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Market volatility, monetary policy and the term premium*

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Abstract

In this paper, we use time-varying VAR models to study the effects of option-implied measures of equity and bond market volatilities on the government bond term premium and key macroeconomic variables. We show that the high correlation between the two volatilities requires that shocks to these variables be jointly identified. We find that a positive shock to the VIX reduces the term premium. We interpret this effect as the result of investors shifting their portfolios away from riskier assets. The positive shock to the VIX also has contractionary and

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disinflationary effects. By contrast, a positive shock to the MOVE, which reflects heightened uncertainty about future changes in interest rates, raises the term premium. Similar to a VIX shock, an increase in bond market volatility also has a contractionary effect, although the negative effects on output and inflation are smaller. Both VIX and MOVE shocks resemble negative demand shocks, albeit of different intensity, to which the central bank responds by easing monetary policy. Depending on the type of volatility impacting the economy, a contraction in output can be associated either with a flattening or steepening of the yield curve.

JEL classification: E43; E44; E52

Keywords: VIX; MOVE; time-varying VAR; market volatility; bonds; equities; term premium; monetary policy.

1 Introduction

This paper provides an empirical assessment of the role that expected financial market volatilities and monetary policy play in the determination of the government bond term premium and key macroeconomic variables. Three main considerations motivate such a focus. First, in financially developed economies such as the United States the long-term interest rate is an important determinant of broad financial conditions and real activity. Second, changes in the long-term interest rate are not driven only by changes in the expected path of future short-term interest rates, as assumed by mainstream macroeconomic theory[1], but also by changes in the term premium. Indeed, the possibility of influencing the term premium directly is one of the motivations behind the large-scale purchases of bonds by the Federal Reserve post-crisis. Third, risk-taking and portfolio rebalancing between bond and equity markets, and their interaction with monetary policy are in principle important, but relatively unexplored, mechanisms in the determination of the term premium.

Risk-neutral measures of expected volatility, such as the Chicago Board Options Ex-

[1] The standard New Keynesian model (Woodford (2003)) is built on the expectation hypothesis, whereby changes in the long-term interest rate only reflect changes in the average expected value of future short-term interest rates.

change Volatility Index (VIX) or the Merrill Lynch Option Volatility Expectations (MOVE) index, represent not only investors' uncertainty about future equity and bond prices, respectively, but also investors' risk aversion[2]. When uncertainty and/or risk aversion increases[3], investors may demand higher compensation for holding risky assets, including long-duration government securities. Furthermore, investors that actively manage their balance sheet may face tighter funding or capital constraints and therefore be forced to reduce their exposures. Thus, market-making capacity and liquidity in the bond market may decline, leading to wider swings in bond yields (eg Gromb and Vayanos (2002), Brunnermeier and Pedersen (2005), He and Krishnamurthy (2008) and Adrian and Shin (2010))[4]. Conversely, a decline in expected volatility may induce investors to take on more risk as well as improve market liquidity, thus leading to a narrowing of term premia[5]. To the extent that monetary policy affects investors' perception of uncertainty and risks and relative risk between equity and bond market, risk-taking in bond markets may therefore constitute an additional channel of monetary transmission.

The interaction between the term premium, market volatility and monetary policy has not received much attention in the empirical literature. Recent empirical work supports the view that a time-varying term premium is an important channel in the monetary

[2]The VIX is the risk-neutral expected volatility of the stock market over the next 30 days and is calculated from options on the SP 500 index. The VIX can be thought of as the sum of two components: expected actual volatility, which is interpreted as a measure of risk, and a variance risk premium, which is related to investorsâ risk aversion (see eg Carr and Wu (2009) and Bekaert and Hoerova (2014)). The MOVE index is constructed in a similar way to the VIX. It is a yield curve weighted index of the normalised implied volatility on 1-month Treasury options which are weighted on the 2, 5, 10, and 30 year contracts over the next 30 days.

[3]Using micro level data Gilchrist and Zakrajsek (2012) suggest that the increases in excess bond premium are associated with reduction in the risk bearing capacity of financial market participants and lead to lower economic activity and assets prices.

[4]Philippon (2009) finds significant effect of credit market risks on bond prices and constructs a measure similar to Tobin's q using bond prices. Results suggest that bond's q fits the investment equation six times better than the Tobin's q.

[5]Time-varying risk premia, including bond term premia, may arise, for example in models of risk averse arbitrageurs (Vayanos and Vila (2009)) and models of risk-neutral investors facing a Value-at-Risk (VaR) capital constraint (Danielsson et al (2004, 2010, 2011); Adrian and Shin (2011)). Chevalier and Ellison (1995) and Shleifer and Vishny (1997) discuss how the assumption of risk-free arbitrage may not hold in practice when arbitrage is conducted by highly specialised investors. Capital plays a central role in the agency relationship between bond dealers and ultimate investors, implying that arbitrage may be limited during periods of higher volatility.

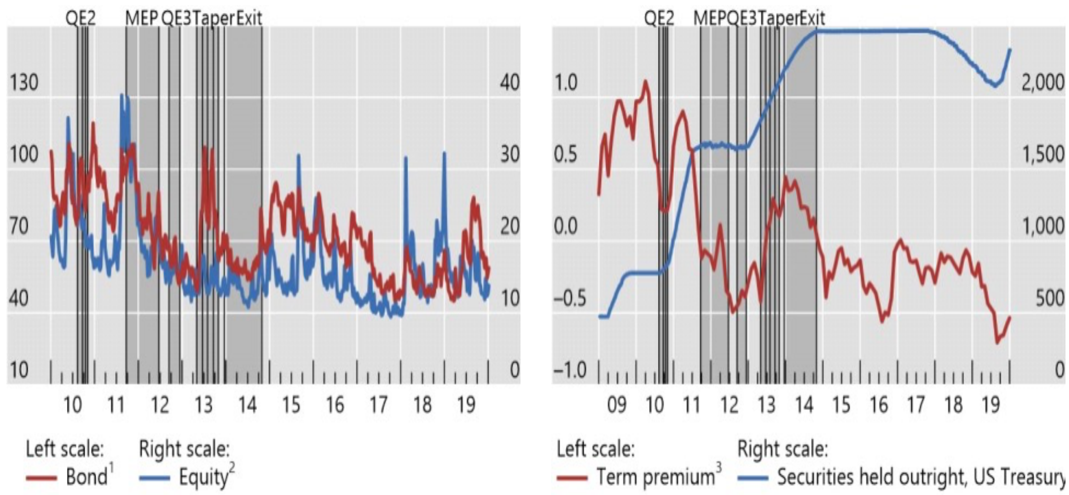
transmission mechanism (Gertler and Karadi (2015)), a finding that is sharply at odds with the standard New Keynesian model (Woodford (2003)). But this work does not examine how the term premium is affected by changes in volatility or other measures of risk aversion or uncertainty. By contrast, other empirical studies have documented that stock market volatility, as measured by the VIX, has relevant macroeconomic effects. Bekaert et al (2013) find that expansionary monetary policy reduces the risk aversion component of the VIX and increases output, while Bruno and Shin (2015) show that a decline in US dollar bank funding costs leads to an increase in bank leverage through the mitigation of volatility risk[6]. Yet none of these studies pay attention to expected bond market volatility and the term premium, despite the bond market having gained greater relevance post-crisis.

Figure 1 suggests that, post-crisis, spells of higher expected bond market volatility, as captured by the MOVE index, have been accompanied by upward movements in the 10-year term premium - for example, during the 2013 taper tantrum episode (Graph 1)[7]. However, other drivers, including asset purchases, may be relevant. An interesting question is whether the VIX also matters for term premium. While it may be tempting to assume that only a measure of expected bond volatility matters for the term premium, the VIX may also be empirically relevant. For one, investors may hold diversified portfolios of bonds and equities. They may therefore rebalance their portfolio when expected returns and perceived risks change. Second, the VIX has been shown to correlate well not only with US equity prices, but also with the prices of a range of other risky assets, including foreign assets. Third, while the MOVE and the VIX tend to co-move, their correlation changes over time. Post-crisis, the two measures have occasionally diverged (Graph 1, left-hand panel). All of this suggests that both volatility indicators, rather than the

[6]See also Hattori et al (2013) for an analysis of the effects of monetary policy on an option-based measure of skewness in the stock market. Bloom (2009) provides an earlier analysis of the effects of uncertainty as measured by spikes in the VIX on employment and industrial production, finding significant but short-lived effects.

[7]The US 10-year Treasury yields shot up by over 100 basis points following the announcement that the Federal Reserve would slow down the pace of bond purchases. Stein (2014) and Adrian et al. (2013) argue that the initial shock was amplified by a spike in bond market volatility, which reduced the market-making capacity of bond dealers, widening bid-ask spreads and drying up market liquidity, see also Morris and Shin (2014).

MOVE alone, may be useful in characterising the overall attitude towards risk and the degree of uncertainty faced by bond investors.



(a) Market Volatility

(b) Term Premium and Fed holding of Treasury Securities

Figure 1: Merrill Lynch Option Volatility Expectations (MOVE) index, yield curve weighted index of the normalised implied volatility on 1-month Treasury options; weekly averages. VIX implied volatility on the SP 500 index; weekly averages. Decomposition of the 10-year nominal yield according to an estimated joint macroeconomic and term structure model; see Hordahl and Tristani (2014). Yields are expressed monthly in zero coupon terms. Sources: Bloomberg; Datastream; Chicago Board Options Exchange; Merrill Lynch.

In this paper, we investigate the role of expected volatilities and monetary policy in influencing the term premium and macroeconomic variables in the United States using structural vector autoregression models. The variables included in the analysis are the VIX, the MOVE, the 10-year term premium, the federal fund rate (the shadow rate after 2008), output and inflation. Our analysis has several key features. First, we estimate VAR models with time-varying coefficients to allow for possible changes in the transmission mechanism, especially after the Great Financial Crisis (GFC) of 2007-9. Second, we employ a measure of the shadow interest rate (Wu and Xia (2016)) to capture changes in monetary policy after the GFC when the policy rate has remained unchanged at its lower bound. Third, we base the identification of the shocks to market volatilities on the time-varying penalty function approach of Uhlig (2004). For a given variable, this consists in selecting the shock that maximises its response over some forecast horizon. In our case, we choose four quarters, but shorter horizons yield similar results[8]. This identification scheme does not require the imposition of zero restrictions on the impact effect of a shock, which would be implausible in the presence of financial variables. Finally, we include both measures of expected volatilities - the MOVE and the VIX - in the model. Given the high correlation between the two measures, joint identification of the shocks to these variables is required to obtain plausible responses. Indeed, if the model includes only the MOVE, a positive shock to this variable is found to reduce the term premium, which is implausible. Disentangling the shocks to the VIX and the MOVE is one of the main contributions of our paper.

Our main finding concerns the different impact of the VIX and the MOVE indices on the term premium and other macroeconomic variables. We find that a positive shock to the VIX, which might reflect an increase in economic uncertainty and/or investors' risk aversion, reduces the term premium. This is consistent with investors increasing their demand for government bonds as they rebalance their portfolios away from riskier assets. The positive shock to the VIX also has contractionary and disinflationary effects, which is consistent with the negative impact that greater economic uncertainty should have on economic activity in general. By contrast, a positive shock to the MOVE, which reflects heightened uncertainty about future changes in interest rates, raises the term premium. Similarly to a VIX shock, an increase in bond market volatility has also a contractionary effect, although the negative effect on output is smaller. The impact on inflation is generally negative or statistically insignificant. Thus, both a VIX shock and a MOVE shock resemble negative demand shocks, albeit of different intensity, to which the central bank responds by easing monetary policy.[9] These findings suggest that it might useful to explicitly include the term premium and market volatilities in macroeconomic models.[10]

To complement our analysis of the term premium and market volatilities, we also

[8]As a robustness check, we also used two quarters, which is the horizon used in Caldara et al. (2016). Results are similar. These are not reported in the paper but are available on request.

[9]See Kumar et al. (2021) for a discussion of demand and supply shocks.

[10]The impulse responses to shocks to equity and bond market volatilities are little changed if we include an indicator of monetary policy uncertainty based on newspapers news as an additional control in our model.

compute the responses of the term spread or slope (the difference between the 10-year Treasury yield and the 3-month Treasury bill). We find that a positive shock to the VIX leads to an initial flattening of the yield curve as the term premium declines, followed by a subsequent steepening of the curve as monetary policy is loosened in response to the decline in output and inflation. By contrast, a positive shock to the MOVE leads to a steepening of the yield curve, which slowly returns to normal after several quarters. At the same time, while there is no clear response of monetary policy and inflation, output declines relative to baseline.

These findings may help shed some light on the relationship between the yield spread and and future GDP growth. The literature (as summarised by Wheelock and Wohar (2009)) generally finds that the yield spread is positively associated with future GDP growth even when a short-term interest rate is included. However, this literature has not consistently explained why this is so. For instance, Hamilton and Kim (2002) decompose the yield spread into an expected interest rate component and a term premium component, finding that both have predictive power. Moreover, Hamilton and Kim (2002) find that interest rate volatility (either computed with a GARCH model or realised) is negatively associated with the term premium and the yield spread but positively associated with future GDP growth. Cyclical changes in interest rate volatility cannot therefore explain why the yield spread or the term premium are positively associated with future GDP growth. Our analysis reaches a similar conclusion regarding the MOVE index (or measures of option-implied interest rate volatility). At the same time, however, our analysis also suggests that shocks to equity volatility might be more relevant in explaining the positive relationship with output growth.

We complete our paper with the analysis of an expansionary monetary policy shock. In this case, it is not possible to use the same identification strategy used for identifying the shocks to market volatilities. Using the same identification scheme leads to implausible responses of output to a shadow interest rate shock. To identify the latter, we use the Proxy SVAR method developed by Mertens and Ravn (2013). This approach is based on using a high-frequency instrument - in our case, the unexpected change in the 2-year US Treasury yield in a tight window around FOMC announcements (as used eg Kuttner (2001), Gurkaynak et al. (2005) and Gertler and Karadi (2015)). We find that an expansionary monetary policy shock leads to a decline in both market volatilities as well as an expansion of output. Inflation also increases but the effect is not statistically significant. The term premium increases on impact but returns towards baseline within three quarters, after which it undershoots its baseline for several quarters. This is consistent with monetary policy easing reducing the perception of risk or risk aversion of investors, which contributes to boosting economic activity, as shown in Bekaert et al. (2013). As an additional check, we also investigate the responses to an asset purchase shock, identified following an approach based on the maximisation of the forecast error variance (Uhlig (2004); Kurmann and Otrok (2013)). Our results suggest that the transmission of the assets purchase shock in the economy is similar to the transmission of shadow rate shock, which is consistent with the findings in Debortoli et al (2020).

The remainder of this paper is organised as follows. Section 2 presents some of the concepts and theoretical arguments that underpin our empirical analysis. Section 3 describes the data and empirical models used to identify and trace the effects of shocks to equity and bond market volatilities and to monetary policy. Section 4 presents the main results, followed by robustness tests. This section also contains the local projection-based responses of the term premium to orthogonal components obtained from equity and bond market volatilities, which help us decide the order of identification of these two variables. Section 5 concludes.

