause any instabilities in the estimates since our procedure relies on linear regressions to estimate most of the parameters (i.e., all those involved in the first step), whereas it uses nonlinear methods only for a much smaller subset of parameters (i.e., those involved in the second step). Nevertheless, we deal with the issues related to small sample inference by resorting to bootstrap techniques in order to compute the standard errors of the estimated parameters and the confidence bands associated with the dynamic responses of key variables following a monetary policy shock.[8]

2.4. Sample Selection

Ideally, the SVARs would be estimated over two distinct subsamples: The first subsample would include the period before the latest financial crisis, whereas the second subsample would capture the subperiod of the financial crisis during which the Fed performed exclusively a conventional monetary policy. Although in principle this sample selection would allow one to assess whether the effects of the conventional monetary policy have changed following the financial crisis, it is not applicable in practice given that the second subsample would contain too few observations to estimate the SVARs.

To circumvent this difficulty, we select the following samples. The first sample covers the period between November 1982 and March 2007, so that it excludes the latest financial crisis. The second sample covers the period between November 1982 and August 2008, and as such it includes the portion of the financial crisis where the conventional monetary policy was important, relative to the unconventional ones. As is common practice, the starting date of both samples is chosen in order to avoid the atypical Fed's operating procedures pursued under the Volcker's episode between October 1979 and October 1982, where little effort, if any, went into stabilizing either the Fed funds rate or the borrowed reserves [see Strongin (1995)].

The ending date of the first sample is selected in order to exclude the financial crisis. Specifically, Calomiris (2009) and Claessens et al. (2010) argue that the beginning of the financial crisis occurred in the spring of 2007, as the subprime delinquency rates increased substantially. Moreover, Mankiw and Ball (2010) point out that the first significant event of the financial crisis arised in April 2007, when New Century Financial, a leading subprime lender in the United States, went bankrupt. This event also corresponds to one of the earliest significant developments in the time lines of the financial crisis outlined by the Federal Reserve Bank of St. Louis and the British Broadcasting Corporation (BBC).[9]

Also, the ending date of the second sample is determined so as to include the part of the financial crisis where the Fed had the ability to implement the conventional monetary policy, but to exclude the portion of the crisis where unconventional monetary policies became dominant. First, note that the Fed actively conducted a conventional monetary policy between April 2007 and August 2008, as it reduced seven times in a row the target Fed funds rate from 5.25 % to 2 %. After this period, however, the possibilities to operate a conventional monetary policy became much more limited, given that the target Fed funds rate declined rapidly toward the zero lower bound to reach the range of 0 to 0.25 % in December 2008. Second, unconventional monetary policies became important after August 2008, as the Fed started to implement most unconventional programs after this date.[10] One important exception is the Term Auction Facility (TAF) program, that took place in December 2007.[11] Fortunately, we can control for the effect of TAF on the reserve variables in order to assess the effects of conventional monetary policy shocks. To see this, note that (i) the Board of Governors collects direct measures for total reserves, TR_t, and borrowed reserves, BR_t, (ii) the measure of borrowed reserves, BR_t, is the sum of borrowings from total credit extended through the Fed's regular discount window program associated with the conventional monetary policy, $BR_{c,t}$, and borrowings from other Federal Reserve liquidity facilities associated with unconventional programs, $BR_{u,t}$, (iii) the measures for $BR_{c,t}$ and $BR_{u,t}$ are not individually available, although the measure for term auction credits, TAF_t is released by the Board of Governors, and (iv) the measure of nonborrowed reserves is computed residually as $NBR_t = TR_t - BR_t$. Note also that, to be consistent with the FOMC's objective for the Fed funds rate, total reserves were maintained around their level prior to December 2007, so that the increase in borrowed reserves (induced mainly by the creation of TAF) was offset through a nearly equal decrease in nonborrowed reserves (by a reduction in the Fed's holdings of securities and other assets). In this context, the corrected measures of reserve variables associated with the conventional monetary policy are constructed as follows: $tr_t = TR_t$, $br_t = BR_{c,t} \approx BR_t - TAF_t$, and $nbr_t = tr_t - br_t$.

For each of the two samples defined above, we estimate the flexible SVAR and compare the responses following monetary policy shocks to document whether the effects have changed following the financial crisis. Note that this represents a conservative analysis since any significant difference is a strong indication of a structural break in the effectiveness of the monetary policy during the financial crisis, given the limited number of additional observations included in the sample covering both the precrisis and crisis periods.[12]

For the two samples, the variables of interest are measured from monthly US data. In particular, ip_t is measured by the industrial production index, p_t is the (all-item, all-urban-consumer) price index, cp_t is the world-export commodity-price index, nbr_t is the nonborrowed reserves adjusted for term auction credits, tr_t is the total reserves, and ff_t is the Fed funds rate.[13] Also, $y_t(\tau)$ is measured by the Fama–Bliss discount bond yields for $\tau = 1, 3, 12, 24, 36, 48$, and 60 months, whereas the term structure factors $f_{1,t}$, $f_{2,t}$, and $f_{3,t}$ are estimated by applying OLS on the Nelson–Siegel yield curve (6) for each month. Following the literature, we use seasonally adjusted data expressed in logarithms, except the Fed funds rate and the yields which are in levels.[14]

3. EMPIRICAL RESULTS

This section first reports some test results to assess the appropriateness of our flexible system and the estimation of the GARCH(1,1) and reserve-market parameters. Then, we present the dynamic responses of key macroeconomic aggregates, term structure factors, and yields for different maturities to compare the effects of monetary policy shocks before and during the financial crisis. We finally perform variance and response decomposition analyses to document which are the fundamental elements underlying the change in the effects of monetary policy shocks on selected variables following the financial crisis, and we check the robustness of the results by using alternative measures of reserves, other sample periods, and different specifications.

3.1. Preliminary Diagnostics and Parameter Estimates

We start by discussing the selection of the lag structure of the reduced form.[15] We use the Akaike information criterion (AIC) to choose the appropriate number of lags (up to 12 lags). This criterion indicates that $\kappa = 6$ over both samples, excluding and including the financial crisis. We use this lag structure for the rest of the paper.

We then report several test results. We ran unit root tests, which indicate that the levels of variables included in the SVAR are first-order integrated, with possible exceptions being total reserves (tr_t), the level factor ($f_{1,t}$), and the curvature factor ($f_{3,t}$) that could be stationary. We do not report these test results since when a SVAR process includes the levels of variables (as in our case), the parameter estimates are consistent whether the levels of variables are stationary or first-order

TABLE 1. p-values for Ljung–Box test of autocorrelation structure

Number of lags	$\varepsilon_{1,t}$	$\varepsilon_{2,t}$	$\varepsilon_{3,t}$	$\varepsilon_{s,t}$	$\varepsilon_{d,t}$	$\varepsilon_{b,t}$	$\varepsilon_{f_1,t}$	$\varepsilon_{f_2,t}$	$\varepsilon_{f_3,t}$
(a) Sample: 1982:11–2007:03									
1	0.736	0.970	0.730	0.713	0.336	0.679	0.950	0.156	0.906
3	0.756	0.701	0.952	0.930	0.230	0.504	0.655	0.532	0.973
6	0.761	0.884	0.991	0.835	0.318	0.785	0.919	0.666	1.000
9	0.361	0.882	1.000	0.896	0.368	0.726	0.965	0.740	0.988
12	0.478	0.303	0.979	0.962	0.376	0.761	0.570	0.890	0.497
(b) Sample: 1982:11–2008:08									
1	0.576	0.842	0.863	0.782	0.277	0.964	0.934	0.070	0.830
3	0.903	0.918	0.975	0.873	0.150	0.503	0.797	0.336	0.987
6	0.951	0.807	0.992	0.869	0.186	0.656	0.978	0.566	1.000
9	0.444	0.699	0.999	0.891	0.264	0.609	0.969	0.695	0.994
12	0.361	0.116	0.947	0.843	0.295	0.368	0.596	0.869	0.277

Note: This table presents the p-values for Ljung–Box test for the autocorrelation structure of residuals standardized by their conditional volatility. The null hypothesis is the lack of autocorrelation in the standardized residuals.

integrated [Sims et al. (1990)]. Table 1 shows the Ljung–Box test results to confirm that the lag structure $\kappa = 6$ is relevant. This test checks whether there is any serial correlation in the structural innovations, standardized by their conditional standard deviations, over horizons of 1, 3, 6, 9, and 12 lags. Empirically, we find that the null hypothesis of no serial correlation can never be refuted.[16]

Table 2 reports the McLeod–Li test results to determine whether the GARCH(1,1) processes represent adequate specifications for the conditional variances of the structural innovations. This test verifies whether there is any autocorrelation in the ratio of the squared structural innovations relative to their conditional variances over horizons of 1, 3, 6, 9, and 12 lags. For both samples, the null hypothesis of no autocorrelation cannot be rejected for almost all horizons.

Table 3 displays the likelihood ratio test results to assess whether the identifying restrictions involved in the flexible SVAR are relevant. This test confronts an unrestricted system relaxing all the restrictions in A_{gr}, A_{gi}, A_{rr}, and A_{ri} to the flexible system (5).[17,18] For both samples, the identifying restrictions seem to be supported by the data.