2 The term premium, the slope and the role of expected volatility in the monetary transmission

The long-term interest rate can be written as the sum of average future short-term rates and the term premium:

$$i_t^m = \frac{1}{m} E_t \left\{ \sum_{j=0}^{m-1} i_{t+j} \right\} + \phi_t^m$$

where ϕ_t^m is m period annualised term premium, i_t^m is m period annualised rate and $E_t \frac{1}{m} \sum_{j=0}^{m-1} i_{t+j}$ is average of short term future rates. The term premium is therefore given by:

$$\phi_t^m = i_t^m - \frac{1}{m} E_t \left\{ \sum_{j=0}^{m-1} i_{t+j} \right\}$$

One can further bifurcate the sum on the right hand side and write it as:

$$\phi_t^m = i_t^m - E_t \frac{1}{m} \left\{ i_t + \sum_{j=1}^{m-1} i_{t+j} \right\}$$

where i_t is a one period rate prevailing at time 0. We can write the slope of the yield (term spread) curve as given below:

$$\underbrace{(i_t^m - i_t)}_{\text{Slope}} = \underbrace{\left(\frac{1}{m} E_t \left\{ \sum_{j=0}^{m-1} i_{t+j} \right\} - i_t \right)}_{\text{Average Expected Future Short Rate - Short Rate}} + \underbrace{\left[i_t^m - \frac{1}{m} E_t \left\{ \sum_{j=0}^{m-1} i_{t+j} \right\} \right]}_{\text{Term Premium}}$$

The slope is made up of the term premium and the difference between the average of the expected future short rates (expected component) and the current short rate. The slope is regarded by many pratictioners as an important indicator in the analysis of the business cycle. An increase in the slope or a steepening of the yield curve is normally associated empirically with lower GDP growth as well as a greater probability of recession. However, there is not yet a clear theory that can explain this fact (Wheelock and Wohar (2009)). One plausible hypothesis is that changes in the slope largely reflect changes in the expected component as monetary policy responds to changes in economic conditions. And if inflation expectations are well anchored, the long-term interest rates should change little. Ang et al (2004) find that only the expected component is significant in predicting output growth. By contrast, Hamilton and Kim (2002) find that both the expected and term premium components are significant in predicting output growth. These authors also find that interest rate volatility affects the yield spread[11].

[11] Kurmann and Otrok (2013) suggest that an exogenous increase in the slope may reflect better news about future productivity, which is expansionary. Gortz et al (2021) provide evidence that positive news shock about TFP generates a significant decline in various credit spread indicators considered in the macro-finance literature.

There are several reasons why expected market volatilities may influence the long-term interest rate and the transmission mechanism more broadly. First, volatilities affect investors' behaviour dynamically. When some of the investors face a capital constraint, investors' risk aversion is endogenous - eg in asset price models with risk-neutral investors facing Value-at-Risk (VaR) and capital constraints (see Danielsson, Shin and Zigrand (2004, 2010, 2011) and Adrian and Shin (2011)). This contrasts with standard models of asset prices with mean variance investors where investors' risk aversion is exogenous and time invariant. Portfolio diversification typically implies that the price of a particular asset (say a bond) depends only on its own volatility and the hedging properties of other assets (ie the covariance of other assets, eg equities). However, when some of the investors actively manage their balance sheets and face a capital constraint, investors' risk aversion depends on the volatilities and covariances of all assets in the portfolio. Hence, in a portfolio with two asset classes - bonds and equities - the term premium depends not only on bond volatility and the correlation of bond returns with those of equities, but also on stock market volatility.

Second, volatilities act to propagate shocks. For those investors that actively manage their balance sheets (such as broker dealers), market volatilities have the additional role of determining the amount of leverage and the overall size of their portfolios. Broker dealer leverage plays a special role in liquidity and hence the smooth functioning of financial markets.

Third, these models with risk-neutral investor suggest that the supply of assets matters. For example, a reduction in the supply of bonds - due to purchases of the central banks, foreign official sector or habitat investors- leads to a reduction in the term premium, other things equal. The impact of given change in supply is expected to be stronger, the larger the volatilities and the higher the leverage, in that both increases investors' risk aversion.

Clearly then, an expansionary monetary policy shock can affect the term premium in various ways. On the one hand, to the extent such a shock dampens market volatility, it has a direct effect of reducing the term premium, with the strength of this effect depending on the joint effect of bond and equity volatilities on investors' portfolio. On the other hand, an expansionary monetary shock can also increase uncertainty about future inflation and interest rates, leading to a rise in the term premium. We contribute to the literature by estimating the effect on term premium and expected component in the presence of market volatilities.

3 Data and Empirical Strategy

3.1 Data

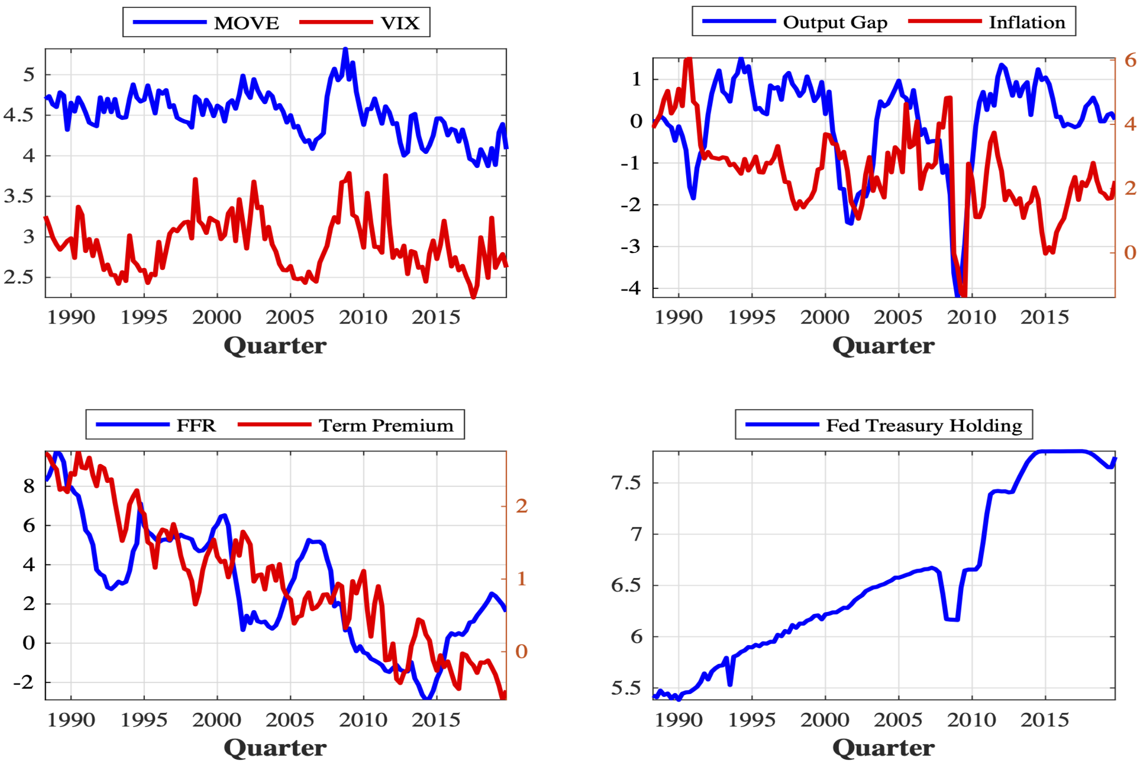


Figure 2: Output gap is obtained using one sided HP filter. Federal funds rate is Wu-Xia Shadow Federal Funds Rate. We have used actual rates for earlier periods. Federal reserve treasury holding is given by log of treasury securities held outright in billions USD.

In our analysis we estimate several VAR models on US quarterly data over the period 1988 to 2019. The baseline model includes the following variables: seasonally adjusted gross domestic product, seasonally adjusted consumer inflation, the fed funds/shadow rate, equity volatility (VIX), bond market volatility (MOVE) and an estimated of the US term premium. In alternative specifications, we also include the 10-year Treasury bond yield, the Federal Reserve holdings of Treasury securities, and a measure of inflation uncertainty. We explore the responses of these variables to four shocks: to the VIX, to the MOVE, to the shadow interest rate, and to asset purchases. The variables are sourced as follows. The term premium is an estimate taken from Hordahl and Tristani (2014) based on the 10 year Treasury yield. US monetary policy is measured by the fed funds/ shadow target rate from Wu and Xia (2016). The shadow rate captures the quantitative easing as well as other interventions by the central bank due to zero lower bound. For robustness, we have also considered the Federal Reserve's holdings of Treasury security[12] - to identify a quantitative easing shock. The measure of inflation uncertainty comes from Binder (2017). The implied bond volatility in the US Treasury market is measured by the MOVE index, while stock volatility is measured by the VIX index. The VIX is the risk-neutral expected volatility of the stock market over the next 30 days calculated from options on the SP 500 index. The MOVE index is constructed in a similar way to the VIX. It is a yield curve weighted inde of the normalised implied volatility on 1-month Treasury options. Unlike the VIX index, the MOVE is not a model-free index because it is estimated from at-the-money options using the Black (1976) model. That said, it is one of the oldest and most watched volatility indicators by market participants. Figure 2 shows the main data being used in the paper.

3.2 Empirical Strategy

3.2.1 Structural Vector Auto Regression

The structural shocks being identified in this paper are based on a vector auto regression (VAR) framework. A reduced form VAR with p lags is given by:

$$Y_t = B_1 Y_{t-1} + B_2 Y_{t-2} + ... + B_l Y_{t-p} + u_t$$

[12] `https://fred.stlouisfed.org/series/TREAST`

where Y_t is a vector of n variables. One can obtain the moving average representation as given below:

$$Y_t = C(L)u_t$$

where $C(L) = \sum_{l=0}^{\infty} C_l L^l$. The reduced form shocks (u_t) and their variance covariance matrix (Σ) are known $\Sigma = E\left(u_t u_t'\right)$. Assuming structural errors with unit variances, the objective is to find a A matrix that satisfies:

$$\Sigma = AE\left(v_t v_t'\right)A' = AA' \quad \text{Where } E\left(v_t v_t'\right) = I$$

Since there are only $n^2 - \frac{n^2-n}{2} = \frac{n(n-1)}{2}$ free elements in Σ, we can only identify $\frac{n(n-1)}{2}$ elements of A. One way to achieve identification is to impose zero restrictions, which constrain the contemporaneous relationships between the selected variables to be zero. One particular form of zero restrictions is the well-known Cholesky decomposition, which implies a recursive formulation. However, in the presence of financial variables, zero restrictions are generally implausible (Gertler and Karadi(2015)). Therefore, we choose alternative identification approaches. The first one is based on Uhlig (2004). We start with Cholesky decomposition of Σ. Let $\tilde{A}$ be the Cholesky decomposition of Σ:

$$\Sigma = \tilde{A}\tilde{A}' \quad u_t = \tilde{A}\tilde{v}_t$$

The Cholesky decomposition identifies n shocks as given above. The main insight from Uhlig (2004) is that there must be an orthogonal matrix Q, i.e. an $n \times n$ matrix Q satisfying $QQ' = I$ so that $A = \tilde{A}Q$. This is because $\tilde{A}\tilde{A}' = AA' = \tilde{A}QQ'\tilde{A}' = \Sigma$. Therefore, we can select given columns of Q to identify a given shock.

3.2.2 Time Varying Penalty Function Approach

We identify the shocks to bond and equity market volatilities by selecting one column of Q at a time. We also identify both of these shocks jointly by selecting two columns of Q together. The bond volatility and shadow rate shocks are also jointly identified by selecting two columns of Q. Let the selected columns of Q be indicated by $q_j = Q\ e_j$

where e_j denotes the jth column of I_n. We define the shock to bond volatility as an innovation that generates the largest increase in bond volatility for the first year. We put bond volatility as the first variable and equity market volatility as the second variable. Therefore, identification is achieved by minimising the penalty function

$$\Psi(q_1) = \sum_{l=0}^{3} -\frac{e_1' C(L) A q_1}{\omega_1}$$

subject to

$$e_1' C(L) A q_1 > 0$$

where ω_1 is the standard deviation of the reduced form shock and the constraint ensures that the response of bond volatility to a shock to itself is positive. After selecting the first column, identification of the second column requires the minimisation of:

$$\Psi(q_2) = \sum_{l=0}^{3} -\frac{e_2' C(L) A q_2}{\omega_1}$$

subject to

$$e_2' C(L) A q_2 > 0$$

$$Q_1^* q_2 = 0$$

where ω_2 is the standard deviation of the second reduced form shock. The first constraint ensures that the response of equity market volatility is positive. The second constraint ensures that the shock to equity volatility and the shock to bond market volatility are orthogonal (Caldara et al., 2016).

We assume $l = 3$, i.e. we identify shocks such that they lead to maximum increase in uncertainty over a period of one year. We also estimate an alternative model in which equity volatility is the first variable and bond market volatility the second variable. The important point to note is that the penalty function approach is based on reduced form coefficients and co-variance matrix. To explore the time variation in the transmission mechanism, we estimate a Bayesian time varying parameter VAR and estimate the impulse responses based on shock identified using penalty function approach at all points in our sample. It is important to highlight that our approach only considers the time variation in the transmission mechanism and not the volatility of primitive shocks affecting the economy, similarly to Cogley and Sargent (2001)[13]. This should not be a concern. Most studies that explore time varying volatility are based on a much larger sample containing the pre-Volcker period. Our sample corresponds to the post-Volcker period. Moreover, our model includes market volatilities as variables.

4 Results and analysis

4.1 Bond and equity market volatilities

This section explores the responses of the model to equity and bond volatility shocks when these shocks are identified separately. Figure 3 shows the responses to an equity volatility shock identified separately from a bond market volatility shock[14]. Output and inflation decrease, suggesting that the shock has effects akin to a negative demand shock. The Federal Reserve responds to this shock by reducing the policy interest rate. The term premium also narrows. Furthermore, the increase in equity volatility also leads to a decline in the bond volatility index. We will revisit this point in sections ahead. Figure 4 shows the responses to a bond volatility shock identified separately from an equity volatility shock. Like the equity volatility shock, the bond volatility shock leads to a decline in output and inflation as well as a reduction in the policy interest rate. The bond volatility shock also reduces the term premium on impact, whose response quickly becomes insignificant.

[13]We use the code for homoscedastic TVP made available by Dimitris Korobilis to draw from posterior and create confidence band for impulse responses.

[14]We implement the identification using a time varying parameter vector auto regression model containing the term premium. The response presented here is for first quarter of 2018Q1. The responses for other time periods (2001Q1, 2006Q1, 2010Q1, and 2013Q1), shown in the online appendix, are similar.

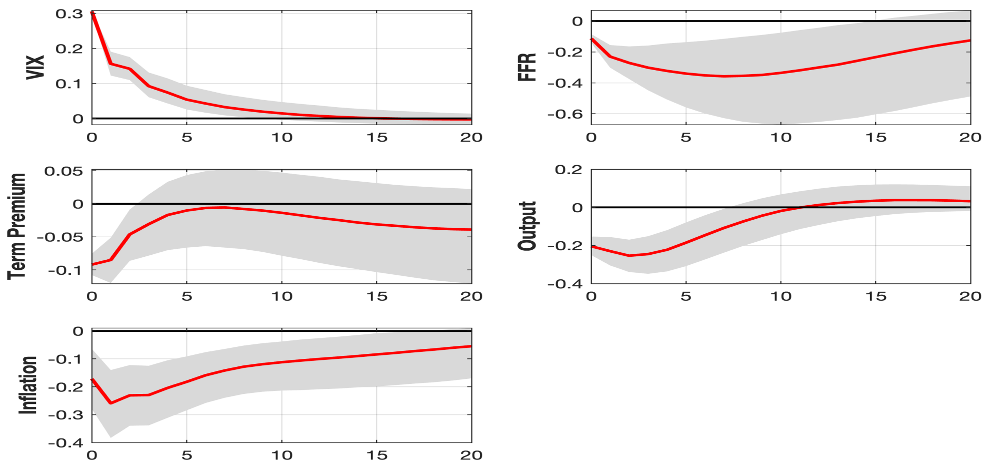


Figure 3: Response of model variables to an equity volatility shock in 2018Q1. The term premium is based on Hordahl and Tristani (2014). The model does not include a bond volatility shock.

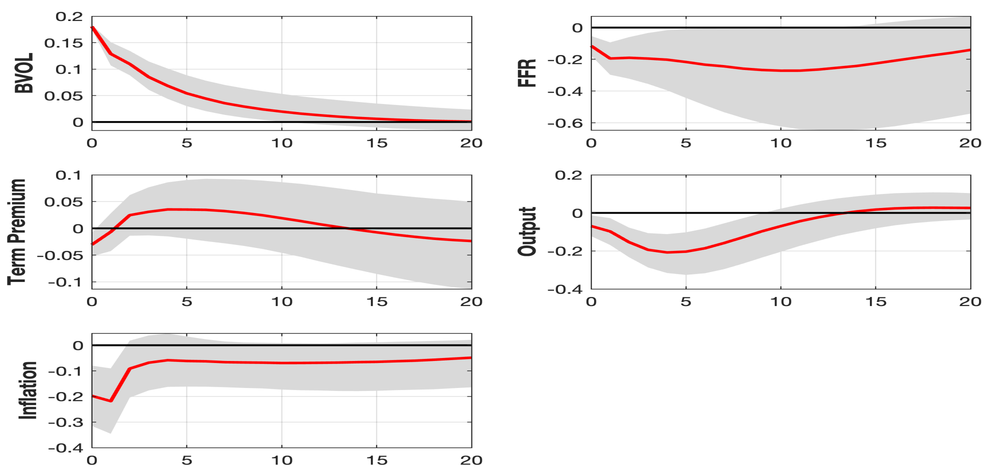


Figure 4: Response of model variables to a bond volatility shock in 2018Q1. The term premium is based on Hordahl and Tristani (2014). The model does not include an equity volatility shock.

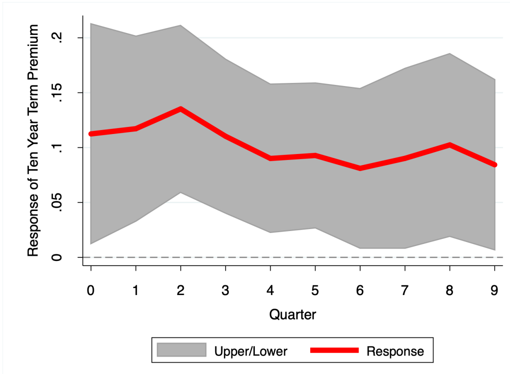
The narrowing of the term premium in response to a bond volatility shock is puzzling.

An increase in the MOVE index reflects that willingness by traders to pay more for protection against unexpected movements in interest rates[15]. Furthermore, other studies (eg Abrahams et al. (2016)) show that the term premium and the MOVE index move together, consistent with the idea that greater uncertainty and risk aversion raise the term premium. This suggests that the separate identification of the two shocks is not able to tease out the spillover from one shock to the other and thus leads to an implausible response. In the next section, we show that this is indeed the case.

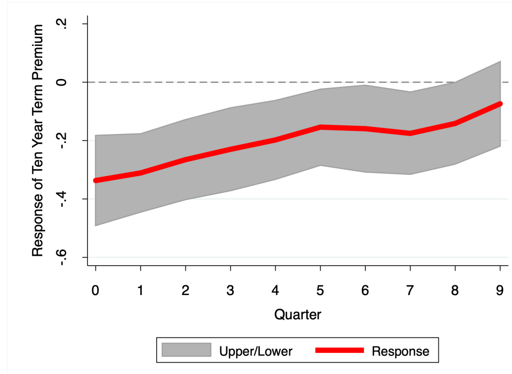
4.2 Disentangling equity and bond market volatilities

We use principal component analysis to obtain two orthogonal components from bond and equity market volatilities. The first component has a high and positive correlation with both equity and bond market volatilities. By contrast, the second component has a high positive correlation with equity market volatility and a high negative correlation with bond market volatility. Thus, the first component captures an increase in both equity and bond market volatilities, whereas the second component captures an increase in equity volatility and a decrease in bond volatility. As figures 5 and 6 show, the first component is positively associated with the term premium, whereas the second component is negatively associated with it. Furthermore, the absolute magnitude of the impact on the term premium is much bigger in the case of the second component. This higher absolute magnitude helps us uncover the direction of the effect of these two volatilities on the term premium.

[15] https://www.brookings.edu/blog/ben-bernanke/2015/04/13/why-are-interest-rates-so-low-part-4-term-premiums/



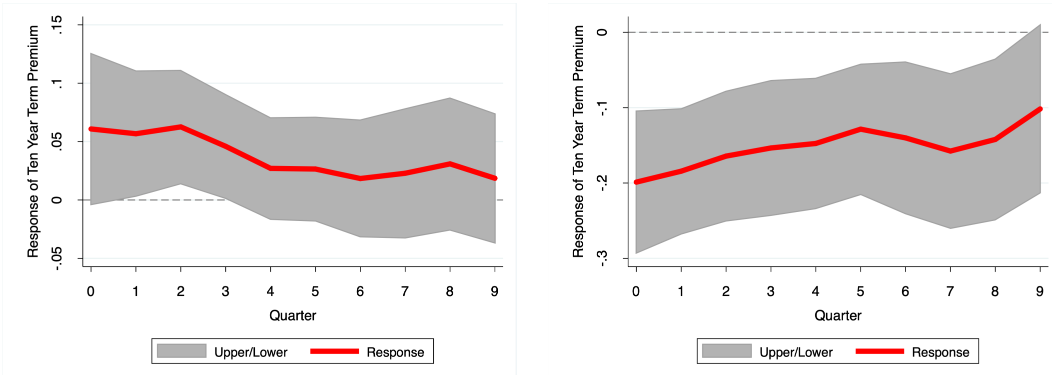
(a) Response of the 10-year term premium to the first orthogonal component



(b) Response of the 10-year term premium to the second orthogonal component

Figure 5: β_1^j from $tp_{t+j} = \beta_0 + \beta_1^j pc_k + \beta_2 \times$ Output Gap$_t + \beta_3 \times$ Inflation$_t + \beta_4 \times$ Federal Funds Rate$_t + \epsilon_t$ for$k = 1, 2 j = 0, 1, ..., 10$ where pc_k for$k = 1, 2$ are two orthogonal components obtained from bond volatility and equity volatility. tp is the 10-year term premium. The left panel is for the first component; the right panel for the second component. Confidence bands are based on newey-west standard errors corrected for heteroscedasticity and first order auto-correlation.

Table 1 gives the change in market volatilities due to a change in the two orthogonal components. Both components have the same effect on equity market volatility. Also, both components change bond volatility by same absolute amount with opposite sign. Suppose the true effects of equity and bond market volatilities on the term premium are x and y respectively. If both x and y are positive (negative), then the effect should be much higher (lower) in absolute amount due to the first component, which is not the case and hence ruled out. Suppose x is positive and y is negative; then the effect of the second component should be positive, which is not the case and hence ruled out. This leaves us with the only possibility that x is negative and y is positive, which mutes the response of first component and reinforces the effect of second component, which is the case here. Therefore, we conclude that an increase in bond volatility increases the term premium and increase in equity market volatility decreases the term premium. We use this insight to choose the order of identification of equity and bond market volatility shock using Uhlig's penalty approach.



(a) Response of the 5-year term premium to the first orthogonal component

(b) Response of the 5-year term premium to the second orthogonal component

Figure 6: β_1^j from $tp_{t+j} = \beta_0 + \beta_1^j pc_k + \beta_2 \times$Output Gap$_t + \beta_3 \times$Inflation$_t + \beta_4 \times$Federal Funds Rate$_t + \epsilon_t$ for$k = 1, 2 j = 0, 1, ..., 10$ where pc_k for $k = 1, 2$ are two orthogonal components obtained from bond volatility and equity volatility. tp is 5-year term premium. The left panel is for the first component; the right panel for the second component. Confidence bands are based on newey-west standard errors corrected for heteroscedasticity and first order auto-correlation.

Table 1: Change in variables due to change in orthogonal components

	(1) MOVE	(2) VIX	(3) MOVE	(4) VIX
Component 1	18.77***	5.026***		
	(21.21)	(21.21)		
Component 2			-18.77***	5.026***
			(-5.89)	(5.89)
Constant	94.44***	19.26***	94.44***	19.26***
	(85.65)	(65.24)	(45.14)	(34.38)
R^2	0.783	0.783	0.217	0.217
N	127	127	127	127

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

4.3 Joint identification of volatility shocks

Identification of shocks to bond and equity market volatilities is achieved by assuming that the two shocks are orthogonal and cause the maximum increase in the two variables over a one year horizon. Since our identification starts from a Cholesky decomposition (as explained in the previous section), the ordering of identification can still be relevant. Therefore, we explore two alternative identifications, similar in spirit to Caldara et al. (2016): in the first one, we identify the bond volatility shock first, whereas in the second one, we identify equity market volatility first.

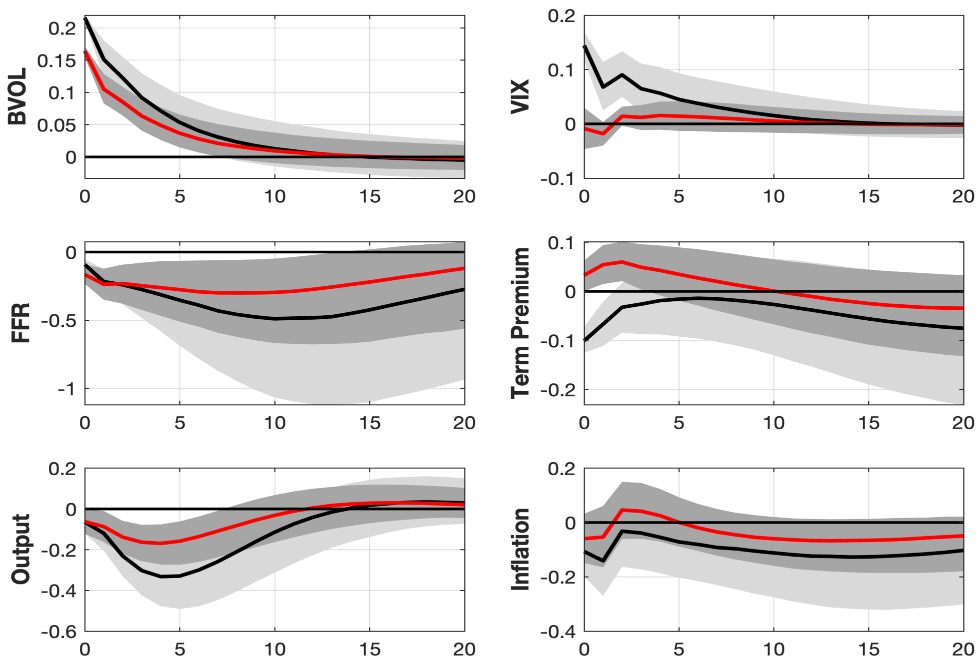


Figure 7: Response of model variables to a bond volatility (MOVE) shock in 2018Q1. Black line is for the bond volatility shock identified first and red line is for the bond volatility shock identified after the equity volatility shock. Both shocks are orthogonal by design and defined as the ones that lead to the maximum increase in the respective volatilities over four quarters. The term premium is based on Hordahl and Tristani (2014).

Figure 7 shows the responses of the model variables to a shock to bond volatility in 2018Q1 using both alternative identification schemes. The black lines correspond to the bond volatility shock identified first and the red lines to the bond volatility shock identified after the equity volatility shock. In both ordering, the increase in bond volatility leads to a decline in interest rate and output. However, Figure 7 shows that the ordering matters for the other variables. Specifically, when the bond volatility shock is identified as second, it does not have any significant effect on equity volatility and inflation. Most importantly, it increases the term premium. Hence, this ordering leads to a response of the term premium that is inconsistent with the prevailing literature and with the responses based on the orthogonal components presented above.

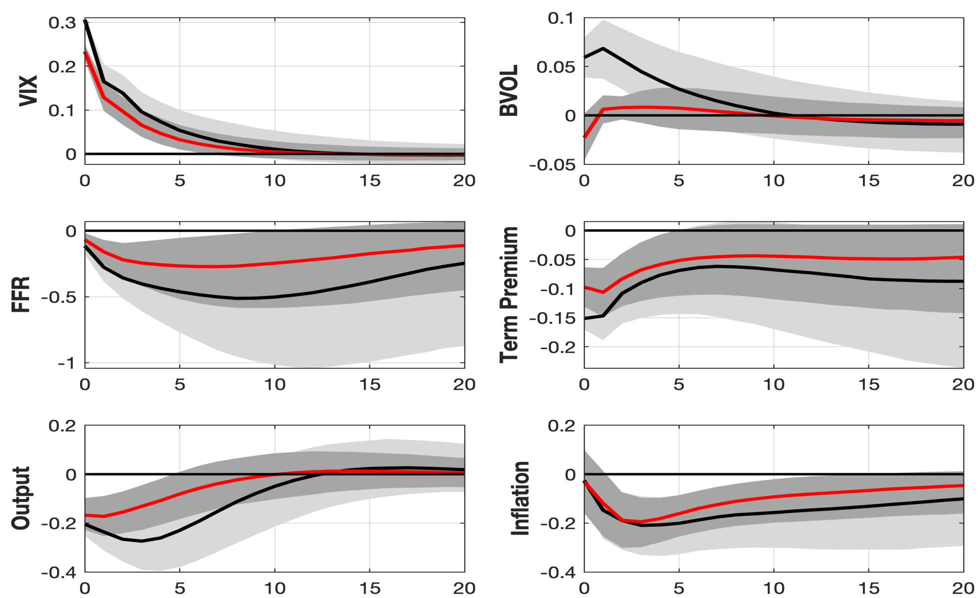


Figure 8: Response of model variables to an equity volatility (VIX) shock in 2018Q1. Black line is for the equity volatility shock identified first and red line is for the equity volatility shock identified after the bond volatility shock. Bond and equity market volatility shocks are orthogonal by design and defined as the shocks that lead to the maximum increase in the respective volatilities over four quarters. The term premium is based on Hordahl and Tristani (2014).

Figure 8 shows the responses to a shock to equity volatility in 2018Q1. The black lines correspond to the equity market volatility shock identified as the first shock, while the red lines correspond to the equity volatility shock identified as the second shock. Again, we can see that the ordering of the variables matters. Specifically, when the equity volatility shock is identified as the second shock, it does not have significant effect on bond volatility. Furthermore, irrespective of the ordering, equity volatility reduces the term premium. The effects on the policy interest rate, inflation and output remain similar across the two orderings. By contrast, the identification of equity volatility as the first shock gives us consistent results. If we identify this shock as the first shock, then it has significant spillover to bond volatility. If we do not control for this spillover as shown in Figure 4, then the bond volatility shock reflects the equity volatility shock, yielding a puzzling response of the term premium. Since equity volatility has a significant spillover to bond volatility, it cannot be the case that it is decreasing the term premium by decreasing risk in the bond market, something that can be inferred by looking at Figure 3. Therefore, other channels such as portfolio re-balancing from equities to bonds can explain this. This is also clear from comparing the responses of equity and bond market volatility indices in Figure 8. In what follows, we therefore identify the shock to equity volatility first and the shock to bond volatility second in all models.

4.4 Main findings

Figure 9 shows the responses to shocks to the VIX and MOVE indices in 2018Q1[16]. The black lines indicate the responses to an equity volatility shock while the red lines indicate those to a bond volatility shock. The equity volatility shock decreases the term premium while the bond volatility shock increases it[17]. Moreover, the equity volatility shock is

[16]We implement the identification using a time varying parameter VAR model containing the term premium. The responses presented here are for the first quarter of 2001. The responses for other time periods (2001Q1, 2006Q1, 2010Q1, and 2013Q1) are presented in an online appendix and show similar results.

[17]The term premium used in this paper is an estimate obtained from another study and hence measures with an error. We do not address the measurement error issue in this paper. The error bands for the term premium are likely to be influenced by the measurement error. Our main point is about the distinct responses of the term premium to shocks to bond and equity volatilities.

significantly more contractionary and also leads to a significant decline in inflation. Both shocks leads to a decline in the policy rate.