We next present empirical evidence for identification conditions. Table 4 shows that, for both samples, all the structural innovations have significant ARCH and/or GARCH coefficients. This confirms that, from a statistical perspective, system (5) is locally identified, that is, A_i is unique apart from changes in the signs and permutations of its rows. Also, note that the structural innovations related to the reserve market (i.e., $\varepsilon_{s,t}$, $\varepsilon_{d,t}$, and $\varepsilon_{b,t}$) display highly persistent conditional variances, while the structural innovations related to the term structure factors

TABLE 2. p-values for McLeod–Li test of variance structure

Number of lags	$\varepsilon_{1,t}$	$\varepsilon_{2,t}$	$\varepsilon_{3,t}$	$\varepsilon_{s,t}$	$\varepsilon_{d,t}$	$\varepsilon_{b,t}$	$\varepsilon_{f_1,t}$	$\varepsilon_{f_2,t}$	$\varepsilon_{f_3,t}$
(a) Sample: 1982:11–2007:03									
1	0.855	0.791	0.536	0.758	0.990	0.373	0.753	0.821	0.527
3	0.917	0.522	0.760	0.042	1.000	0.792	0.819	0.978	0.795
6	0.730	0.751	0.850	0.058	0.994	0.931	0.562	0.956	0.856
9	0.816	0.851	0.755	0.144	0.997	0.970	0.671	0.982	0.950
12	0.894	0.867	0.901	0.102	0.998	0.976	0.557	0.747	0.966
(b) Sample: 1982:11–2008:08									
1	0.945	0.748	0.417	0.212	0.904	0.540	0.850	0.777	0.734
3	0.785	0.399	0.521	0.005	0.975	0.780	0.886	0.970	0.950
6	0.708	0.477	0.813	0.029	0.996	0.954	0.288	0.964	0.962
9	0.650	0.595	0.731	0.066	0.999	0.944	0.389	0.993	0.995
12	0.817	0.327	0.906	0.098	0.998	0.977	0.258	0.809	0.996

Note: This table presents the p-values for McLeod–Li test for the autocorrelation structure of squared residuals standardized by their conditional volatility. The null hypothesis is the lack of autocorrelation in the squared standardized residuals.

TABLE 3. Likelihood ratio tests

(a) Sample: 1982:11–2007:03	
Unrestricted vs. recursive	Unrestricted vs. flexible
0.003	0.409
(b) Sample: 1982:11–2008:08	
Unrestricted vs. recursive	Unrestricted vs. flexible
0.003	0.325

Note: This table presents bootstrapped p-values for the likelihood ratio tests for the restrictions associated with the recursive and flexible systems against the unrestricted one.

(i.e., $\varepsilon_{f_i,t}$ for $i = 1, 2, 3$) have fairly persistent conditional variances as measured by the sum of the ARCH and GARCH coefficients.

Table 5 reports the Wald test results to verify whether each nonzero parameter in the fourth row of A_i is identical to the corresponding parameters in all other rows. For both samples, we reject these hypotheses for all considered parameters. This implies that the monetary policy shock is uniquely (or globally) identified, given that the fourth equation of system (5) is statistically distinct from all other equations.

We finally present the estimates of the reserve-market parameters in Table 6. For both samples, the estimates of the slopes of demand for total reserves, α, and

TABLE 4. Parameter estimates of the conditional variance specification for the structural innovations

	Sample: 1982:11–2007:03		Sample: 1982:11–2008:08	
	ARCH	GARCH	ARCH	GARCH
ε_1	0.126	0.688	0.199	0.095
	(0.032)	(0.123)	(0.041)	(0.134)
ε_2	0.172	0.759	0.159	0.716
	(0.044)	(0.108)	(0.038)	(0.081)
ε_3	0.199	0.359	0.184	0.383
	(0.040)	(0.136)	(0.038)	(0.132)
ε_s	0.201	0.799	0.591	0.395
	(0.019)	(0.019)	(0.048)	(0.053)
ε_d	0.421	0.498	0.474	0.459
	(0.038)	(0.096)	(0.043)	(0.079)
ε_b	0.028	0.954	0.053	0.926
	(0.015)	(0.062)	(0.019)	(0.044)
ε_{f_1}	0.193	0.516	0.185	0.501
	(0.026)	(0.120)	(0.023)	(0.096)
ε_{f_2}	0.116	0.674	0.109	0.724
	(0.030)	(0.116)	(0.029)	(0.103)
ε_{f_3}	0.117	0.786	0.140	0.727
	(0.029)	(0.119)	(0.029)	(0.100)

Note: This table presents the estimates of ARCH and GARCH coefficients of the conditional variance specification for the structural innovations in equation (12). ε_1, ε_2, and ε_3 are the structural innovations associated with goods market variables. ε_s, ε_d, and ε_b are the structural innovations associated with the reserve market variables. ε_{f_1}, ε_{f_2}, and ε_{f_3} are the structural innovations associated with the three-term structure factors. The bootstrapped standard errors are presented in the parentheses.

of supply of borrowed reserves, β, display the predicted signs. Also, the estimates of ϕ_d (which are close to one) and ϕ_b (which are far from minus one) suggest that the Fed offsets almost entirely shocks to demand for total reserves, but does not respond substantially to shocks to supply of borrowed reserves. Note that this last result is against the assumption underlying the monetary authority's feedback rule associated with the recursive system (8).

3.2. Dynamic Responses

We now present the central part of our analysis, in which we compare the effects of monetary policy shocks before and during the financial crisis. For this purpose, we estimate the flexible system for each sample and construct the dynamic responses of selected variables following a positive, one unconditional standard deviation,

TABLE 5. Joint tests of global identification

	1982:11–2007:03	1982:11–2008:08
H_1: $a_{41} = a_{j1}$ for $j = 1, 2, 3, 5, 6$ & $a_{41} = a_{i,71}$ for $i = 1, 2, 3$	0.002	0.002
H_2: $a_{42} = a_{j2}$ for $j = 1, 2, 3, 5, 6$ & $a_{42} = a_{i,72}$ for $i = 1, 2, 3$	0.004	0.004
H_3: $a_{43} = a_{j3}$ for $j = 1, 2, 3, 5, 6$ & $a_{43} = a_{i,73}$ for $i = 1, 2, 3$	0.002	0.002
H_4: $\frac{1+\phi_b}{\sigma_s} = 0$, $\frac{1+\phi_b}{\sigma_s} = \frac{1}{\sigma_b}$, $\frac{1+\phi_b}{\sigma_s} = a_{i,74}$ for $i = 1, 2, 3$	0.008	0.026
H_5: $-\frac{\phi_d+\phi_b}{\sigma_s} = 0$, $-\frac{\phi_d+\phi_b}{\sigma_s} = \frac{1}{\sigma_d}$, $-\frac{\phi_d+\phi_b}{\sigma_s} = -\frac{1}{\sigma_b}$, $\frac{\phi_d+\phi_b}{\sigma_s} = a_{i,75}$ for $i = 1, 2, 3$	0.006	0.008
H_6: $\frac{\beta\phi_b-\alpha\phi_d}{\sigma_s} = 0$, $\frac{\beta\phi_b-\alpha\phi_d}{\sigma_s} = \frac{\alpha}{\sigma_d}$, $\frac{\beta\phi_b-\alpha\phi_d}{\sigma_s} = \frac{\beta}{\sigma_b}$, $\frac{\beta\phi_b-\alpha\phi_d}{\sigma_s} = a_{i,76}$ for $i = 1, 2, 3$	0.006	0.004

Note: This table presents bootstrapped p-values for Wald statistics for the hypotheses that a given parameter in the fourth row is identical to the corresponding parameters in all other rows in system (5). H_i for $i = 1, \ldots, 6$ is the hypothesis associated with the parameter restrictions on the ith element of the fourth row. A rejection of any of these hypotheses (H_1–H_6) is a sufficient condition for the global identification of the monetary policy shock based on system (5).

TABLE 6. Parameter estimates of the specification for the reserve market

	Sample: 1982:11–2007:03	Sample: 1982:11–2008:08
α	0.003	0.003
	(0.001)	(0.001)
β	0.415	1.046
	(0.406)	(0.355)
ϕ_d	0.927	0.998
	(0.015)	(0.027)
ϕ_b	0.009	−0.007
	(0.007)	(0.008)
σ_s	0.045	0.041
	(0.005)	(0.013)
σ_d	0.019	0.021
	(0.003)	(0.003)
σ_b	0.103	0.314
	(0.097)	(0.077)

Note: This table presents the parameter estimates of the specification for the reserve market in equation (4). α is the negative of the slope of the demand for total reserves, whereas β is the slope of the supply of borrowed reserves. ϕ_d and ϕ_b capture the Fed's responses to shocks to the total demand for reserves and to shocks to the supply of borrowed reserves, respectively. σ_d, σ_b, and σ_s are the parameters scaling the structural innovations. The bootstrapped standard errors are presented in the parentheses.

monetary policy shock. Figures 1 and 2 display, respectively, the responses obtained for the samples excluding and including the financial crisis.