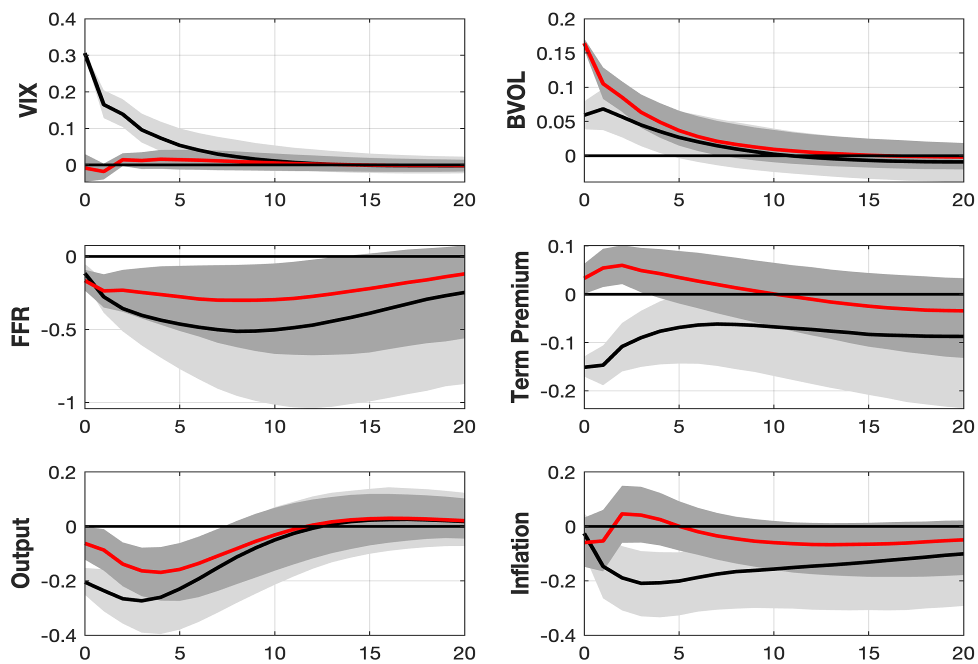


Figure 9: Response of model variables to bond (red) and equity (black) volatility shock in 2018Q1. The bond and equity market volatility shocks are orthogonal by design and identified as the shocks that lead to the maximum increase in the respective volatilities over four quarters. The term premium is based on Hordahl and Tristani (2014).

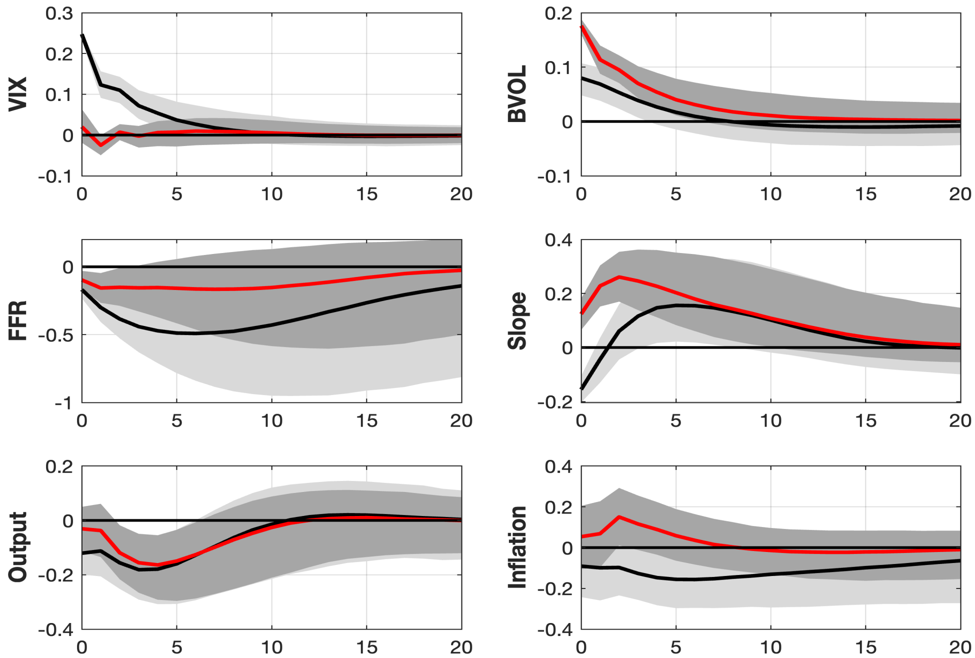


Figure 10: Response of model variables to bond (red) and equity (black) volatility shocks in 2018Q1. Bond and equity market volatility shocks are orthogonal by design and identified as the shocks that lead to maximum increase in the respective volatilities over four quarters. Slope is the difference between the 10-year government bond yield and the three month treasury yield. The term premium is based on Hordahl and Tristani (2014).

Figure 10 displays the responses to equity and bond market volatility shocks in 2018Q1 from a model in which we replace term premium with the yield curve slope. The equity volatility shock decreases the slope on impact, while the bond volatility shock increases it, but in the medium run the effect of these two shocks on the slope are very similar. Also, both shocks decrease output by an economically significant amount.

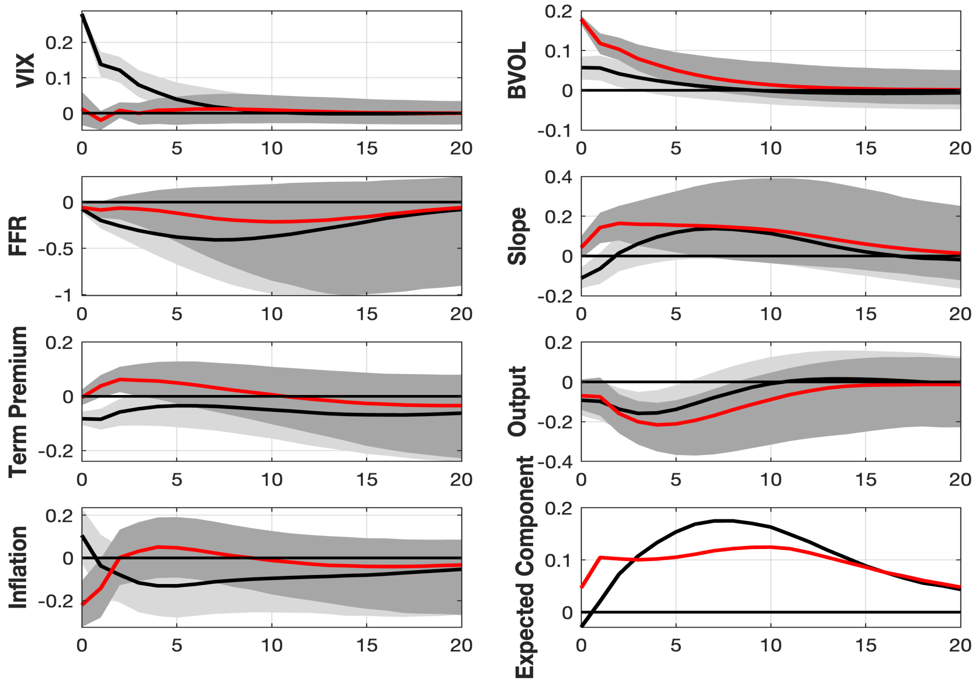


Figure 11: Response of model variables to bond (red) and equity (black) volatility shocks in 2018Q1. Bond and equity market volatility shocks are orthogonal by design and identified as the shocks that lead to the maximum increase in the respective volatilities over four quarters. Slope is the difference between the 10-year government bond yield and the three month treasury yield. Expected component is the difference between the average of expected future policy rate and the current rate. The term premium is based on Hordahl and Tristani (2014).

Figure 11 shows the responses of a model that includes both the term premium and the slope. The bond volatility shock increases the slope on impact, while the equity volatility shock decreases it. However, in the medium run the effects of both shocks is to make the yield curve steeper, although for different reasons. In response to a bond volatility shock, a significant part of the yield curve steepening reflects a widening of the term premium. By contrast, in response to the equity volatility shock, the term premium narrows. In this case, a large part of the yield curve steepening in the medium run reflects a change in the expected interest rate component. This is because the short term rates falls sharply and future short term rates do not change proportionately. Finally, both shocks lead to a drop in output.

4.5 Monetary policy shock

To identify the monetary policy shock, one can try to use the same approach as in the previous sections. However, we show in this section that this approach yields implausible results. Figure 12 refers to the case in which we keep the VIX and the MOVE indices as the first and second variables respectively, adding the shadow interest rate as the third variable. In response to a positive interest rate shock (a tightening of monetary policy), both inflation and output increase. Gertler and Karadi (2015) find similar behavior of prices using a Cholesky decomposition. Hence, we choose a different identification strategy. https://www.overleaf.com/project/61568ff2227105b325c84ca0

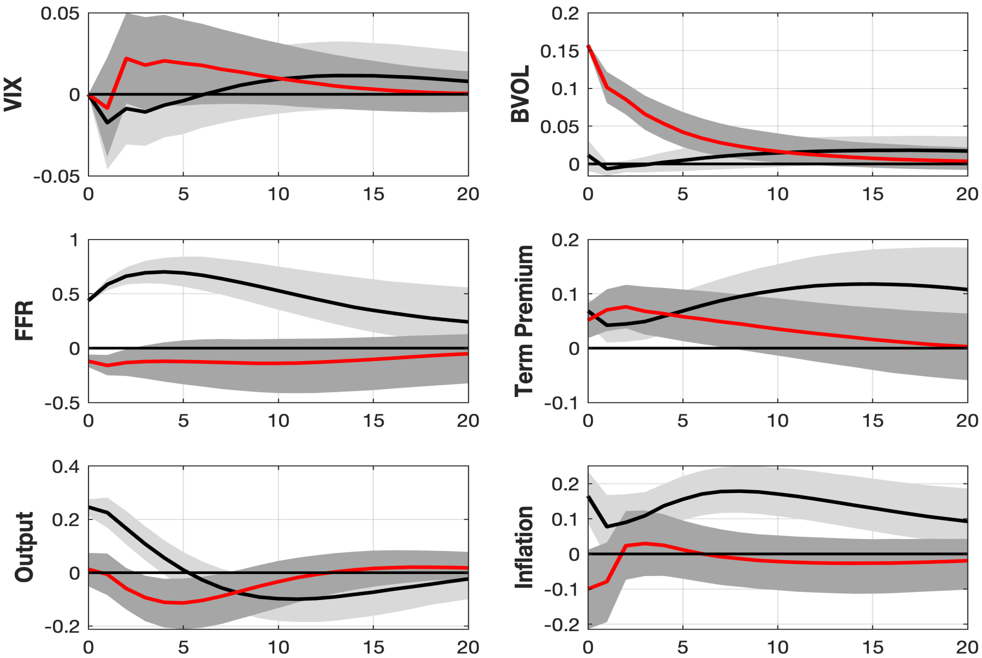


Figure 12: Response of model variables to bond volatility (red) and shadow rate (black) shocks in 2018Q1. Bond market volatility and shadow rate shocks are orthogonal by design and identified as the shocks that lead to the maximum increase in bond volatility and the shadow rate over four quarters. The term premium is based on Hordahl and Tristani (2014).

We identify the shock to monetary policy through the Proxy SVAR method (Mertens and Ravn (2013)), which is similar to an instrumental variable regression. Let the relationship between structural and reduced form shocks is given by:

$$A\nu_t = u_t$$

Suppose we have a set of proxies given by m_t $(k \times 1)$. Let us bifurcate $\nu_t = \left[\nu'_{1t_{k\times 1}}, \nu'_{2t_{(n-k)\times 1}}\right]'$

For identification, we need three conditions:

$$E\left[m_t \nu'_{1t_{k\times 1}}\right] = \Phi_{k\times k}$$

$$E\left[m_t \nu'_{2t_{(n-k)\times 1}}\right] = 0$$

$$E\left[m_t X'_t\right] = 0$$

where $X_t = \left[Y'_{t-1}, Y'_{t-2}, \ldots.., Y'_{t-p}\right]'$. The first and second conditions are similar to the relevance and exclusion restrictions in an instrumental variable estimation, respectively. The third constraint is not necessary: even if some proxies $\tilde{m}_t$ are correlated with the history of dependent variable, one can obtain m_t by projecting $\tilde{m}_t$ on X_t. These assumptions on m_t translate into linear restrictions on A. One can solve for A using these linear restrictions and thereafter the impulse responses can be obtained using:

$$R(L) = C(L)A$$

In our case, we use one instrument for one structural shock, thereby obtaining exact identification. Specifically, we use a series of high-frequency monetary policy surprises series - the unexpected changes in the 2-year US Treasury yield within a tight window around FOMC announcements - based on Kuttner (2001), Gurkaynak et al. (2005) and Gertler and Karadi (2015). The key identifying assumption is that news about the economy on the FOMC day does not affect the policy choice; only information available the previous day is relevant. Based on this assumption, these instruments are orthogonal to within-period movements in economic and financial variables and affect the economy only through interest rate movements. [18]. Since the instrument variable is only available after 2004, the estimation is conducted over a shorter sample period, 2004Q4-2018Q4.

[18] These high frequency instruments can also capture shocks to the forward guidance, see Gurkaynak et al. (2005)

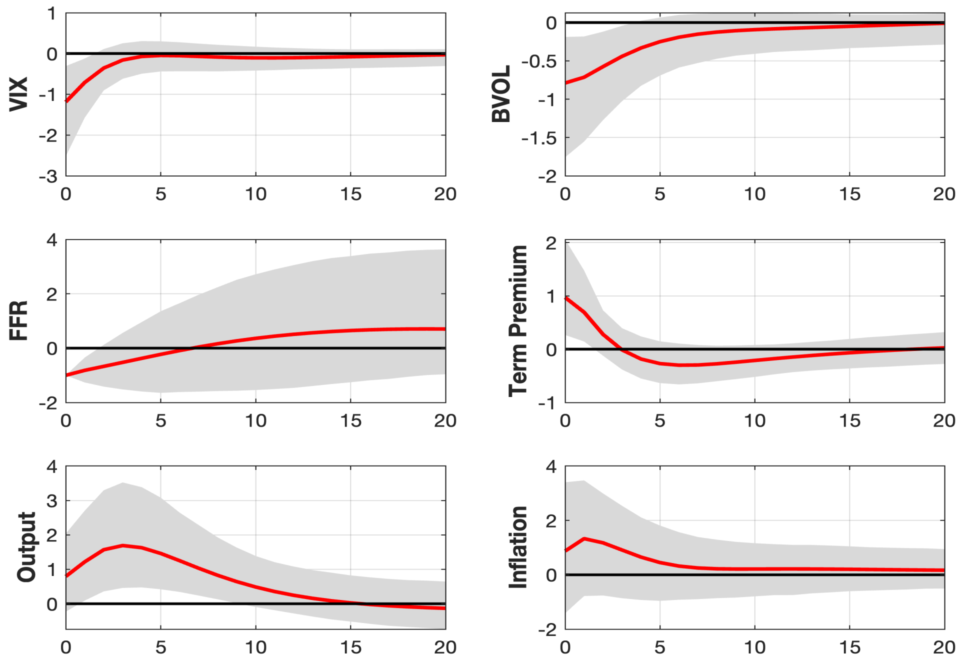


Figure 13: Response of model variables to a shadow rate shock identified using Proxy SVAR based on Gertler Karadi (2015) type instrument. The term premium is based on Hordahl and Tristani (2014).

Figure 13 displays the responses to an expansionary monetary policy shock (a reduction in the shadow rate). The shock leads to a reduction in both equity and bond market volatilities and an expansion in output. We obtain roughly similar results if we replace the VIX with a measure of the variance risk premium, obtained by subtracting a measure of the conditional variance obtained from a GARCH(1,1) model, which is the simplest and most robust model within the family of volatility models. These findings confirm those in Bekaert et al. (2013), whose analysis focuses only on the VIX: a channel through which an expansionary monetary policy leads to an expansion in output is by reducing investors' risk aversion. In our case, despite a drop in bond volatility, the term premium also increases temporarily as the reduction in equity volatility dominates.

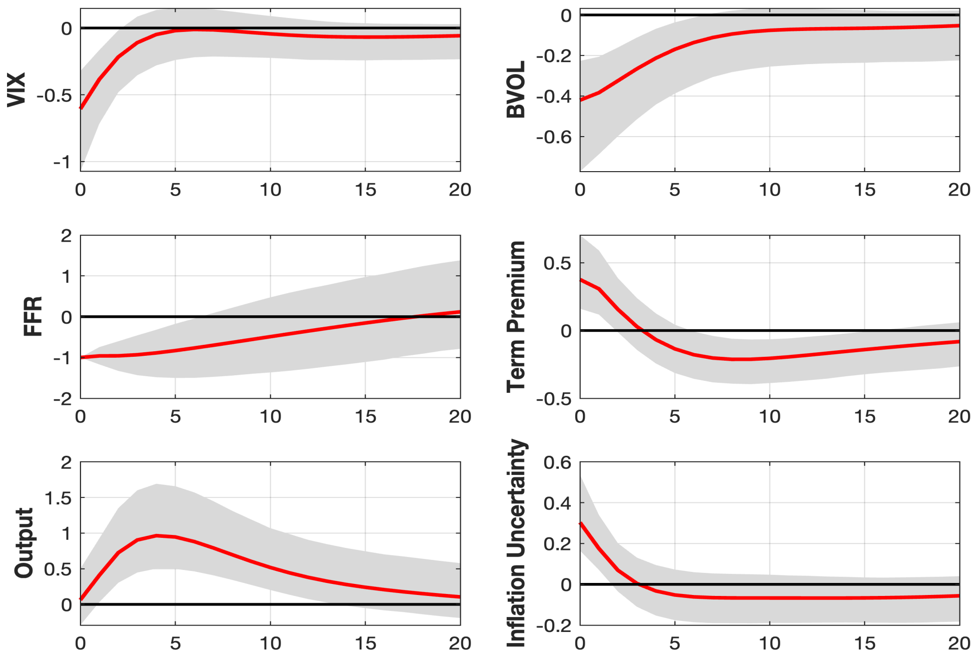


Figure 14: Response of model variables to a shadow rate shock identified using Proxy SVAR based on Gertler Karadi (2015) type instrument.

We also estimate another model in which we replace inflation with a measure of inflation uncertainty obtained from Binder (2017). As shown in Figure 14, the response of all variables is very similar to those in Figure 13, although inflation uncertainty increases temporarily. Hence, the short-lived widening of the term premium appears to be consistent with an increase in inflation uncertainty (eg Wright (2011)) as well as a shift towards equities as the economy expands.

4.6 Robustness

4.6.1 Alternative measures of the term premium

So far, all the results presented in this paper are based on the estimate of the term premium by Hordahl and Tristani (2014) (HT). This section examines the robustness of these results to two popular alternative measures of the term premium: those based on Kim and Wright (2005) (KW) and Adrian, Crump and Moench (2013) (ACM), respectively. Although obtained from models that have a very similar theoretical structure, estimates can differ significantly at times, presumably owing to the estimation being based on a different set of empirical variables.[19].

[19] https://www.federalreserve.gov/econres/notes/feds-notes/robustness-of-long-maturity-term-premium-estimates-20170403.htm

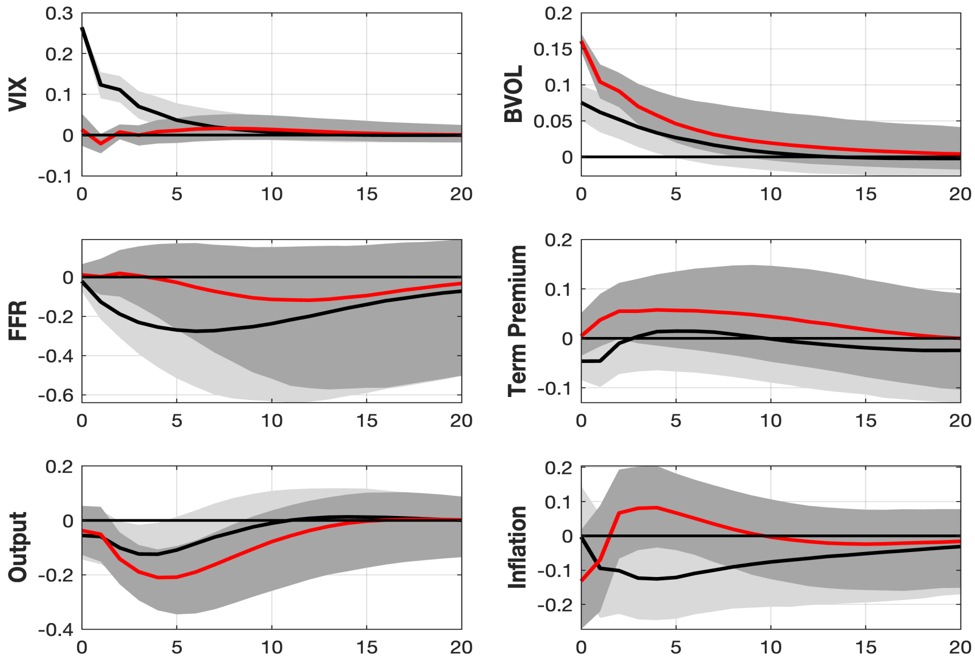


Figure 15: Response of model variables to bond (red) and equity (black) volatility shocks in 2018Q1. Bond and equity market volatility shocks are orthogonal by design and identified as the shocks that lead to the maximum increase in the respective volatilities over four quarters. The term premium is based on Kim and Wright (2005).

Figure 15 reports the responses to equity and bond volatility shocks in 2018Q1 based on the KW term premium estimate.[20] The responses are similar as in the baseline case. However, the shock to the VIX leads to a shorter lived decline in the term premium. Another different is that the shock to bond volatility is more contractionary than a shock to the VIX, which is presumably related to milder interest rate response.

[20]We implement the identification using a time varying parameter VAR. The responses presented here are for first quarter of 2001 from a model containing the term premium estimate of Kim and Wright (2005). The responses for other time periods (2001Q1, 2006Q1, 2010Q1, and 2013Q1) are similar and are available in an online appendix.

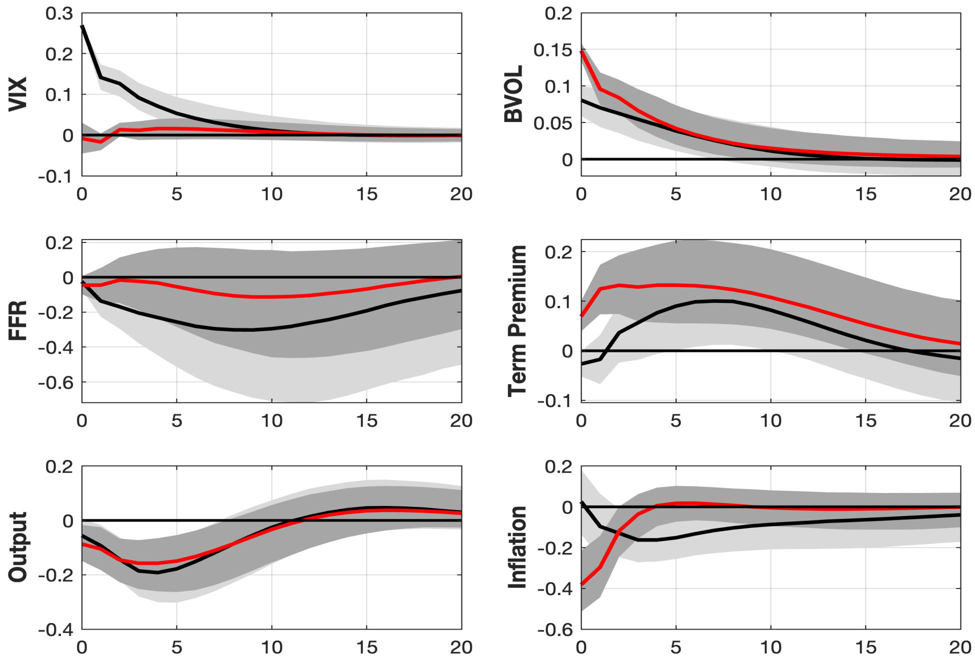
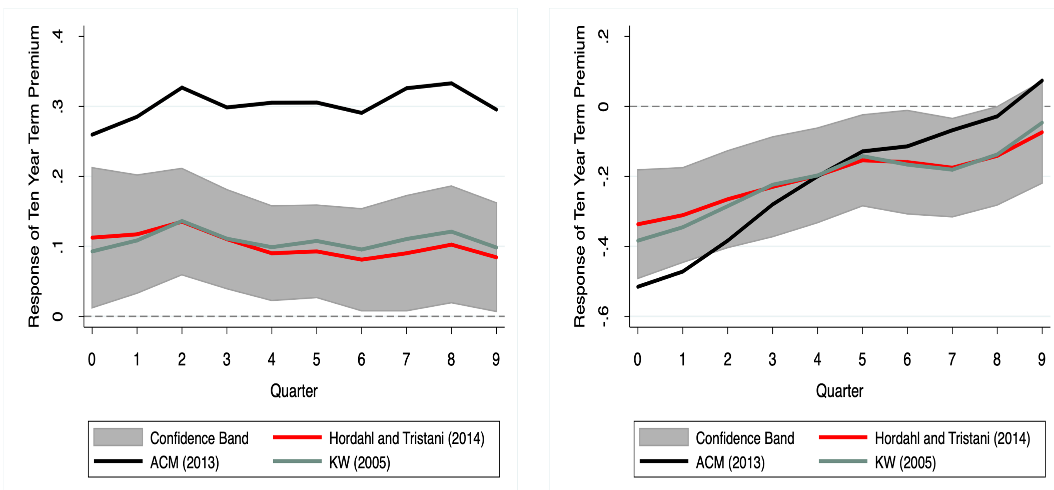


Figure 16: Response of model variables to bond (red) and equity (black) volatility shocks in 2018Q1. Bond and equity market volatility shocks are orthogonal by design and identified as the shocks that lead to the maximum increase in the respective volatilities over four quarters. The term premium is based on Adrian, Crump and Moench (2013).

Figure 16 displays the responses to equity and bond market volatility shocks in 2018Q1 based on the ACM term premium estimate. The responses are qualitatively similar but differ somewhat quantitatively. In particular, the shock to bond volatility leads to a persistent increase in the term premium; and the shock to equity volatility leads to a decline in the term premium only on impact, followed by an increase above baseline several quarters later. Indeed, after several quarters, both shocks lead to an increase in the term premium by a similar magnitude. This latter result appears in contradiction with the argument made in Section 4.2. However, as shown in Figure 17, the response of the ACM term premium to first orthogonal component of volatilities is substantially larger than that of the other measures of the term premium. And, starting from quarter

3, the absolute magnitude of the response to the first component is larger than the absolute magnitude of the response to the second component. This is only possible if both shocks increase the term premium from quarter 3 onward. As mentioned earlier, if both shocks increase the term premium, then the effect of first component should be positive and larger in magnitude than the effect of the second component. This is exactly what happens in the case of the ACM term premium in Figure 14. By contrast, in the case of the KM term premium, the response to the orthogonal components is very similar to those of the HT term premium. Although the response of term premium based on KM turns positive in Figure 13 from quarter 3 onward, these responses are not significant. Therefore, we can conclude that differences in the responses reflect differences in the estimation of the term premium and not in the identification scheme.



(a) Response of the term premium to the first orthogonal component

(b) Response of the term premium to the second orthogonal component

Figure 17: β_1^j from $tp_{t+j} = \beta_0 + \beta_1^j pc_k + \beta_2 \times$ Output Gap$_t + \beta_3 \times$ Inflation$_t + \beta_4 \times$ Federal Funds Rate$_t + \epsilon_t$ for$k = 1, 2 j = 0, 1, ..., 10$ where pc_k for $k = 1, 2$ are two orthogonal components obtained from bond volatility and equity market volatilities. tp is the 10-year term premium. Left panel corresponds to the first component and the right panel to the second component. Confidence bands are based on newey-west standard errors corrected for heteroscedasticity and first order auto-correlation.

4.6.2 Inclusion of monetary policy uncertainty

Figure 18 shows the responses to equity and bond volatility shocks in 2018Q1 from a model that includes a measures of monetary policy uncertainty (MPU)[21]. Even with this variable, the shock to bond volatility continues to increase the term premium, while the shock to equity volatility reduces it. The responses of other variables are also very similar to the ones reported before, except for a statistically insignificant response of the policy rate.

[21]We use MPU index based on ten news papers which is available at https://www.policyuncertainty.com/bbd_monetary.html.

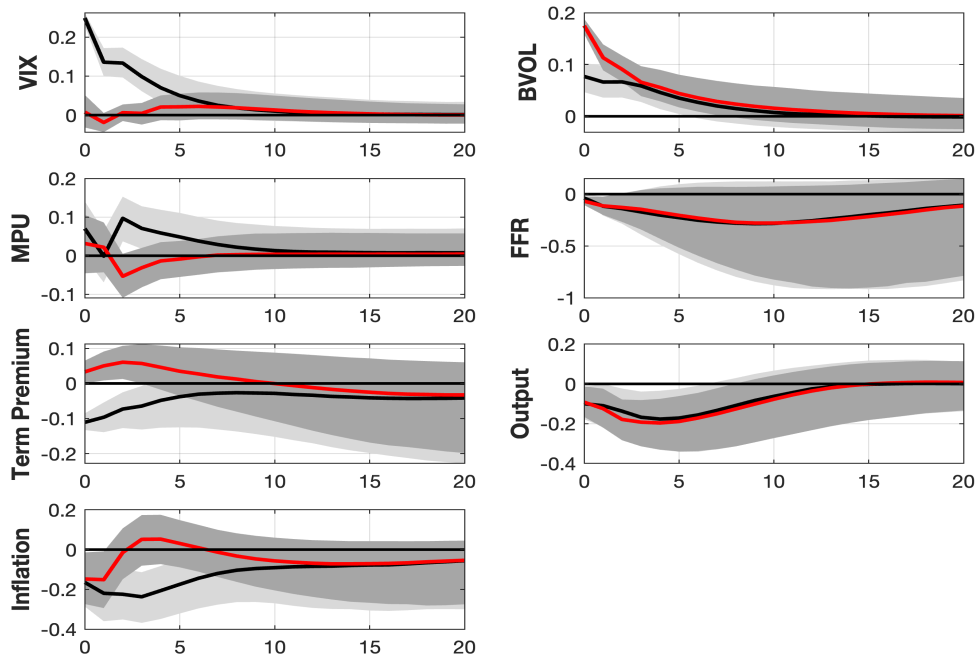


Figure 18: Response of model variables due to bond (red) and equity (black) volatility shock in 2018Q1. Bond and equity market volatility shocks are the shocks which lead to maximum increase in these volatilities over a year due to four quarter consecutive positive changes. These two shocks are orthogonal by design. Term Premium is based on Hordahl and Tristani (2014). Monetary policy uncertainty is based on 10 major US newspapers.

4.6.3 Monetary policy shock and five-year term premium

Figures 19 shows the responses to a shock to the federal fund shadow rate for a model that includes an estimate of the five-year term premium instead of the ten-year term premium. In this case, the results are similar except for the fact that the increase in the term premium is smaller. This suggests that an expansionary monetary policy shock leads to an increase in the term premium across a range of maturities but, intuitively, the size of the effect is related to the maturity.

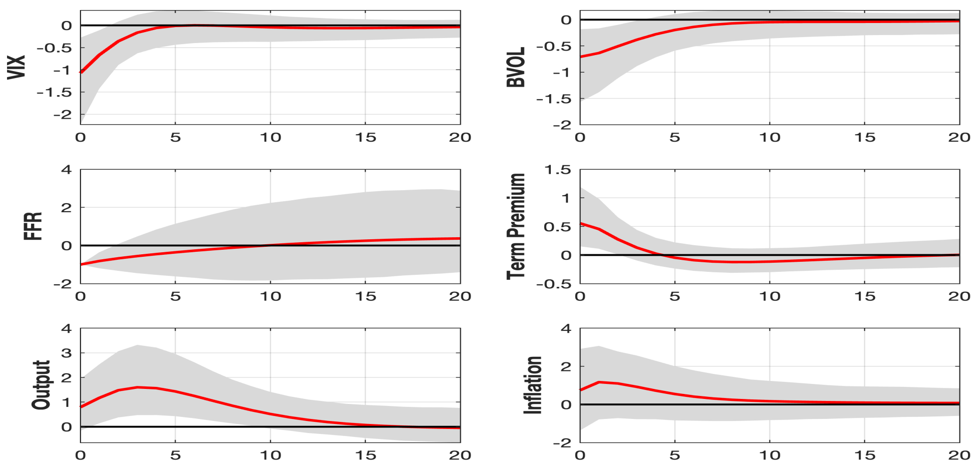


Figure 19: Response of model variables due to a shadow interest rate shock identified using Proxy SVAR based on Gertler & Karadi (2015) type instrument. The term Premium is based on Hordahl and Tristani (2014).

Figure 20 reports the same exercise except for the fact that a measure of inflation uncertainty replaces inflation. Again, the responses are very similar.