Focusing on the precrisis sample, we find that the response of output is positive and hump shaped, reaching its peak around 15 months after the shock. The price

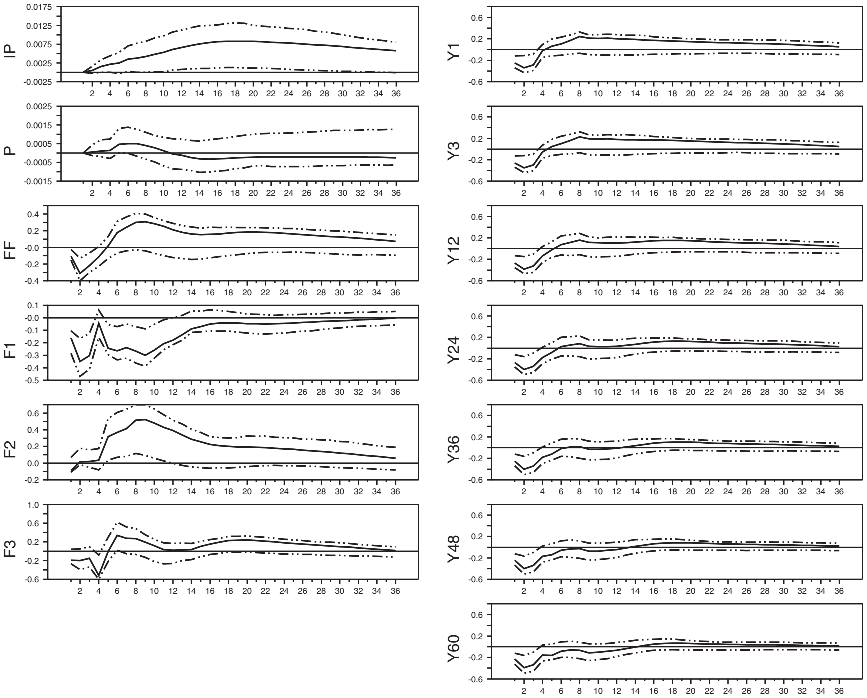

FIGURE 1. Dynamic responses for the flexible system: Sample excluding the financial crisis. The solid lines are the dynamic responses of selected variables following a positive monetary policy shock, where these responses are computed from the flexible system. The dashed lines correspond to the 68% bootstrapped confidence intervals. IP, P, and FF are output, the price level, and the Fed funds rate, respectively; F1, F2, and F3 are the level, slope, and curvature of the yield curve; and $Y\tau$ is the yield on zero coupon Treasury bonds with τ months to maturity. The sample is from November 1982 to March 2007.

level exhibits a fairly muted overall response, which is positive in the first months but eventually becomes negative. In this regard, there is no price puzzle, where the latter refers to the anomalous decrease of the price level, following an unanticipated monetary easing, reported in several empirical studies [e.g., Sims (1992)]. The response of the Fed funds rate is negative during the first five months following an expansionary monetary policy shock. This result lends support to the so-called vanishing-liquidity-effect hypothesis, according to which the fall in the interest rate following an unexpected monetary expansion has become smaller and less persistent in the post-1982 period [e.g., Christiano (1995), Pagan and Robertson (1995)]. In sum, these responses of macroeconomic aggregates are consistent with well-accepted beliefs about the dynamic effects of the monetary policy.

Also, the responses of term structure factors, obtained for the precrisis sample, provide the following information. The level of the yield curve decreases persistently for almost 30 months, although the bulk of the decline occurs before the first

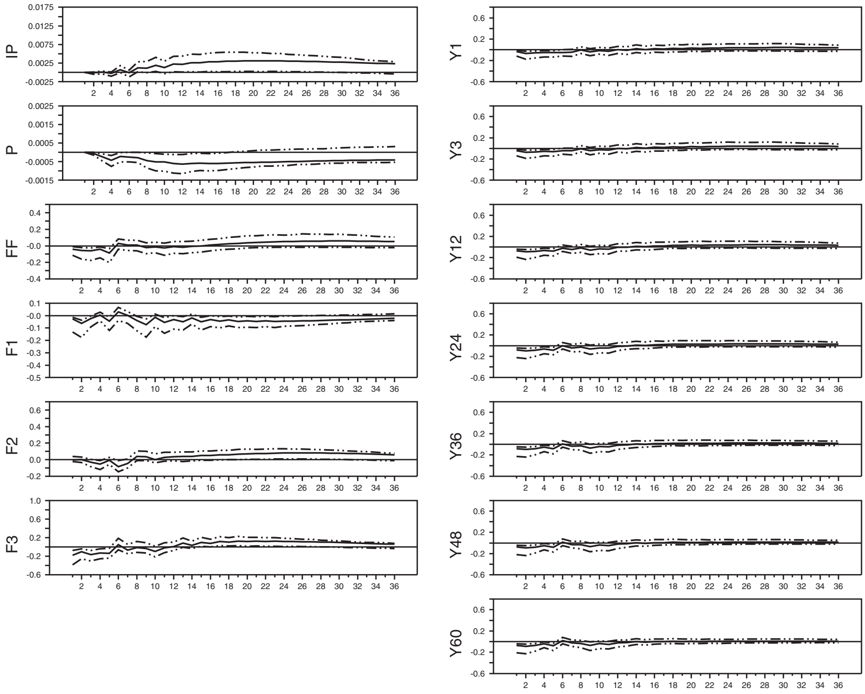

FIGURE 2. Dynamic responses for the flexible system: Sample including the financial crisis. The solid lines are the dynamic responses of selected variables following a positive monetary policy shock, where these responses are computed from the flexible system. The dashed lines correspond to the 68% bootstrapped confidence intervals. IP, P, and FF are output, the price level, and the Fed funds rate, respectively; F1, F2, and F3 are the level, slope, and curvature of the yield curve; and Yτ is the yield on zero coupon Treasury bonds with τ months to maturity. The sample is from November 1982 to August 2008.

four months. The response of the slope of the yield curve is negative and hump shaped, attaining a trough 8 months after the shock. The response of the curvature of the yield curve is relatively muted: It is negative for the first five months and positive afterward, although it is insignificant for almost all horizons. Finally, the yields for all maturities decrease following the unanticipated monetary easing, although they return fairly rapidly to their preshock levels. Note that the impact responses of yields are similar across maturities. This effect is mainly attributable to the response of the level of the yield curve. However, the persistence of the responses of yields tend to be more pronounced as the maturity increases: It takes about four months for the yields at the short end of the term structure to return to their preshock levels, whereas it takes up to 13 months for the yields at the long end. This feature is primarily explained by the decrease of the slope of the yield curve following an unexpected monetary expansion. Overall, the responses of selected variables highlight that the expansionary monetary policy implemented by the Fed before the financial crisis led to persistent increases of output, as well as short-lived decreases of the Fed funds rate and yields for different maturities.

Turning to the sample that includes the financial crisis, we observe that the responses of output, the price level, and the Fed funds rate are small in magnitude over most horizons. Likewise, the responses of term structure factors and yields are always economically insubstantial. Importantly, the comparison of these results to those obtained for the precrisis sample suggests that the monetary policy during the financial crisis was not as effective in influencing the macroeconomic aggregates and the yield curve.

To gain more insights about when this change in the effectiveness of the monetary policy occurred, we compare several sets of dynamic responses obtained by reestimating the flexible system for different samples, which start in November 1982 and include one additional month to end at each period between March 2007 and August 2008. Empirically, the dynamic responses of key variables obtained for the samples ending before January 2008 always display similar shape and magnitude than to those already reported for the precrisis sample (ending in March 2007). Moreover, the responses computed for the samples ending in January 2008 and afterward resemble those obtained from our original sample including the financial crisis (ending in August 2008). Overall, the structural break in the responses of the variables of interest suggests that the monetary policy might have lost its effectiveness at the beginning of year 2008. For brevity, Figure 3 focuses on this structural break by depicting the responses computed for our original samples excluding and including the financial crisis, as well as for the samples ending in December 2007 and January 2008.

Finally, recall that the results presented so far are obtained from the flexible SVAR, which relaxes some restrictions commonly imposed to identify monetary policy shocks and their effects. In principle, it is possible that the imposition of such restrictions leads erroneously to different conclusions about the effectiveness of the monetary policy. To exemplify this point, Figures 4 and 5 exhibit the dynamic responses obtained by estimating the recursive system (8) on each sample. Note that these responses depict a similar shape, but a more pronounced persistence, compared to those obtained by Evans and Marshall (1998) from system (8) over the 1965:1 to 1995:12 period. However, for the precrisis sample, the results differ from those generated from the flexible system in three important dimensions. First, there is a price puzzle: The price level persistently declines. Second, the response of the level of the yield curve is initially muted and the response of the slope is positive. Third, the responses of the Fed funds rate and yields are long lived. Perhaps more importantly, for the sample including the financial crisis, the results obtained from the recursive and flexible systems are strikingly different, as the responses of all selected variables computed from (8) are economically substantial and statistically significant over most horizons. In fact, the recursive system implies that the responses of each variable display similar magnitudes and shapes across both samples, suggesting incorrectly that the monetary policy was as effective during the precrisis and crisis periods. For completeness, note

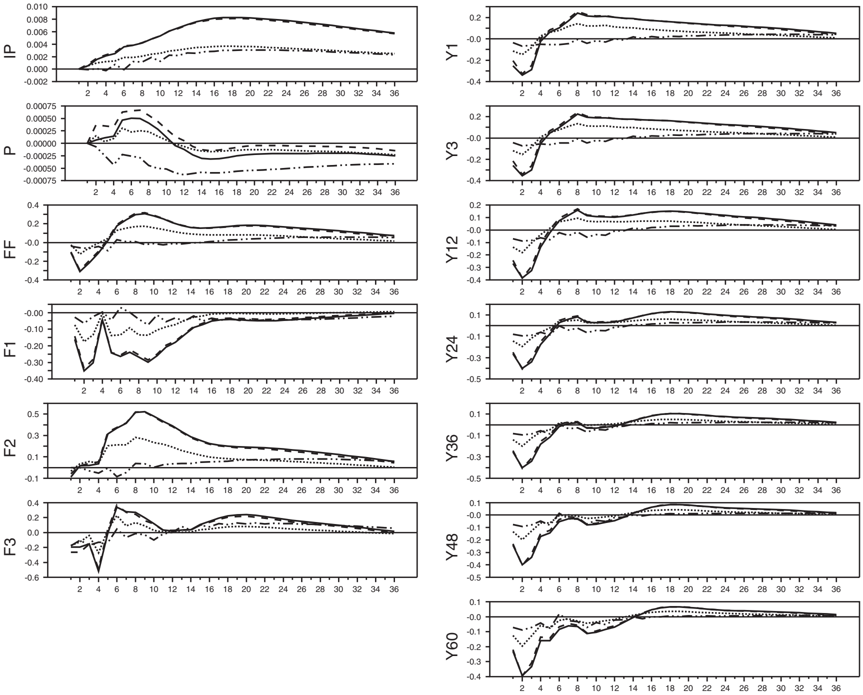

FIGURE 3. Dynamic responses for the flexible system: Expanding window. The solid, dashed, dotted, and dashed-dotted lines are the dynamic responses of selected variables following a positive monetary policy shock, where these responses are computed from the flexible system based on sample periods ending in March 2007, December 2007, January 2008, and August 2008, respectively. The staring period for all samples is November 1982. IP, P, and FF are output, the price level, and the Fed funds rate, respectively; F1, F2, and F3 are the level, slope, and curvature of the yield curve; and $Y\tau$ is the yield on zero coupon Treasury bonds with τ months to maturity.

that applying a likelihood ratio test indicates that the restrictions involved in (8) are strongly jointly rejected, which confirms that the identifying assumptions underlying the recursive system are not supported by the data (see Table 3).