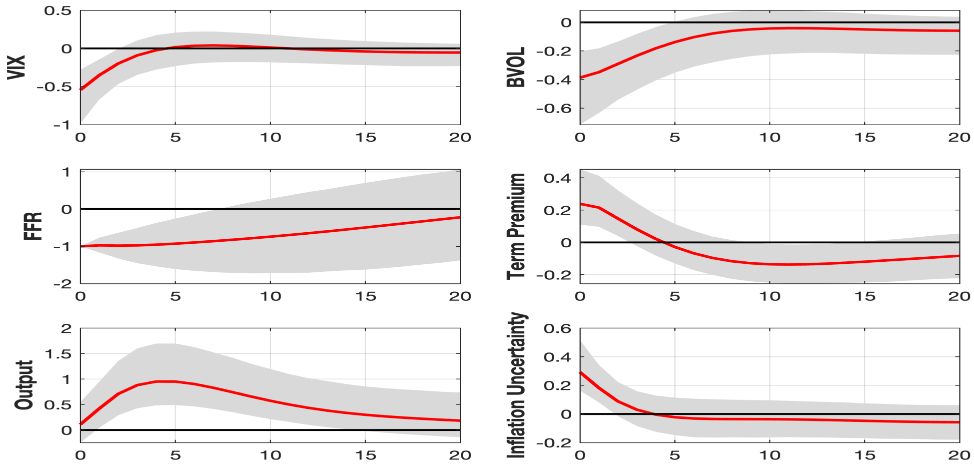


Figure 20: Response of model variables due to shadow rate shock identified using Proxy SVAR based on Gertler & Karadi (2015) type instrument. Term Premium is based on Hordahl and Tristani (2014).

4.6.4 Shock to asset purchases

As a further test of robustness, we consider the role of central bank asset purchases explicitly in the model, instead of capturing their effects through changes in the shadow rate. Since November 2008, the Federal Reserve has carried out four rounds of asset purchases or quantitative easing (QE). Central bank asset purchases may reduce investors' perception of macroeconomic risk and uncertainty and/or improve their risk tolerance, stabilising market volatility and long-term interest rate.[22]

We base the identification of the QE shock on the forecast error variance decomposition over a period of twenty quarters.[23] Thus, the QE shock is the one that explains the largest forecast error variance in the growth of Federal Reserve's holdings of treasury securities over twenty quarters. As shown in Figure 21, our identification is able to capture

[22]See eg Borio and Disyatat (2010) for a discussion of QE and other unconventional monetary policy measures.

[23]An online appendix provides the details of this estimation procedure based on Kurmann and Otrok (2013)).

the QE announcements post-crisis, especially the continuation of QE after 2013 (Dedola et al. (2021)).

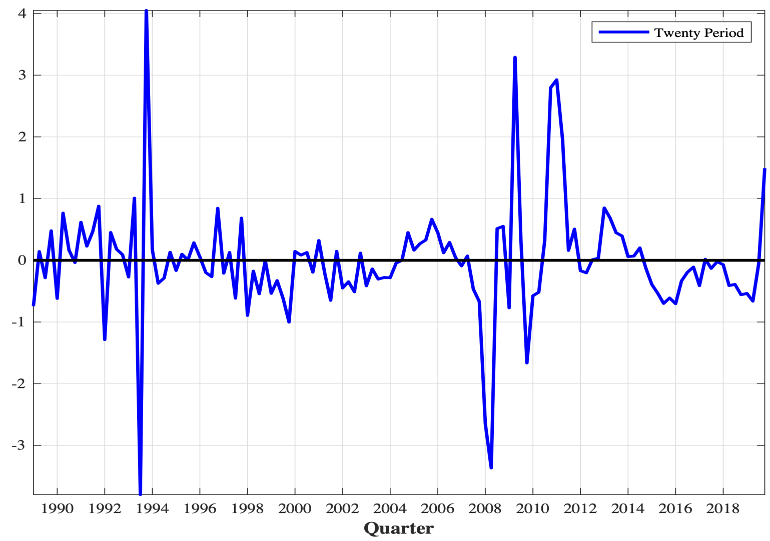


Figure 21: Asset purchase shock identified using max share identification. Asset purchase shock is the shock explaining maximum forecast error variance of federal reserve treasury holdings for twenty quarters.

Figure 22 reports the responses to a QE shock. The shock is very sharp and persists for less than or equals to a year. Interestingly, this shock has strong effects on output and inflation (although the inflation response is negative on impact). Debortoli et al. (2020) find that asset purchase shocks are as effective as interest rate shocks in influencing real activities. On the other hand, results obtained in Eggertsson and Woodford (2003) and Ikeda et al. (2020) suggest that asset purchase shocks are likely to be less effective in comparison to interest rate shocks. Our results lean towards the findings in Debortoli et al. (2020).

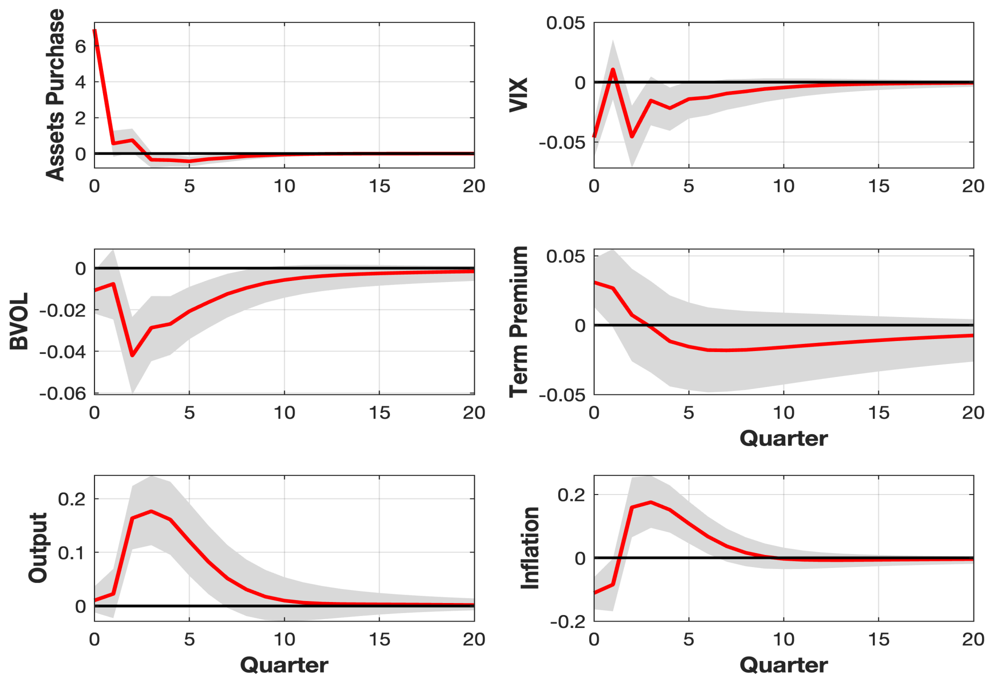


Figure 22: Response of model variables due to asset purchase (QE) shock identified using twenty quarters forecast error variance. Asset purchase shock is the shock explaining maximum forecast error variance of federal reserve treasury holdings for twenty quarters. Term Premium is based on Hordahl and Tristani (2014).

The QE shock leads to a significant decline in both bond and equity market volatilities, similarly to an expansionary interest rate shock. Hence, in terms of reducing the market risk, the asset purchase shock is also as effective as expansionary interest rate shock. The QE shock also increases the term premium, which is consistent with investors shifting their demand from fixed income towards riskier assets.

5 Conclusion

In this paper we have studied the interaction between the term premium, expected market volatility and monetary policy. This interaction received limited attention in the literature, and our paper addressed this gap. Recent studies have documented both the response and the influence of monetary policy on stock market volatility and how the latter influences leverage and economic activity (Bekaert et al., 2013; Bruno and Shin, 2015). Yet little analysis has been undertaken to understand the response and influence of monetary policy and both bond and equity market volatilities on the term premium, despite the fact that post-crisis unconventional monetary policy measures had the stated intent of directly reducing the term premium.

Our main finding is that both expected market volatilities have contractionary effects on economic activity and inflation, which tend to be associated with a loosening of monetary policy. Yet, the response of the term premium differs depending on the type of shock. A shock to the VIX normally leads to a narrowing of the term premium, which can be interpreted as a shift of investors from riskier assets towards safer government securities. By contrast, a shock to the MOVE leads to a widening of the term premium. The fact that expected market volatilities are associated with a significant impact on macroeconomic variables suggest that future research should aim at incorporating the role of expected market volatilities into macroeconomic models.

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Online Appendix

A Supplementary Results

A.1 Market Volatilities and Term Premium: Time Varying Response

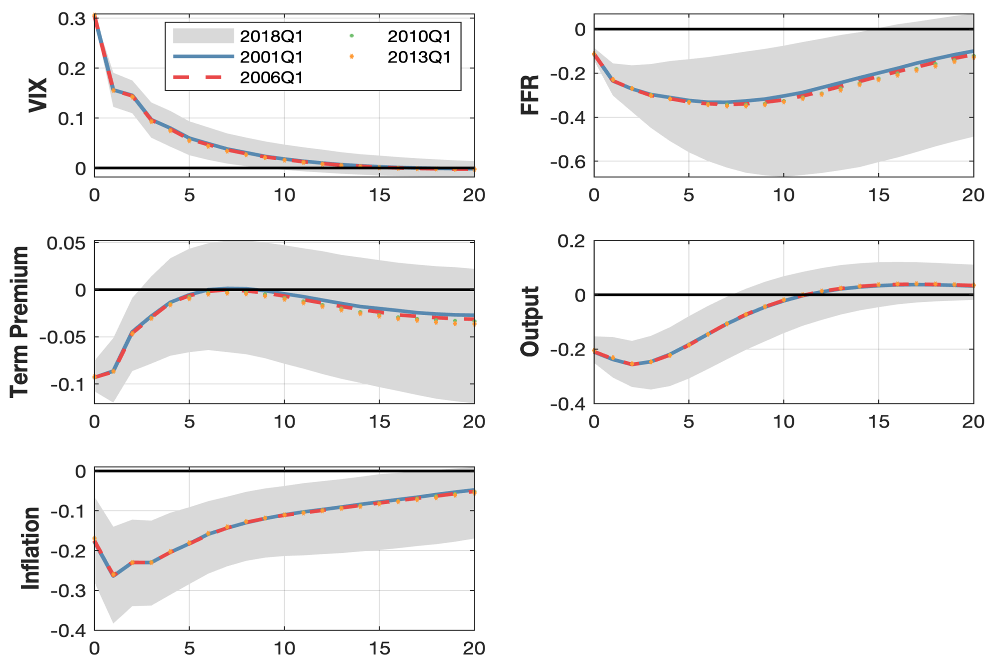

Figure A.1: Response of model variables due to equity volatility shock; term premium is based on Hordahl and Tristani (2014).

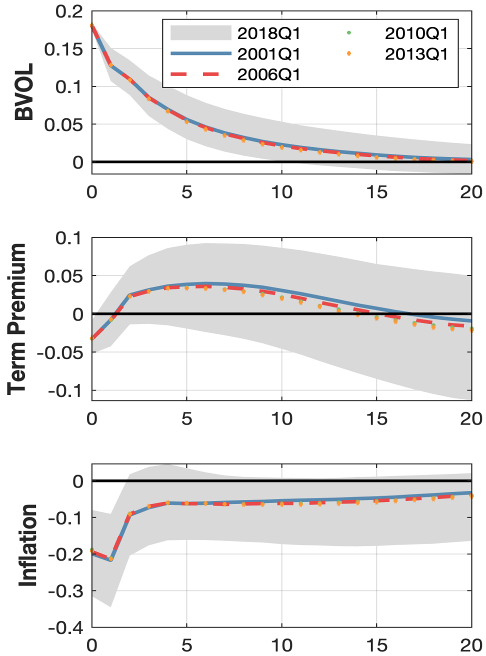

Figure A.2: Response of model variables due to bond volatility shock. Term Premium is based on Hordahl and Tristani (2014).

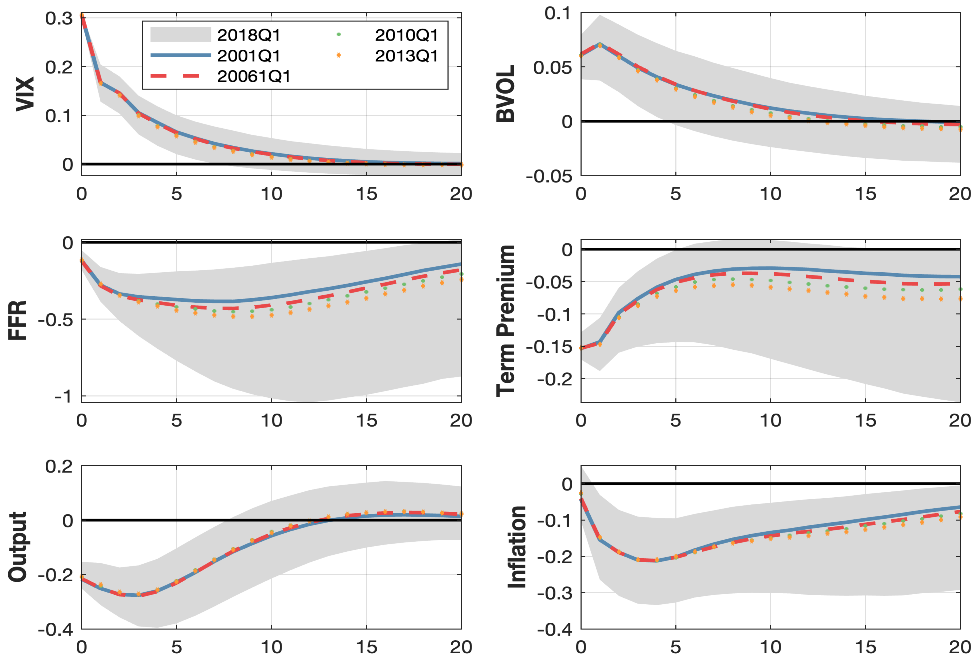

Figure A.3: Response of model variables due to equity volatility shock. Term Premium is based on Hordahl and Tristani (2014).

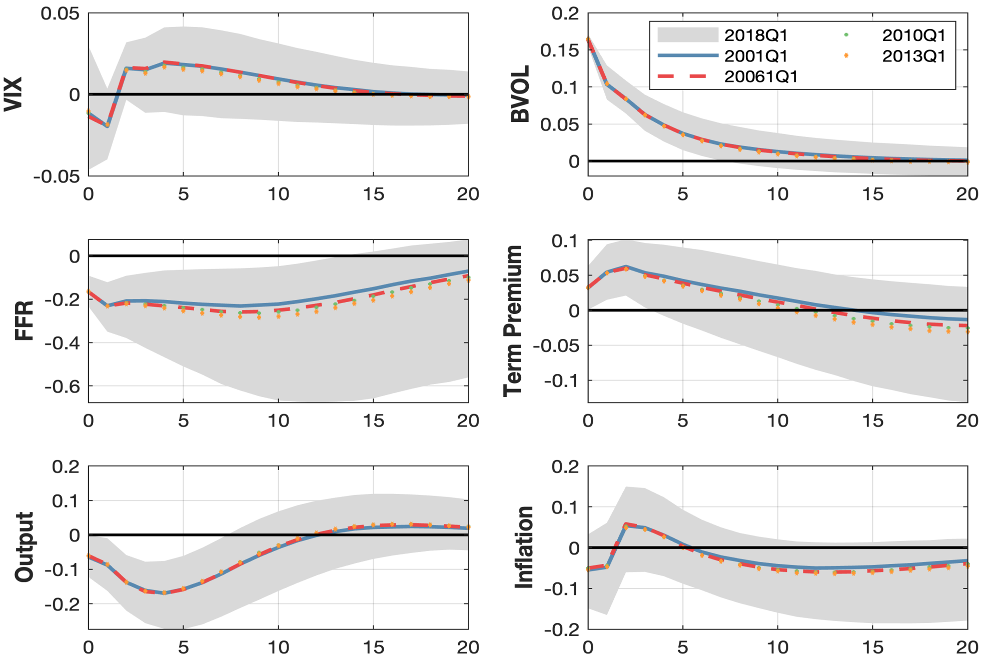

Figure A.4: Response of model variables due to bond volatility shock. Term Premium is based on Hordahl and Tristani (2014).

A.2 Market Volatilities and Slope: Time Varying Response

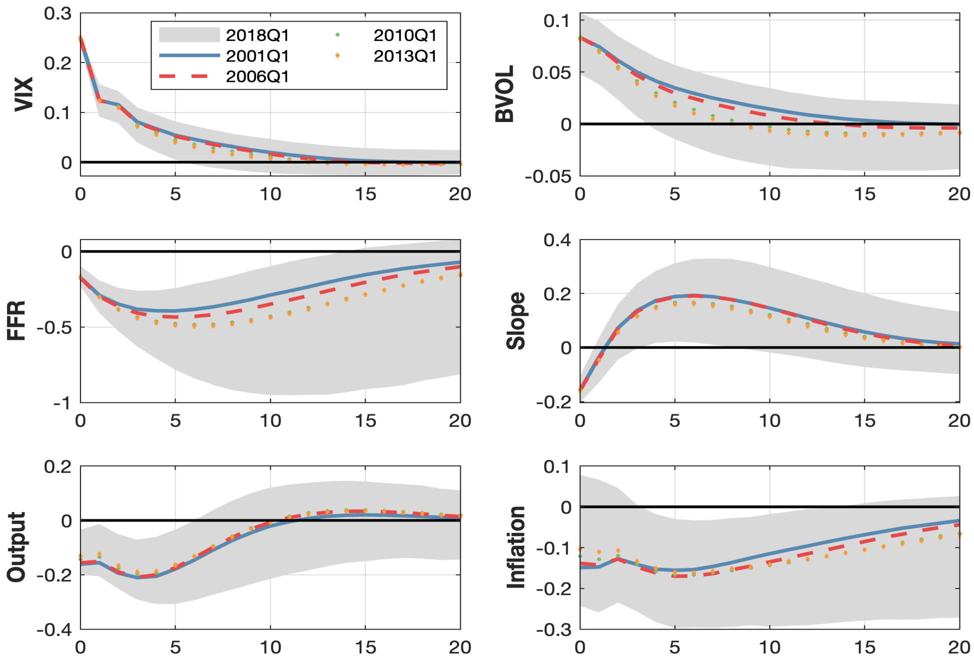

Figure A.5: Response of model variables due to equity market volatility shock. Slope is the difference between yield of 10 year government bond and three month treasury yield.

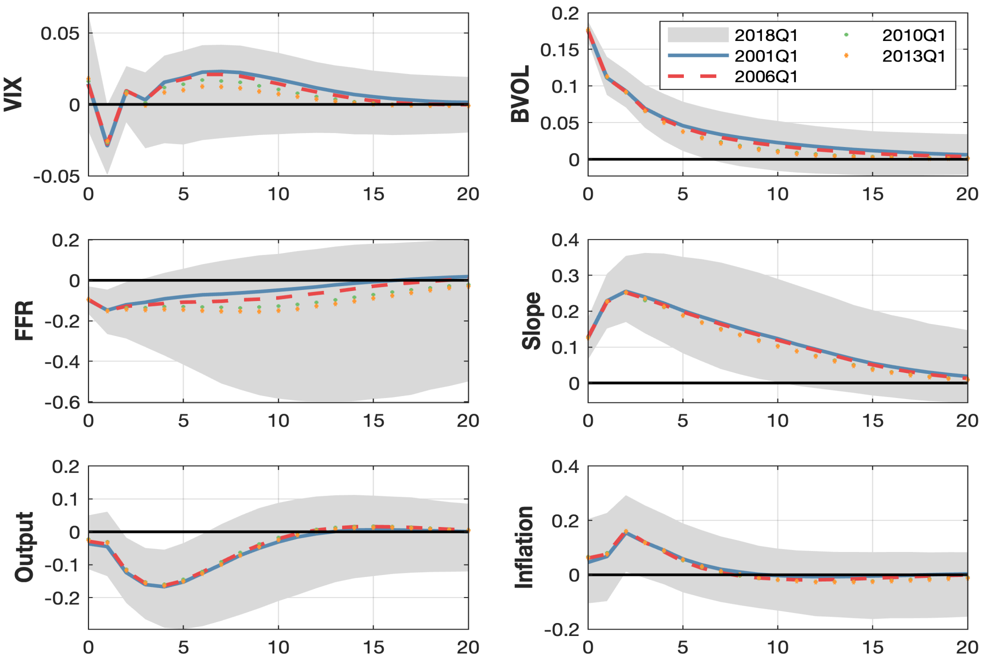

Figure A.6: Response of model variables due to bond volatility shock. Slope is the difference between yield of 10 year government bond and three month treasury yield.

A.3 Market Volatilities, Slope, Term Premium, and Expected Component: Time Varying Response

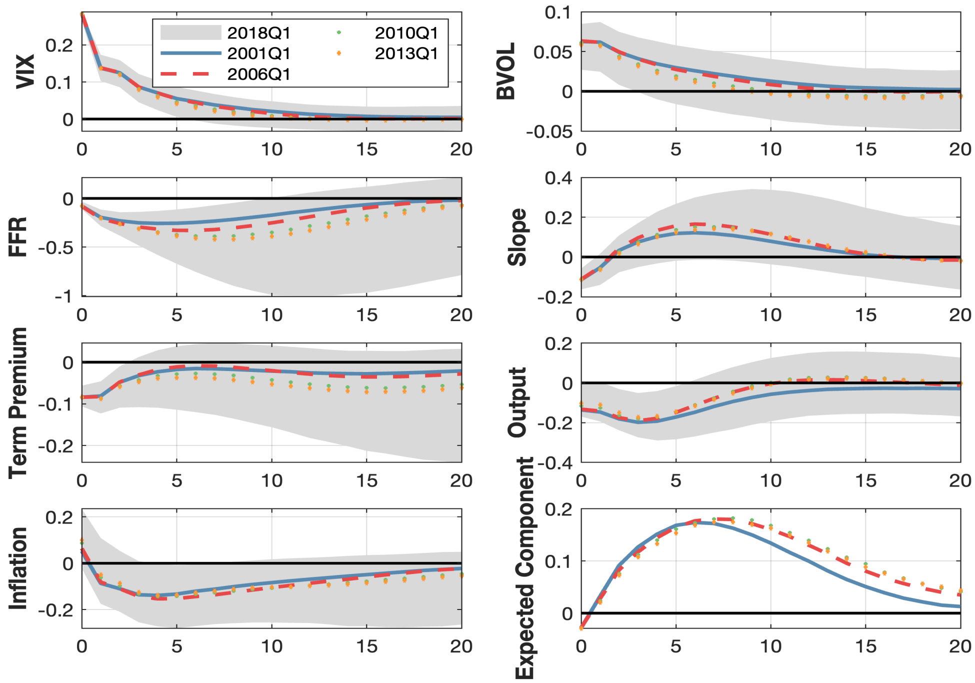

Figure A.7: Response of model variables due to equity volatility shock. Slope is the difference between yield of 10 year government bond and three month treasury yield. Expected component is difference between the average of expected future short term rate and current short term rate. Term Premium is based on Hordahl and Tristani (2014).

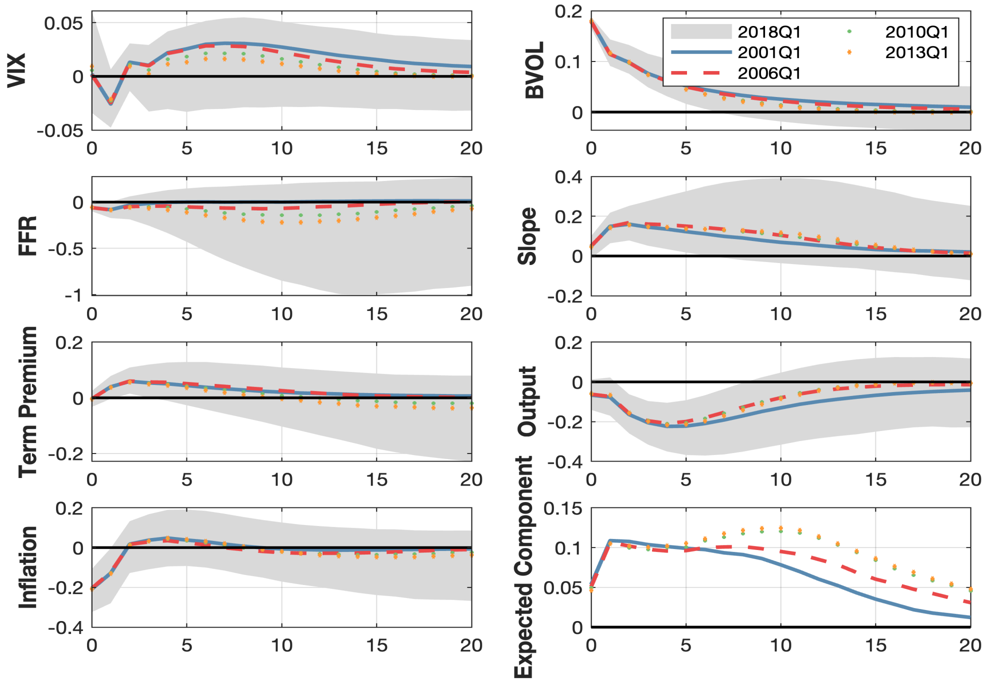

Figure A.8: Response of model variables due to bond volatility shock. Slope is the difference between yield of 10 year government bond and three month treasury yield. Expected component is difference between the average of expected future short term rate and current short term rate. Term Premium is based on Hordahl and Tristani (2014).

A.4 First and Second Moment Interest Rate Shock: Time Varying Response

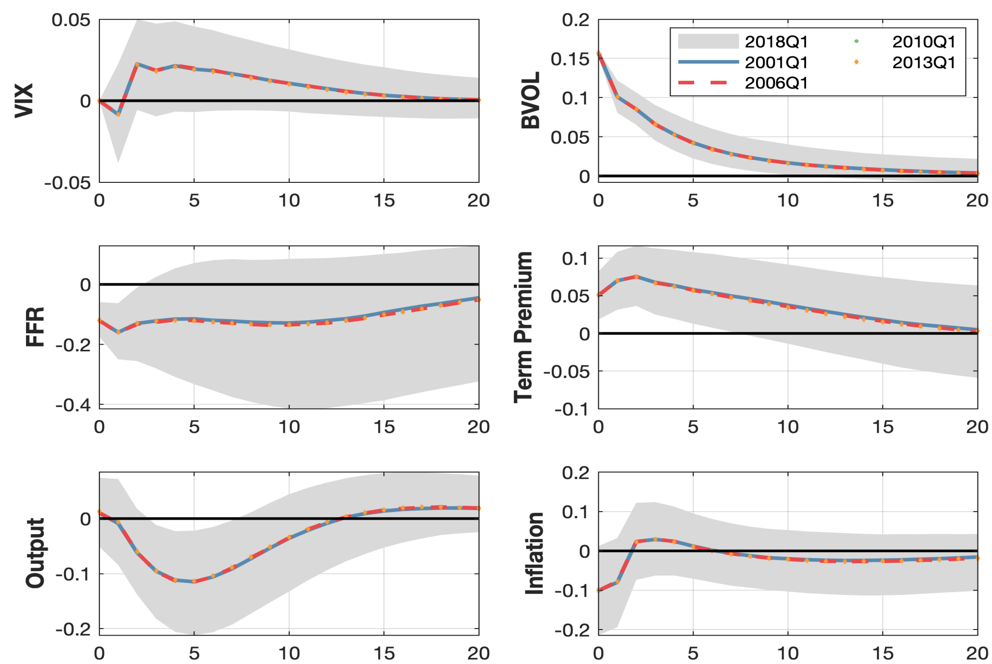

Figure A.9: Response of model variables due to bond volatility shock. Term Premium is based on Hordahl and Tristani (2014).

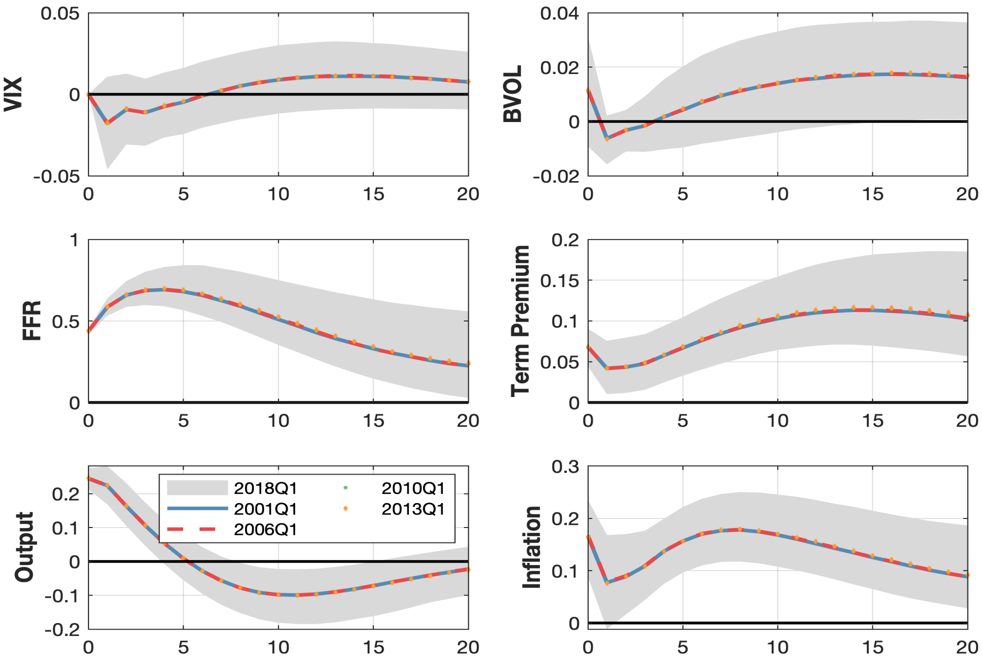

Figure A.10: Response of model variables due to shadow rate shock. Term Premium is based on Hordahl and Tristani (2014).

A.5 Market Volatilities and Alternative Measures of Term Premium: Time Varying Response

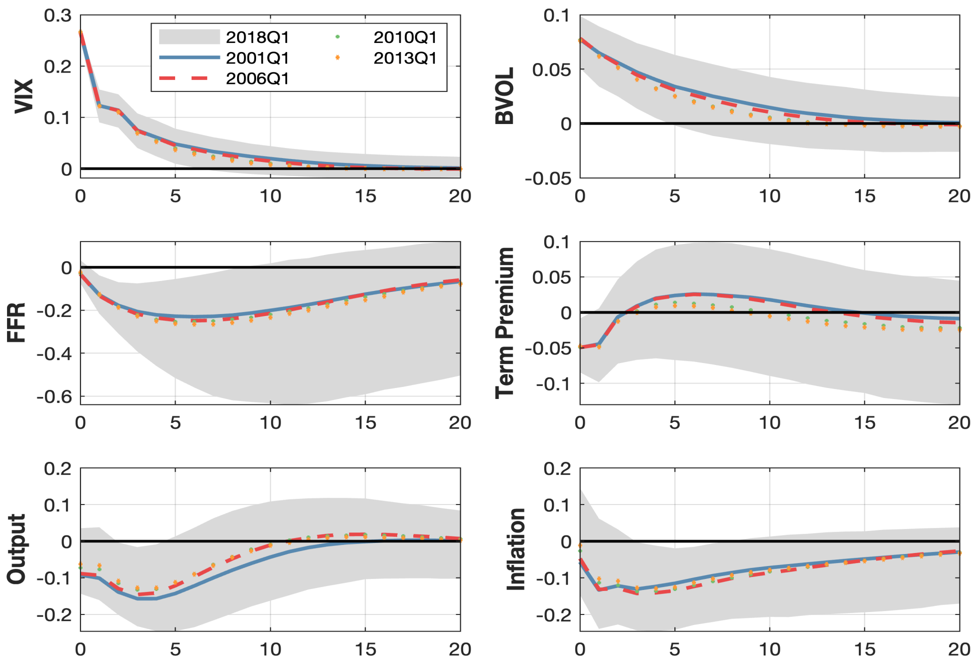

Figure A.11: Response of model variables due to equity volatility shock; Term Premium is based on Kim and Wright (2005).