3.3. Variance and Response Decompositions

At this point, it is instructive to perform two extensions using the flexible system: a variance decomposition and a response decomposition. First, we undertake a variance decomposition analysis to assess the contributions of monetary policy shocks to the forecast error variances of selected variables. Figures 6 and 7 display the contributions obtained for the samples excluding and including the financial crisis. For the precrisis period, we find that monetary policy shocks explain a sizeable part of the fluctuations of most variables. Specifically, for output and

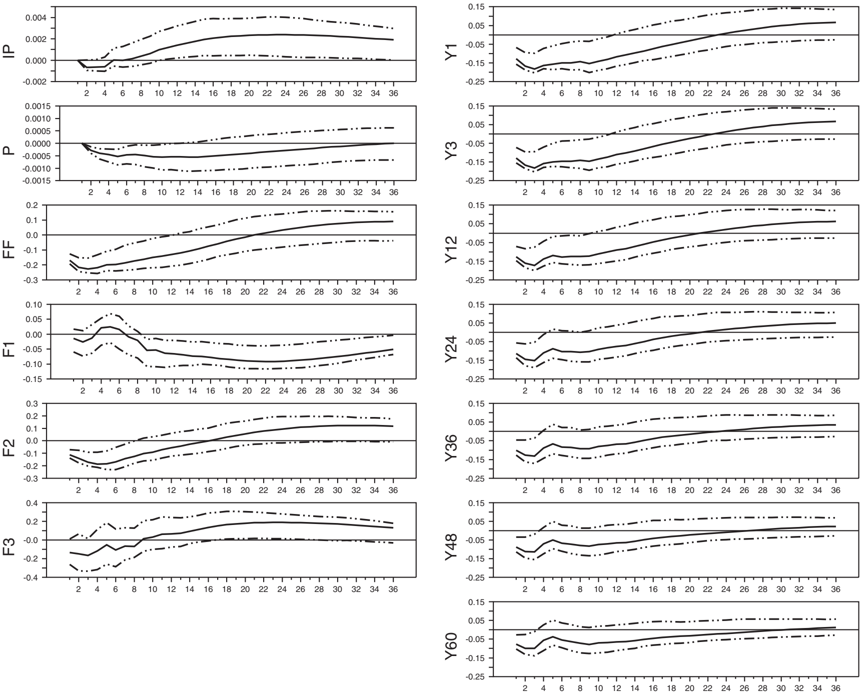

FIGURE 4. Dynamic responses for the recursive system: Sample excluding the financial crisis. The solid lines are the dynamic responses of selected variables following a positive monetary policy shock, where these responses are computed from the recursive system. The dashed lines correspond to the 68% bootstrapped confidence intervals. IP, P, and FF are output, the price level, and the Fed funds rate, respectively; F1, F2, and F3 are the level, slope, and curvature of the yield curve; and Yτ is the yield on zero coupon Treasury bonds with τ months to maturity. The sample is from November 1982 to March 2007.

the Fed funds rate, this portion is 0% and 20% at impact, whereas it increases to approximately 45% and 30% over longer horizons. For the price level, the monetary policy shocks explain only a negligible part of the fluctuations. For the level, slope, and curvature of the yield curve, the portion is roughly 15%, 5%, and 5% in the short run, while it raises to 50%, 40%, and 20% in the long run. For the yields of different maturities, the contributions of monetary policy shocks are nearly 20% in the short and long runs. In contrast, for the sample including the financial crisis, the contributions of monetary policy shocks are negligible for all variables. In sum, the variance decomposition analysis reveals the existence of a structural break in the effectiveness of the monetary policy, since the policy shocks no longer explain the variability of macroeconomic aggregates and yields during the financial crisis. This result accords with the conclusion reached from the dynamic responses presented above.

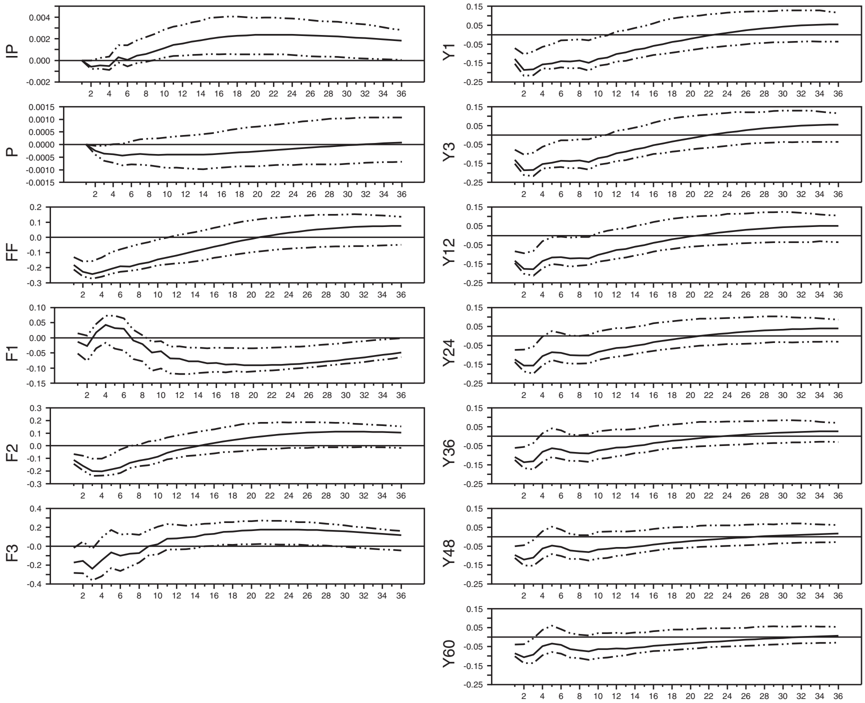

FIGURE 5. Dynamic responses for the recursive system: Sample including the financial crisis. The solid lines are the dynamic responses of selected variables following a positive monetary policy shock, where these responses are computed from the recursive system. The dashed lines correspond to the 68% bootstrapped confidence intervals. IP, P, and FF are output, the price level, and the Fed funds rate, respectively; F1, F2, and F3 are the level, slope, and curvature of the yield curve; and Yτ is the yield on zero coupon Treasury bonds with τ months to maturity. The sample is from November 1982 to August 2008.

In the second extension, we do a response decomposition analysis to document which are the fundamental elements underlying the change in the effects of monetary policy shocks on the yield curve following the financial crisis. To this end, we first follow Campbell and Ammer (1993) to express the unexpected change in the yield with maturity τ, $\tilde{y}_{t+1}(\tau) = [y_{t+1}(\tau) - E_t y_{t+1}(\tau)]$, as the sum of the revisions in investors' expectations of future inflation rate, $\tilde{y}_{\pi,t+1}(\tau) = \frac{1}{\tau}(E_{t+1} - E_t)\sum_{j=1}^{\tau}\pi_{t+1+j}$, real rate of return, $\tilde{y}_{r,t+1}(\tau) = \frac{1}{\tau}(E_{t+1} - E_t)\sum_{j=1}^{\tau} r_{t+1+j}$, and excess return (risk premium), $\tilde{y}_{x,t+1}(\tau) = \frac{1}{\tau}(E_{t+1} - E_t)\sum_{j=1}^{\tau} x_{t+1+j}(\tau + 1 - j)$. We then compute the impact response of each of these terms to a positive monetary policy shock (see the appendix).[19] Table 7 presents this decomposition for each sample.

For the precrisis period, the impact responses of yields for different maturities are negative, as shown in the preceding section. The decomposition of these

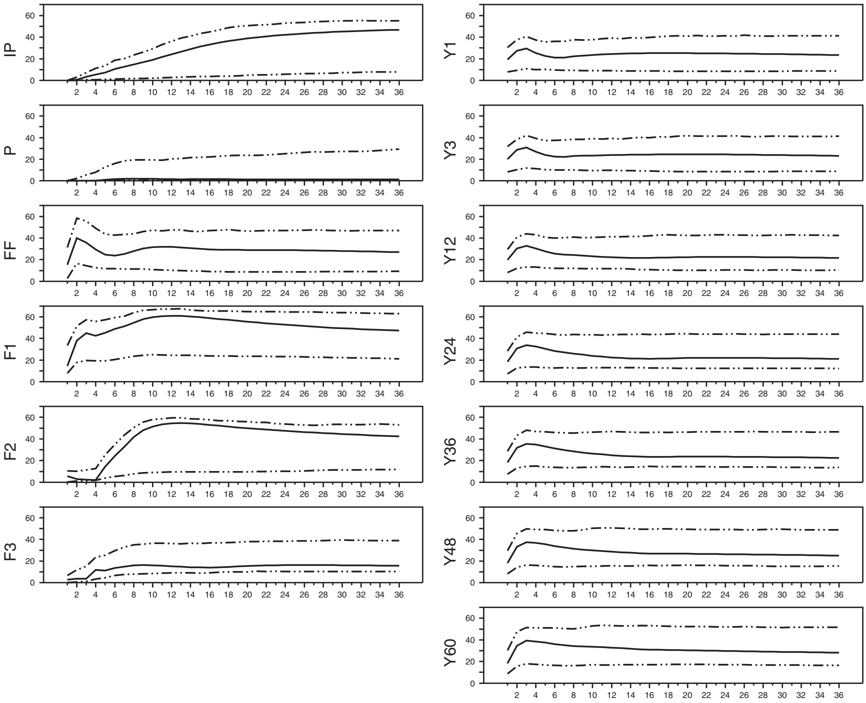

FIGURE 6. Variance decompositions for the flexible system: Sample excluding the financial crisis. The solid lines are the percentages of the fluctuations of selected variables attributable to monetary policy shocks, where these contributions are computed from the flexible system. The dashed lines correspond to the 68% bootstrapped confidence intervals. IP, P, and FF are output, the price level, and the Fed funds rate, respectively; F1, F2, and F3 are the level, slope, and curvature of the yield curve; and Yτ is the yield on zero coupon Treasury bonds with τ months to maturity. The sample is from November 1982 to March 2007.

responses reveals that they are mainly explained by downward revisions in expectations of future real rate of return for the short end of the yield curve, and by downward revisions in expectations of future excess return for the long end. However, the immediate declines of yields following an unanticipated monetary easing are never attributable to revisions in expectations about future inflation rate. For the sample including the financial crisis, the initial responses of yields are much smaller in magnitude. The decomposition analysis highlights that these muted responses reflect insubstantial revisions in expectations of future real rate of return, excess return, and inflation rate. Intuitively, these results suggest that, although before the financial crisis investors were taking into account the information about the conventional monetary policy in forming their expectations about future real rates and risk premia embedded in government yields, they have stopped paying attention to such policy actions after the crisis.

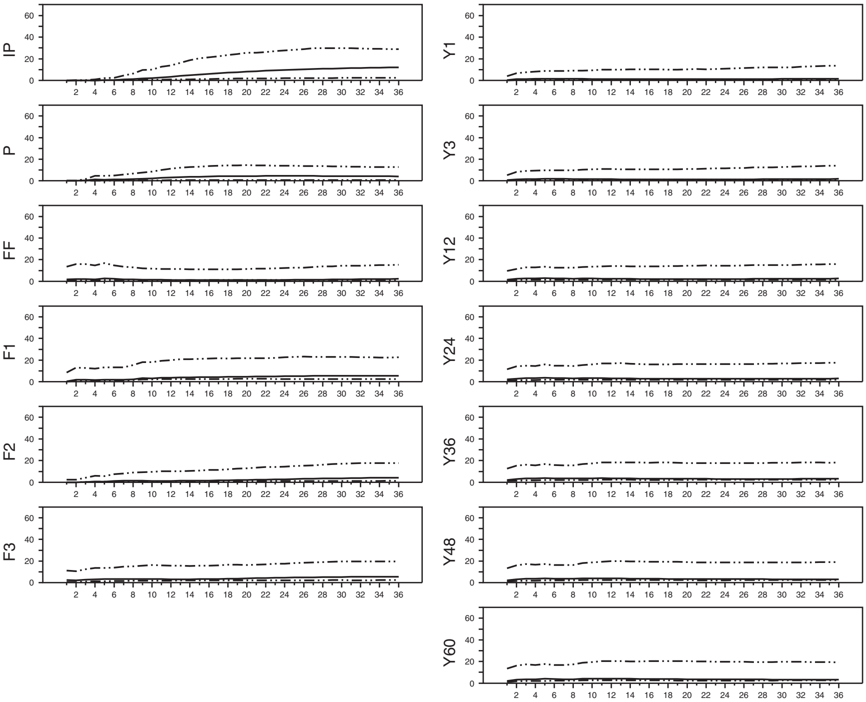

FIGURE 7. Variance decompositions for the flexible system: Sample including the financial crisis. The solid lines are the percentages of the fluctuations of selected variables attributable to monetary policy shocks, where these contributions are computed from the flexible system. The dashed lines correspond to the 68% bootstrapped confidence intervals. IP, P, and FF are output, the price level, and the Fed funds rate, respectively; F1, F2, and F3 are the level, slope, and curvature of the yield curve; and $Y\tau$ is the yield on zero coupon Treasury bonds with τ months to maturity. The sample is from November 1982 to August 2008.

3.4. Robustness Checks

So far, our analysis suggests that following the financial crisis there has been a substantial reduction in the effects of the monetary policy on selected variables, and, in particular, on yields. In this section, we check the robustness of the dynamic responses of yields in three important dimensions. First, we follow Carpenter and Demiralp (2008) by replacing total reserves, tr_t, in the formulation (4) by total balances at the Fed, that is, the sum of total reserves, tr_t, and contractual clearing balances, ccb_t.[20] The latter component is the balances contracted (between an institution and its respective Reserve Bank) in order to maintain a level of balances in excess of the amount necessary to satisfy the institution's reserve balance requirements.[21] The intuition behind this robustness check is that the Fed funds rate can be viewed as the one that clears the market for balances, rather than the market for reserves. Second, we consider February 1994, instead of November

TABLE 7. Campbell and Ammer decomposition of initial responses of yields

τ	$\frac{\partial \tilde{y}_{\pi,t}(\tau)}{\partial \varepsilon_{s,t}}$	$\frac{\partial \tilde{y}_{r,t}(\tau)}{\partial \varepsilon_{s,t}}$	$\frac{\partial \tilde{y}_{x,t}(\tau)}{\partial \varepsilon_{s,t}}$	$\frac{\partial \tilde{y}_{t}(\tau)}{\partial \varepsilon_{s,t}}$
(a) Sample: 1982:11–2007:03				
1	0.0001	−0.2528	0.0000	−0.2528
	(0.0002)	(0.0761)	(0.0000)	(0.0762)
3	0.0000	−0.2944	0.0366	−0.2578
	(0.0001)	(0.0948)	(0.0198)	(0.0765)
12	0.0000	0.0419	−0.3101	−0.2682
	(0.0000)	(0.0963)	(0.0407)	(0.0754)
24	0.0000	0.0997	−0.3643	−0.2646
	(0.0000)	(0.0676)	(0.0377)	(0.0694)
36	0.0000	0.0972	−0.3511	−0.2539
	(0.0000)	(0.0378)	(0.0407)	(0.0618)
48	0.0000	0.0746	−0.3167	−0.2421
	(0.0000)	(0.0197)	(0.0442)	(0.0547)
60	0.0000	0.0482	−0.2796	−0.2314
	(0.0000)	(0.0114)	(0.0429)	(0.0488)
(b) Sample: 1982:11–2008:08				
1	−0.0001	−0.0356	0.0000	−0.0357
	(0.0000)	(0.0172)	(0.0000)	(0.0172)
3	−0.0001	−0.0542	0.0096	−0.0447
	(0.0000)	(0.0221)	(0.0066)	(0.0188)
12	−0.0001	−0.0380	−0.0324	−0.0704
	(0.0000)	(0.0167)	(0.0151)	(0.0256)
24	0.0000	−0.0085	−0.0731	−0.0817
	(0.0000)	(0.0077)	(0.0257)	(0.0293)
36	0.0000	0.0076	−0.0890	−0.0814
	(0.0000)	(0.0046)	(0.0302)	(0.0292)
48	0.0000	0.0119	−0.0888	−0.0770
	(0.0000)	(0.0044)	(0.0302)	(0.0279)
60	0.0000	0.0090	−0.0806	−0.0716
	(0.0000)	(0.0032)	(0.0280)	(0.0263)

Note: This table presents the decomposition of the initial response of yields to an expansionary monetary policy shock into the initial responses of their components. The initial response of yields is presented in the right-most column and corresponds to the initial responses presented in Figures 1 and 2. The bootstrapped standard errors are presented in parentheses.

1982, as the starting date of both of our samples. Among others, Vilasuso (1999) argues that the effects of the monetary policy depend on the Fed's operating procedures. In the fall of 1982, the Fed adopted borrowed reserves operating procedures, whereas in February 1994, the Fed adopted the current practice of announcing its target for the Fed funds rate.[22] Third, we amend the specification to include contemporaneous interactions and dynamic feedbacks across the various term structure factors. Recall that in the analysis reported above, the small-scale SVAR associated with each factor implicitly assumed that the factors have no influence on each other.

Figures 8 and 9 depict the dynamic responses of yields associated with total balances (first column), the alternative starting date (second column) for each sample, and the specification in which the factors are mutually related (third column). Importantly, these responses display similar magnitudes and shape than those reported in Section 3.2. That is, for the precrisis period, the yields for all maturities decrease following an unanticipated monetary easing, although they return fairly rapidly to their preshock levels. Specifically, the impact responses of yields are similar across maturities, but the persistence of the responses tends to be more pronounced as the maturity increases. In contrast, for the sample including the financial crisis, the responses of yields for all maturities are always negligible.