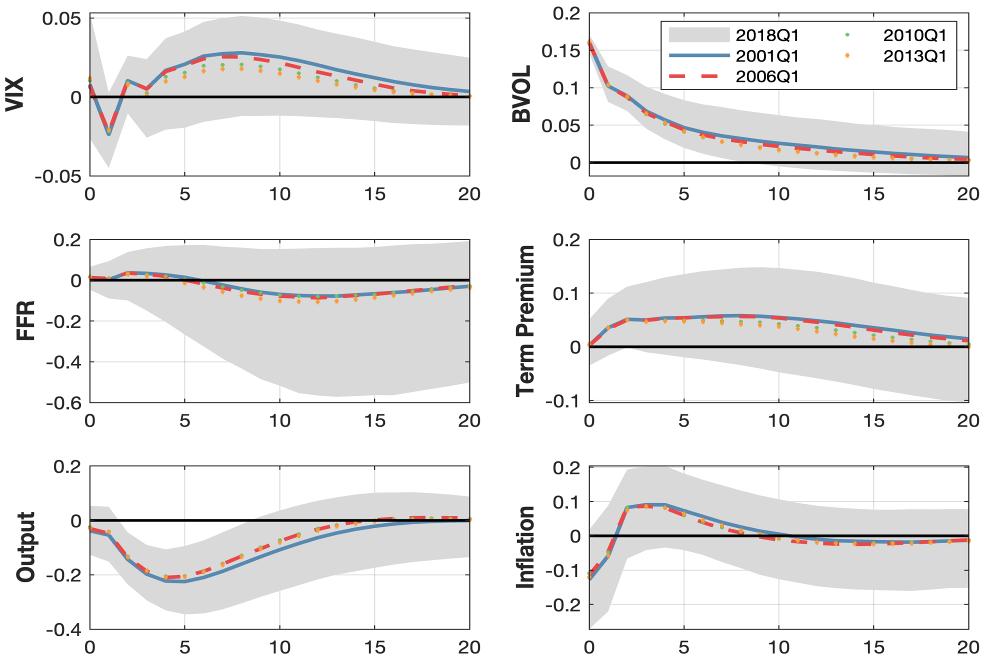

Figure A.12: Response of model variables due to bond volatility shock. Term Premium is based on Kim and Wright (2005).

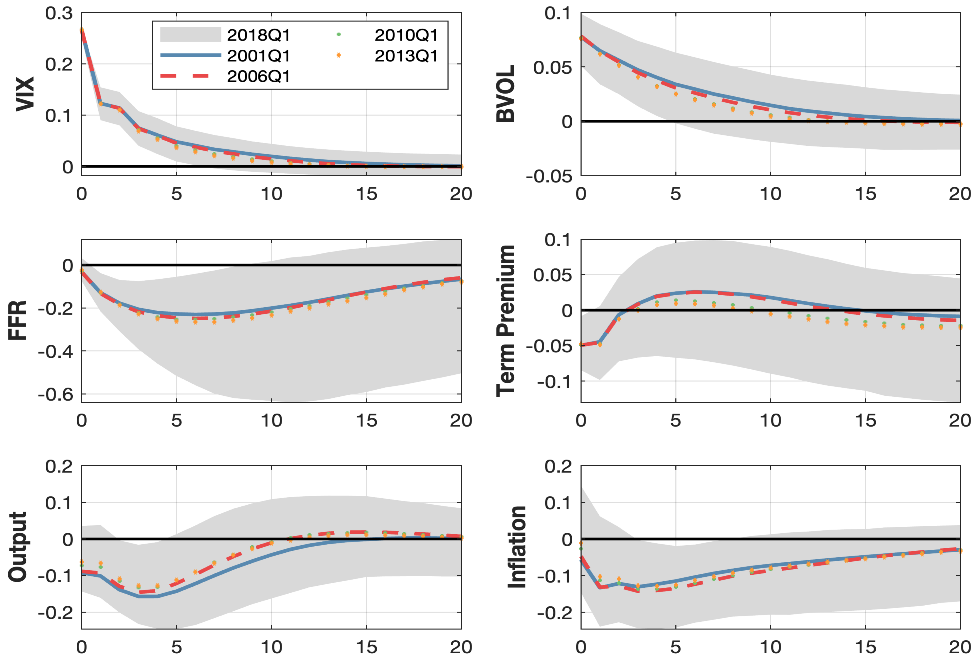

Figure A.13: Response of model variables due to equity volatility shock. Term Premium is based on Adrian, Crump and Moench (2013) (ACM).

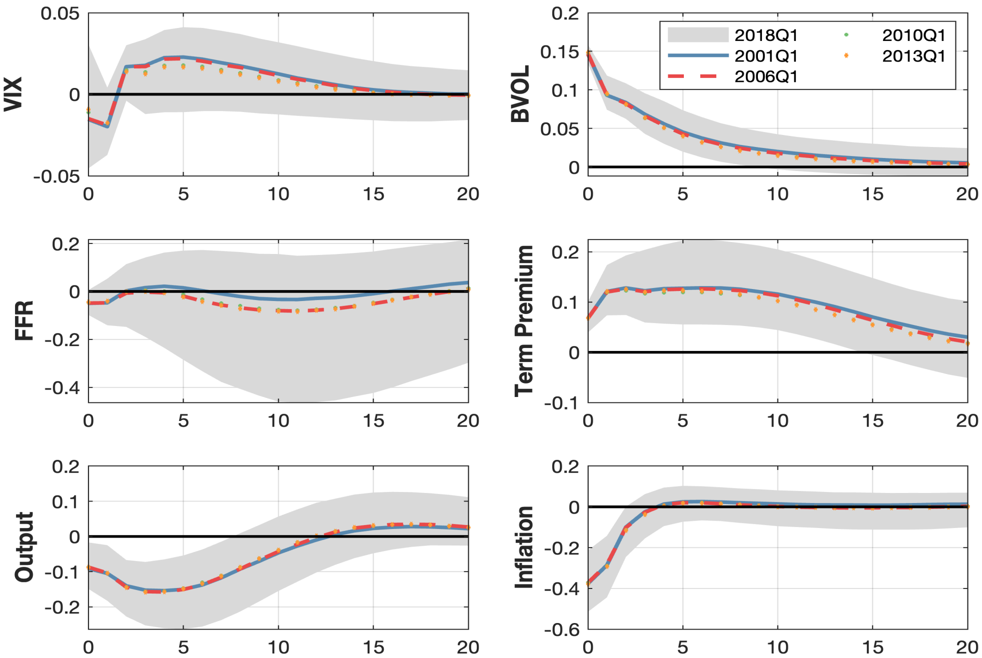

Figure A.14: Response of model variables due to bond volatility shock. Term Premium is based on Adrian, Crump and Moench (2013) (ACM).

A.6 Market Volatilities, Monetary Policy Uncertainty and Term Premium

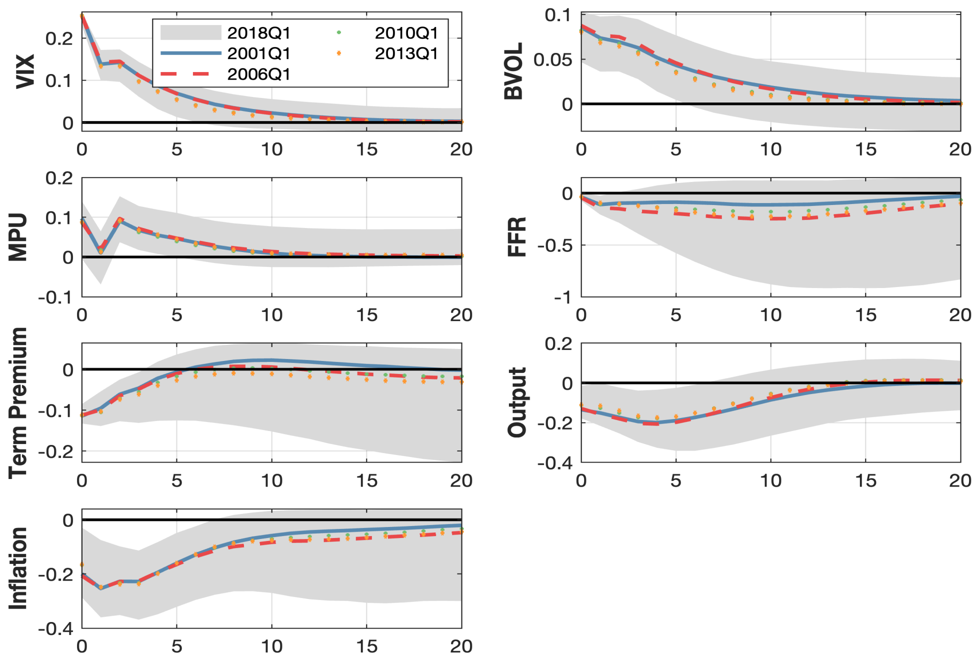

Figure A.15: Response of model variables due to equity (black) volatility shock. Term Premium is based on Hordahl and Tristani (2014). Monetary policy uncertainty is based on 10 major US newspapers.

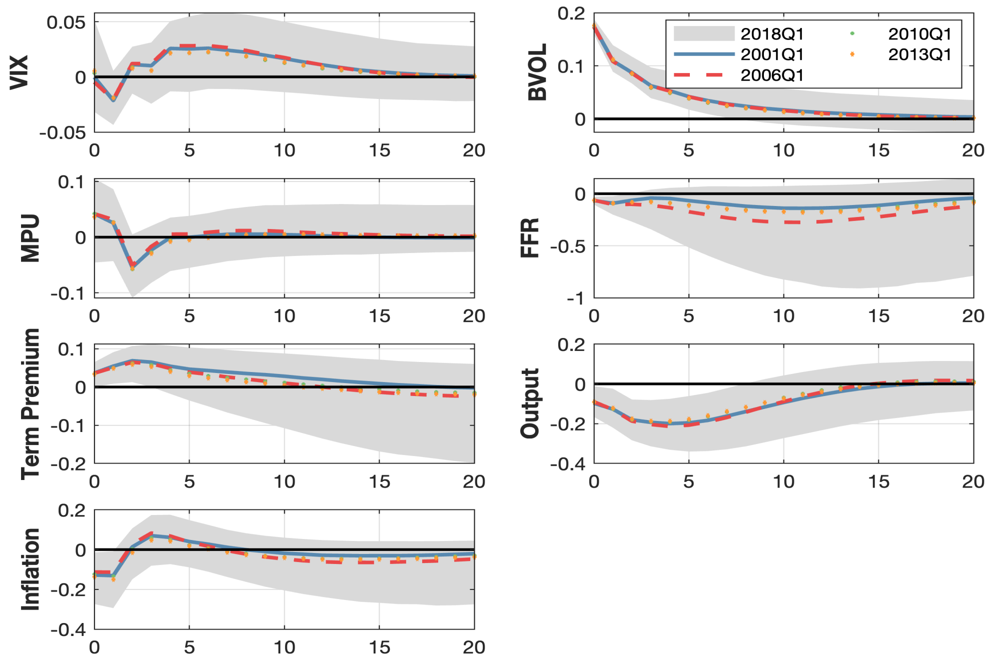

Figure A.16: Response of model variables due to bond volatility shock. Term Premium is based on Hordahl and Tristani (2014). Monetary policy uncertainty is based on 10 major US newspapers.

B Identification Based on Forecast Error Variance

Identifying unconventional monetary policy (assets purchase) shock is challenging. We identify this shock as a shock which explains maximum forecast error variance of growth of federal reserve treasury holding for a given period of time.

We can obtain the impulse response given by Cholesky decomposition as given below:

$$\tilde{R}(L) = C(L)\tilde{A}$$

The impulse response from any arbitrary decomposition is given by:

$$R(L) = C(L)A$$

Since $A = \tilde{A}Q$

$$R(L) = C(L)\tilde{A}Q \implies R(L) = \tilde{R}(L)Q$$

The point is that the impulse response to any arbitrary decomposition can be obtained by multiplying the impulse response from Cholesky decomposition with an orthonormal matrix of $n \times n$. The response at time l is related as $R_l = \tilde{R}_l Q$. Therefore we can finally write

$$Y_t = \tilde{R}(L)\tilde{v}_t = R(L)v_t = \tilde{R}_l Q v_t$$

The k-step ahead prediction error of Y_{t+k}, given all the data up to and including $t-1$, is given by

$$e_{t+k}(k) = \sum_{l=0}^{k} \tilde{R}_l Q v_{t+k-l}$$

The variance of k-step ahead prediction error of Y_{t+k} is given by

$$E\left(e_{t+k}(k), e_{t+k}(k)'\right) = \Sigma(k) = \sum_{l=0}^{k} \tilde{R}_l \tilde{R}_l'$$

Where $\Sigma(0) = \Sigma$. One can decompose $\Sigma(k)$ among n shocks in the model as give below.

$$\Sigma(k) = \sum_{j=1}^{n} \Sigma(k, j)$$

$$\Sigma(k, j) = \sum_{l=0}^{k} \tilde{R}_l q_j \left(\tilde{R}_l q_j\right)'$$

Where q_j is a vector of unit length. Therefore, we can write the forecast error variance given by one shock of interest as

$$\Sigma(k,1) = \sum_{l=0}^{k} \tilde{R}_l q_1 \left(\tilde{R}_l q_1\right)'$$

We can write the the forecast error variance explained by q_1 for our variable of interest i between time period $\underline{k} \leq k \leq \bar{k}$

$$\Sigma(k,1) = e_i' \left(\sum_{\underline{k}}^{\bar{k}} \sum_{l=0}^{k} \tilde{R}_l q_1 \left(\tilde{R}_l q_1\right)' \right) e_i$$

Where e_i is a selection vector with one at the i th place. Uhlig (2004) method solves for q_1 that maximizes this variance. Our problem is:

$$q_1^* = \arg\max_{q_1} e_i' \left(\sum_{\underline{k}}^{\bar{k}} \sum_{l=0}^{k} \tilde{R}_l q_1 \left(\tilde{R}_l q_1\right)' \right) e_i$$

Subject to $q_1' q_1 = 1$.

$$q_1^* = \arg\max_{q_1} e_i' \left(\sum_{\underline{k}}^{\bar{k}} \sum_{l=0}^{k} \tilde{R}_l q_1 \left(\tilde{R}_l q_1\right)' \right) e_i = \left(\sum_{\underline{k}}^{\bar{k}} \sum_{l=0}^{k} \text{trace}\left(e_i e_i'\right) \tilde{R}_l q_1 \left(\tilde{R}_l q_1\right)' \right)$$

$$= \left(\sum_{\underline{k}}^{\bar{k}} \sum_{l=0}^{k} \text{trace}\left(\tilde{R}_l q_1\right)' \left(e_i e_i'\right) \tilde{R}_l q_1 \right)$$

$$= q_1' \left(\sum_{\underline{k}}^{\bar{k}} \sum_{l=0}^{k} \tilde{R}_l' \left(e_i e_i'\right) \tilde{R}_l \right) q_1$$

$$= q_1' S q_1$$

Subject to $q_1' q_1 = 1$. Where $S = \left(\sum_{\underline{k}}^{\bar{k}} \sum_{l=0}^{k} \tilde{R}_l' \left(e_i e_i'\right) \tilde{R}_l \right)$. We use the fact that for any three square matrices D, E, F of same dimension; trace (DEF) = trace(FDE). The maximization problem can therefore be expressed as a Lagrangian:

$$L = q_1' S q_1 + \lambda \left(q_1' q_1 - 1 \right)$$

The first order condition is given by:

$$S q_1 = \lambda q_1$$

This is the definition of an eigenvalue decomposition, with q_1 being the eigenvector of S that corresponds to eigenvalue λ. Since $q_1' q_1 = 1$, we can rewrite the first order condition as:

$$q_1' S q_1 = q_1' \lambda q_1 = \lambda q_1' q_1 = \lambda$$

Since λ is scalar. Thus maximizing $q_1' S q_1$ amounts to finding the maximum eigenvalue of S. The vector q_1 is the eigenvector associated with the maximum eigenvalue λ. We find the eigenvector corresponding to the highest eigenvalue and that solves the problem.

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