4. CONCLUSION

In this paper, we have analyzed whether the Fed had the ability through its conventional monetary policy to affect key economic and financial variables, and, in particular, the term structure of interest rates, during the recent financial crisis. To do so, we have first identified conventional monetary policy shocks and their effects by exploiting the conditional heteroskedatasticity of the structural innovations of the variables in the system. This methodology relaxes some of the identifying assumptions commonly used in earlier studies, leading to a rich specification of the Fed's feedback rule. We have then estimated the effects of conventional monetary policy shocks on two samples: The first sample excludes the financial crisis, whereas the second sample includes earlier part of the financial crisis where the conventional monetary policy was important relative to the unconventional ones.

Our main conclusion is that the conventional monetary policy has lost most of its effectiveness shortly after the beginning of the financial turmoil. In particular, for the precrisis sample, we find that the response of output is positive and hump shaped, the price level gradually increases to reach a plateau, whereas the Fed funds rate and yields of government bonds for all selected maturities display sharp, but short lived, declines following a positive conventional monetary policy shock. In contrast, for the sample that includes the financial crisis, we observe that the responses of key macroeconomic aggregates and yields are always negligible. Furthermore, disentangling the impact responses of yields highlights that the dramatic change in these responses following the financial crisis can be explained by the substantial changes in the responses of revisions in investors' expectations of future real rate of return and excess return. These results are robust to using alternative measures of key variables, sample periods, and specifications.

Our analysis points to two implications for policy makers. First, our findings document that using recursive systems involving erroneous short-run restrictions

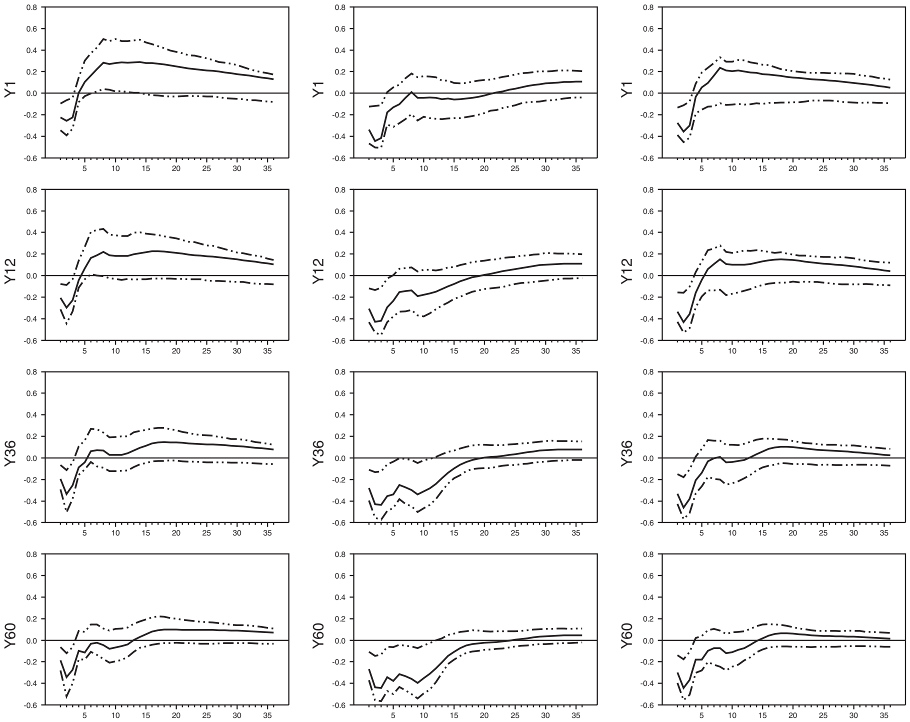

FIGURE 8. Dynamic responses for the flexible system: Robustness for the sample excluding the financial crisis. The solid lines are the dynamic responses of yields following a positive monetary policy shock, where these responses are computed from the flexible system. The dashed lines correspond to the 68% bootstrapped confidence intervals. Yτ is the yield on zero coupon Treasury bonds with τ months to maturity. In the first column, the sample is from November 1982 to March 2007 and the total reserves are replaced by total balances, i.e., the sum of total reserves (TR) and contractual clearing balances (CCB). In the second column, the sample is from February 1994 to March 2007 and the usual measure of total reserves is used. In third column, the sample is from November 1982 to March 2007 and the usual measure of total reserves is used, but we amend the specification to include contemporaneous interactions and dynamic feedbacks across the three-term structure factors.

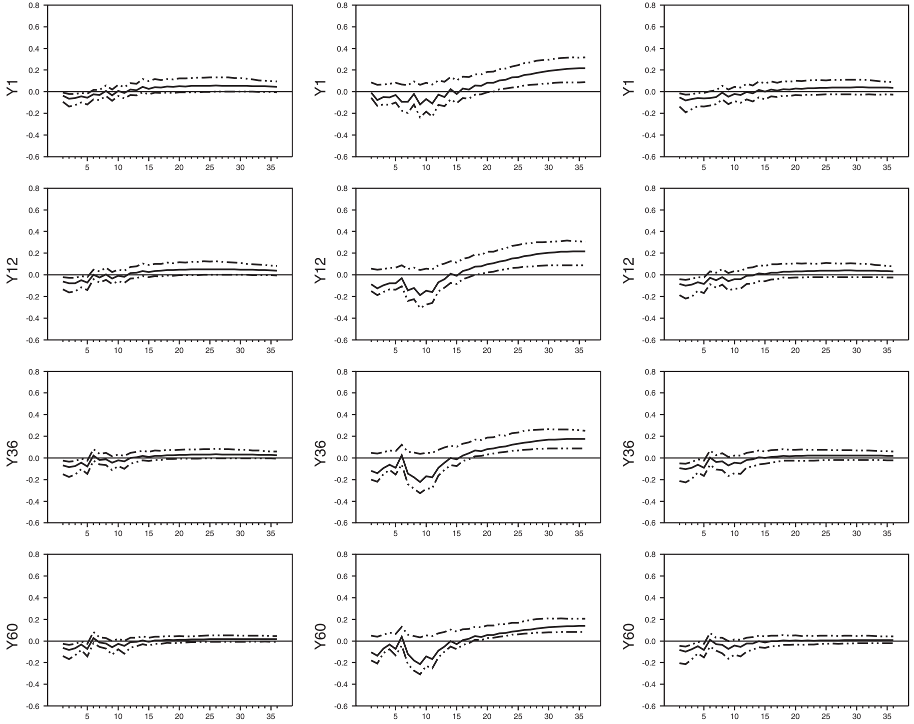

FIGURE 9. Dynamic responses for the flexible system: Robustness for the sample including the financial crisis. The solid lines are the dynamic responses of yields following a positive monetary policy shock, where these responses are computed from the flexible system. The dashed lines correspond to the 68% bootstrapped confidence intervals. $Y\tau$ is the yield on zero coupon Treasury bonds with τ months to maturity. In the first column, the sample is from November 1982 to August 2008 and the total reserves are replaced by total balances, i.e., the sum of total reserves (TR) and contractual clearing balances (CCB). In the second column, the sample is from February 1994 to August 2008 and the usual measure of total reserves is used. In third column, the sample is from November 1982 to August 2008 and the usual measure of total reserves is used, but we amend the specification to include contemporaneous interactions and dynamic feedbacks across the three-term structure factors.

substantially overestimates the duration for which the conventional monetary policy remained effective after the financial turmoil. This highlights the importance of, not only closely, but also accurately, monitoring the effects of the conventional monetary policy, given that as long as this policy is effective it should be prioritized over the unconventional policy since the latter is more expensive to operate. Second, our results suggest that the conduct of the conventional monetary policy has led investors to significantly revise their expectations about future real rates and risk premia before the financial crisis, but not during the crisis. This stresses the importance of the Fed's communications to affect investors' expectations in order to increase the effectiveness of the conventional monetary policy, especially during financial turmoils.

NOTES

1. As usual, the conventional policy refers to short-term government debt purchases via open market operations with the short-term objective of a desired quantity of reserves and/or a desired Fed funds rate. The unconventional policies refer to the cases where the Fed actively uses its balance sheet to directly affect market prices and conditions [see Borio and Disyatat (2009)].

2. These results are consistent with a handful of papers analyzing the impact of such policy during the financial crisis. For example, Medeiros and Rodriguez (2011) find for the United States that neither the level nor the curvature of the yield curve responds significantly to conventional monetary policy shocks, while the slope responds only slightly in the short run. Similarly, Abbassi and Linzert (2011) find that the conventional monetary policy of the European Central Bank has been ineffective during the financial crisis. However, these papers impose certain restrictions to identify conventional monetary policy shocks, which we bypass with our flexible approach.

3. Although this specification is used in only a handful of papers, it has proven useful to analyze the effects of the conventional monetary policy [Bernanke and Mihov (1998), Normandin and Phaneuf (2004), Lanne and Lutkepohl (2008), Bouakez and Normandin (2010), Lutkepohl (2012)].

4. Setting λ to 0.0609 is appropriate for two reasons. First, Diebold and Li (2006) show that λ determines the maturity at which the loading on the medium-term, or curvature, factor achieves it maximum, and that $\lambda = 0.0609$ when the maturity is 30 months—i.e., the average of the maturities of two or three years that are commonly used for this purpose. Second, Gilli et al. (2010) show that $\lambda = 0.0609$ offers the empirical advantage that the resulting factor loadings are not highly correlated.

5. Alternative methods implement the identification through heteroskedasticity by estimating the variances of the structural innovations for each preselected volatility regimes [Rigobon (2003), Lanne and Lutkepohl (2008)], or by modeling these variances as Markov regime switching processes [Lanne et al. (2010)]. These methods and the procedure used in this paper share the same intuition: Heteroscedasticity adds equations to the system, allowing the number of equations to match the number of unknown parameters.

6. The SVAR (11) is specified in detail in the appendix.

7. Empirically, we consider a broad grid of starting values for the parameters in A, Θ_1, and Θ_2. Also, we use the Broyden–Fletcher–Goldfarb–Shanno (BFGS) algorithm to maximize the likelihood function, which converges fairly quickly (within 10 and 150 iterations) and yields similar estimates for all the starting values used. The convergence criterion invoked in the algorithm is the following: The maximum absolute or relative change (in absolute values) across all parameter estimates between the current and previous iterations is smaller than 0.00001. Note that the convergence of the ML estimation procedure suggests that the identification conditions are satisfied.

8. We implement the following bootstrap procedure based on Pascual et al. (2006). First, the standardized structural innovations are computed as the ratio of the estimated innovations to the estimated conditional standard deviations. Second, the standardized structural innovations are resampled

(with replacement) to obtain 500 bootstrapped samples. Third, from the bootstrapped standardized structural innovations and the estimated parameters of (11) and (12), the bootstrapped samples are constructed for unstandardized structural innovations, macroeconomic aggregates, and term structure factors. Fourth, the parameters involved in (11) and (12) are reestimated for each bootstrapped sample from the two-step approach described above, and the results obtained across different bootstrapped samples allows us to compute the standard errors of the estimates. Fifth, the reestimated parameters for each bootstrapped sample are used to compute the dynamic responses of the variables after a monetary policy shock, and the resulting empirical distributions obtained across different bootstrapped samples allows us to construct the confidence bands associated with the responses.

9. Both the Federal Reserve Bank of St. Louis and the BBC mark this event as the second one on their time lines. The first event mentioned by the Federal Reserve Bank of St. Louis is the announcement, in February 2007, that the Federal Home Loan Mortgage Corporation (Freddie Mac) will no longer buy the most risky subprime mortgages and mortgage-related securities (http://timeline.stlouisfed.org/pdf/CrisisTimeline.pdf). The first event highlighted by the BBC is the revelation of huge subprime losses, in February 2007, by the Hong Kong & Shanghai Banking Corporation (HSBC) (http://news.bbc.co.uk/2/hi/8242825.stm).

10. For example, the Asset-Backed Commercial Paper Money Market Mutual Fund Liquidity Facility took place in September 2008, the Commercial Paper Funding Facility was implemented in October 2008, the Money Market Investor Funding Facility was created in October 2008, the Term Asset-Backed Securities Lending Facility occurred in November 2008, while the four rounds of quantitative easing started in December 2008, November 2010, September 2012, and January 2013.

11. Three other unconventional monetary policies were created before August 2008. Specifically, the Term Discount Window Program, announced in August 2007, allowed provisions of term financing for as long as 30 days (and eventually to 90 days). This program, however, involved relatively small changes in the Fed's usual operations compared to the other unconventional policies. Also, the Term Securities Lending Facility and the Primary Dealer Credit Facility, both created in March 2008, were intended for primary dealers, and not for depository institutions. Hence, these programs should not have any significant effect on the identification of the conventional monetary policy based on Fed funds rate and reserve variables.

12. Given the conservative nature of our empirical approach, a lack of any significant difference between the empirical results based on the two samples cannot, however, be interpreted as the absence of a structural break.

13. In order to maximize the number of observations available during the period of financial crisis, we follow numerous studies, including Sims (1992), Kim and Roubini (2000), and Bouakez and Normandin (2010), by measuring output by the industrial production index, which is released at a monthly frequency, instead of gross domestic product (GDP), which is only available at a quarterly frequency. Although, one can approximate GDP on a monthly basis, such an interpolation relies heavily on the observed industrial production [see Leeper et al. (1996), Bernanke et al. (1997), Bernanke and Mihov (1998), Christiano et al. (1999), Lanne and Lutkepohl (2008)] and may invalidate the identifying assumption stipulating that the goods market variables are not instantaneously affected by the reserve market variables, i.e., $A_{gr} = 0$ [Bernanke and Mihov (1998)].

14. The series ip_t and ff_t as well as TR_t, BR_t, and TAF_t, used to construct tr_t and nbr_t, are released by the Board of Governors, while p_t, cp_t, and $y_t(\tau)$ are obtained from the US Bureau of Labor Statistics, the International Financial Statistics, and the Center for Research in Security Prices, respectively.

15. In practice, we add to the reduced form associated with (11) a constant term and several dummy variables. In particular, we use dummy variables to control for the dramatic changes in the nonborrowed reserves of 37.09% and −64.08% in September 2001 and April 2008. Note that these variations are most likely unrelated to exogenous changes in the orientation of the monetary policy, but rather reflect endogenous responses of the Fed to the September 11 attacks and financial crisis events. Hence, controlling for these changes allows one to obtain a measure of monetary policy shocks that better isolate the discretionary component of the policy from the systematic response of the Fed. We also add

a dummy variable for the period between December 2007 and August 2008, that is, the episode during which the TAF program was in effect. Interestingly, the exclusion of this dummy variable does not alter any of the results reported in our analysis, which suggests that the way we correct the measures of reserve variables to distinguish the conventional monetary policy from the unconventional ones is adequate (see Section 2.4). Finally, we include a dummy variable for the financial crisis period between April 2007 and August 2008 to control for potential structural breaks due to the financial crisis.

16. Note that the Bayesian information criterion (BIC) selects the lag structure $\kappa = 2$ for the samples excluding and including the financial crisis. However, this lag structure leads to standardized structural innovations that are serially correlated for some horizons.

17. For both the samples, the unrestricted system is statistically identified, given that all variables display conditional heteroskedasticity. However, the structural innovations cannot be interpreted economically, since A_i is unique only up to changes in the signs and permutations of its rows.

18. Our bootstrap procedure for the likelihood ratio test follows from McLachlan (1987). Specifically, we first generate bootstrap samples based on the empirical specification and parameter estimates under the null hypothesis that the identifying restrictions involved in the flexible SVAR hold. For each bootstrap sample, we estimate the flexible and unrestricted systems and compute the likelihood ratio statistic. The bootstrapped p-values are calculated based on the empirical distribution of the test statistic obtained from the bootstrap samples.

19. Note that the impact response of the unexpected change in the yield $\tilde{y}_{t+1}(\tau)$ is identical to the impact response of the yield $y_t(\tau)$, presented in Figures 1 and 2.

20. The series ccb_t is released by the Board of Governors.

21. This program was established in 1980 to provide access to Federal Reserve services for banks with low or zero reserve requirements. Note that until the 1990s the contractual clearing balance program was not used by many institutions. However, the proportion of contractual clearing balances in total balances increased steadily from the early 1990s to the end of 2003, when it reached its maximum accounting for slightly more than 27% of total reserves. Since then, it has steadily decreased to almost 0% in July 2012, when the program was eliminated by the Fed in order to reduce reserve administration burden on institutions and the Fed.

22. As Thornton (2001) notes, this practice does not necessarily imply that the Fed implements a pure Fed funds rate targeting strategy and does not consider a mixed strategy depending on the macroeconomic and financial market conditions. In fact, optimal operating procedures were still somewhat nonspecific and depended on macroeconomic and financial market conditions [Board of Governors of the Federal Reserve System (1994)].

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APPENDIX

A.1. STACKED SVAR SYSTEM AND ITS FIRST-ORDER REDUCED FORM

In this section, we explicitly define the stacked SVAR system and the corresponding first-order reduced form VAR. The single SVAR system that includes all three separate flexible systems can be written as in (11), where matrices A and B are defined as follows:

$$A = \begin{pmatrix} A_{gg} & A_{gr} & A_{g1} & A_{g2} & A_{g3} \\ A_{rg} & A_{rr} & A_{r1} & A_{r2} & A_{r3} \\ A_{1g} & A_{1r} & A_{11} & 0 & 0 \\ A_{2g} & A_{2r} & 0 & A_{22} & 0 \\ A_{3g} & A_{3r} & 0 & 0 & A_{33} \end{pmatrix} \quad \text{and}$$

$$B_j = \begin{pmatrix} B_{gg,j} & B_{gr,j} & B_{g1,j} & B_{g2,j} & B_{g3,j} \\ B_{rg,j} & B_{rr,j} & B_{r1,j} & B_{r2,j} & B_{r3,j} \\ B_{1g,j} & B_{1r,j} & B_{11,j} & 0 & 0 \\ B_{2g,j} & B_{2r,j} & 0 & B_{22,j} & 0 \\ B_{3g,j} & B_{3r,j} & 0 & 0 & B_{33,j} \end{pmatrix},$$

for $j = 1, \ldots, \kappa$. The corresponding first-order SVAR can then be written as follows:

$$\tilde{A}\tilde{Z}_t = \tilde{B}\tilde{Z}_{t-1} + \tilde{\varepsilon}_t, \tag{A.1}$$

where

$$\begin{aligned} \tilde{Z}_t &= [Z_t, \ldots, Z_{t-\kappa}]', \\ \tilde{\varepsilon}_t &= [\varepsilon_t, 0, \ldots, 0]', \\ \tilde{A} &= \text{diag}\{A, \underbrace{I, \ldots, I}_{\kappa-1}\}, \end{aligned}$$

$$\tilde{B} = \begin{pmatrix} B_1 & B_2 & B_3 & \ldots & B_{\kappa-1} & B_\kappa \\ I & 0 & 0 & \ldots & 0 & 0 \\ 0 & I & 0 & \ldots & 0 & 0 \\ \vdots & \vdots & \vdots & \ldots & \vdots & \vdots \\ 0 & 0 & 0 & \ldots & I & 0 \end{pmatrix},$$

and I is the identity matrix. The corresponding reduced form VAR can be written as

$$\tilde{Z}_t = \Phi\tilde{Z}_{t-1} + \tilde{\nu}_t,$$

where $\Phi = \tilde{A}^{-1}\tilde{B}$, $\tilde{\nu}_t = \tilde{A}^{-1}\tilde{\varepsilon}_t$, and $E[\tilde{\nu}_t\tilde{\nu}_t'] = \tilde{A}^{-1}\tilde{A}^{-1\prime}$.

A.2. INITIAL RESPONSE DECOMPOSITION

In this section, we show how the initial responses of yields to monetary policy shocks can be decomposed into the initial responses of their components. We start by showing that the unexpected change in yield of a zero coupon bond with a maturity of τ in period $t+1$, $\tilde{y}_{t+1}(\tau) = E_{t+1}[y_{t+1}(\tau)] - E_t[y_{t+1}(\tau)]$, can be decomposed into unexpected changes in future inflation rate ($\tilde{y}_{\pi,t+1}(\tau)$), real rate of return ($\tilde{y}_{r,t+1}(\tau)$), and risk premium (excess return) ($\tilde{y}_{x,t+1}(\tau)$) as follows:

$$\tilde{y}_{t+1}(\tau) = \tilde{y}_{\pi,t+1}(\tau) + \tilde{y}_{r,t+1}(\tau) + \tilde{y}_{x,t+1}(\tau), \tag{A.2}$$

where

$$\tilde{y}_{\pi,t+1}(\tau) = \frac{1}{\tau}(E_{t+1} - E_t)\sum_{j=1}^{\tau}[\pi_{t+1+j}], \tag{A.3a}$$

$$\tilde{y}_{r,t+1}(\tau) = \frac{1}{\tau}(E_{t+1} - E_t)\sum_{j=1}^{\tau}[r_{t+1+j}], \tag{A.3b}$$

$$\tilde{y}_{x,t+1}(\tau) = \frac{1}{\tau}(E_{t+1} - E_t)\sum_{j=1}^{\tau}[x_{t+1+j}(\tau + 1 - j)], \tag{A.3c}$$

and π_t, r_t, and $x_t(\tau)$ are inflation, real rate of return, and risk premium (excess return) on a zero coupon bond with a maturity of τ in period t, respectively. The derivation of equation (A.2) follows from Campbell and Ammer (1993). Let $\rho_t(\tau)$ denote the log nominal price of a zero coupon bond with τ periods to maturity in period t. Then, the log nominal one period return on this bond held from t to $t+1$, is given by

$$b_{t+1}(\tau) = \rho_{t+1}(\tau - 1) - \rho_t(\tau). \tag{A.4}$$

Given that $\rho_{t+\tau}(0) = 0$, iterating forward the above equation and taking expectations conditional on the information set in period $t+1$ yield

$$\rho_{t+1}(\tau) = -E_{t+1}\sum_{j=1}^{\tau-1} b_{t+1+j}(\tau - j). \tag{A.5}$$

Define the log excess one period return on this bond as

$$x_{t+1}(\tau) = b_{t+1}(\tau) - \pi_{t+1} - r_{t+1}, \tag{A.6}$$

where π_{t+1} and r_{t+1} are the inflation rate and the real rate of return in period $t+1$, respectively. Given that $y_t(\tau) = -\rho_t(\tau)/\tau$, substituting equation (A.6) into equation (A.5) yields

$$y_{t+1}(\tau) = \frac{1}{\tau}E_{t+1}\sum_{j=1}^{\tau}[x_{t+1+j}(\tau + 1 - j) + \pi_{t+1+j} + r_{t+1+j}]. \tag{A.7}$$

Subtracting the expectation of equation (A.7) conditional on information in period t from that conditional on the information in period $t+1$ yields equation (A.2).

Having derived the decomposition of yields, we now show how the initial responses of yields to monetary policy shocks can be decomposed into the initial responses of their components. This requires empirical measures for $\tilde{y}_{\pi,t+1}(\tau)$, $\tilde{y}_{r,t+1}(\tau)$, and $\tilde{y}_{x,t+1}(\tau)$. To this end, we now show that $\tilde{y}_{t+1}(\tau)$, $\tilde{y}_{\pi,t+1}(\tau)$, $\tilde{y}_{r,t+1}(\tau)$, and $\tilde{y}_{x,t+1}(\tau)$ can be written as linear functions of the structural innovations from the first-order SVAR (A.1). First, we consider $\tilde{y}_{t+1}(\tau)$. Note that

$$y_{t+1}(\tau) = \alpha_{\tau,1} f_{1,t+1} + \alpha_{\tau,2} f_{2,t+1} + \alpha_{\tau,3} f_{3,t+1},$$

where $\alpha_{\tau,i}$ for $i = 1, 2, 3$ are defined in Section 2.1. Then, it is easy to see that

$$\begin{aligned}\tilde{y}_{t+1}(\tau) = (E_{t+1} - E_t)y_{t+1}(\tau) &= (\alpha_{\tau,1}e_7' + \alpha_{\tau,2}e_8' + \alpha_{\tau,3}e_9')\tilde{A}^{-1}\tilde{\varepsilon}_{t+1}, \\ &\equiv k_y(\tau)\tilde{\varepsilon}_{t+1}.\end{aligned}$$

where e_i denotes the ith column of the $N \times N$ identity matrix and N is the number of rows in $\tilde{z}_t$.

Second, we consider $\tilde{y}_{\pi,t+1}(\tau)$. Note that the inflation in period $t+1$, π_{t+1}, is defined as the difference in the price between t and $t+1$, i.e., $\pi_{t+1} = p_{t+1} - p_t$, and the price in period t, p_t, is the second element of the state vector z_t. Then,

$$\begin{aligned}\tilde{y}_{\pi,t+1}(\tau) &= \frac{1}{\tau}(E_{t+1} - E_t)\sum_{j=1}^{\tau}[\pi_{t+1+j}], \\ &= \frac{1}{\tau}(E_{t+1} - E_t)\sum_{j=1}^{\tau}[p_{t+1+j} - p_{t+j}], \\ &= \frac{1}{\tau}e_2'(\Phi - I)\sum_{j=1}^{\tau}\Phi^{j-1}\tilde{A}^{-1}\tilde{\varepsilon}_{t+1}, \\ &\equiv k_\pi(\tau)\tilde{\varepsilon}_{t+1}.\end{aligned}$$

Third, we consider $\tilde{y}_{r,t+1}(\tau)$. Note that the real rate of return in period $t+1$, r_{t+1}, can be written as the difference between the one-period holding period return on a bond with one period to maturity, $b_{t+1}(1)$, and the inflation in period $t+1$, π_{t+1}, i.e., $r_{t+1} = b_{t+1}(1) - \pi_{t+1}$. Note also that $y_t(1) = b_{t+1}(1)$ and $\pi_{t+1} = p_{t+1} - p_t$. Then,

$$\begin{aligned}\tilde{y}_{r,t+1}(\tau) &= \frac{1}{\tau}(E_{t+1} - E_t)\sum_{j=1}^{\tau}[r_{t+1+j}], \\ &= \frac{1}{\tau}(E_{t+1} - E_t)\sum_{j=1}^{\tau}[b_{t+1+j}(1) - \pi_{t+1+j}], \\ &= \frac{1}{\tau}(E_{t+1} - E_t)\sum_{j=1}^{\tau}[y_{t+1+j}(1) - (p_{t+1+j} - p_{t+j})], \\ &= \left(\frac{1}{\tau}(E_{t+1} - E_t)\sum_{j=1}^{\tau}[\alpha_{1,1}f_{1,t+j} + \alpha_{1,2}f_{2,t+j} + \alpha_{1,3}f_{3,t+j}]\right) - k_\pi(\tau)\tilde{\varepsilon}_{t+1}, \\ &= \frac{1}{\tau}(\alpha_{1,1}e_7' + \alpha_{1,2}e_8' + \alpha_{1,3}e_9')\left(\sum_{j=1}^{\tau}\Phi^{j-1}\right)\tilde{A}^{-1}\tilde{\varepsilon}_{t+1} - k_\pi(\tau)\tilde{\varepsilon}_{t+1} \\ &\equiv k_r(\tau)\tilde{\varepsilon}_{t+1}.\end{aligned}$$

Finally, we consider $\tilde{y}_{x,t+1}(\tau)$, which is the residual component in the decomposition.

Hence,

$$\begin{aligned}\tilde{y}_{x,t+1}(\tau) &= [k_y(\tau) - k_\pi(\tau) - k_r(\tau)]\tilde{\varepsilon}_{t+1}\\ &\equiv k_x(\tau)\tilde{\varepsilon}_{t+1}.\end{aligned}$$

Having shown that $\tilde{y}_{t+1}(\tau)$, $\tilde{y}_{\pi,t+1}(\tau)$, $\tilde{y}_{r,t+1}(\tau)$, and $\tilde{y}_{x,t+1}(\tau)$ can be written as linear functions of the structural innovations, it is then easy to see that the initial response of yields to monetary policy shocks $(\partial\tilde{y}_{t+1}(\tau)/\partial\varepsilon_{s,t+1})$ can be decomposed into initial responses of their components as follows:

$$\begin{aligned}\frac{\partial\tilde{y}_{t+1}(\tau)}{\partial\varepsilon_{s,t+1}} &= k_y(\tau)e_4 = \frac{\partial\tilde{y}_{\pi,t+1}(\tau)}{\partial\varepsilon_{s,t+1}} + \frac{\partial\tilde{y}_{r,t+1}(\tau)}{\partial\varepsilon_{s,t+1}} + \frac{\partial\tilde{y}_{x,t+1}(\tau)}{\partial\varepsilon_{s,t+1}},\\ &= k_\pi(\tau)e_4 + k_r(\tau)e_4 + k_x(\tau)e_4.\end{aligned}$$