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monetary policy; quantitative easing; long-term interest rate;  
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# Market volatility, monetary policy and the term premium

Sushanta K Mallick,<sup>#</sup> M S Mohanty and Fabrizio Zampolli<sup>\*</sup>

## Abstract

Based on empirical VAR models, we investigate the role of (option-implied) stock and bond market volatilities and monetary policy in the determination of the US 10-year term premium. Our preliminary findings are that an unexpected loosening of monetary policy – through a cut in the federal funds rate in the pre-crisis sample or an increase in bond purchases post-Lehman – typically leads to a decline in both expected stock and bond market volatilities and the term premium. However, while conventional monetary policy boosts economic activity in the pre-crisis period, bond purchases are found to have no statistically significant real effects post-crisis. Second, expected equity market volatility (VIX) is found to be more important than bond market volatility (MOVE). Pre-crisis, a shock to the VIX leads to a concomitant rise in the MOVE, a contraction of economic activity, a fall in broker-dealer leverage and a rise in the term premium, consistent with pro-cyclical swings in market liquidity. Post-crisis, an innovation to the VIX is instead associated with a drop in the term premium, suggesting the prevalence of flight to quality effects.

Keywords: bond market volatility; VIX; unconventional monetary policy; quantitative easing; long-term interest rate; term premia.

JEL classification: E43, E44, E52

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# 1. Introduction

This paper provides an empirical assessment of the role that measures of expected financial market volatility and monetary policy play in the determination of the government bond term premium. Three main considerations motivate such a focus. First, in financially sophisticated economies such as the United States the long-term interest rate is an important determinant of broad financial conditions and potentially of 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,<sup>1</sup> 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 its interaction with monetary policy and bond dealers' leverage 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 Exchange Volatility Index (VIX) or the Merrill Lynch Option Volatility Expectations (MOVE) index, are a proxy not only for investors' uncertainty about future equity and bond prices, respectively, but also for investors' risk aversion.<sup>2</sup> When uncertainty or risk aversion increases, investors may demand higher compensation for holding risky assets, including long-duration government securities. Furthermore, investors that actively manage their balance sheet (such as bond dealers) 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)). 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.<sup>3</sup> To the extent that monetary policy affects investors' perception of uncertainty and risks, risk-taking in bond markets may therefore constitute an additional channel of monetary transmission.

<sup>1</sup> 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.

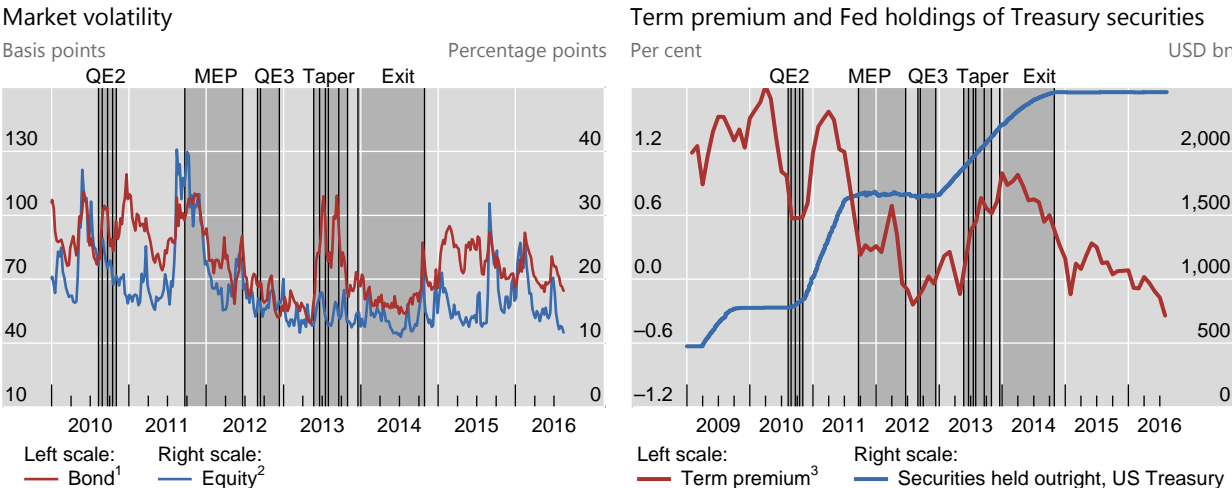
<sup>2</sup> The VIX is the risk-neutral expected volatility of the stock market over the next 30 days and is calculated from options on the S&P 500 index. The VIX can be thought as the sum of two components: expected actual volatility, which is interpreted as a measure of the risk, and a variance risk premium, which is related to investors' risk aversion (see eg Carr and Wu (2009) and Bekaert and Hoerova (2014)). The MOVE index is constructed in a roughly 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.

<sup>3</sup> 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.

The interaction between the term premium, expected 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 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 expected volatility or other measures of risk aversion or uncertainty. By contrast, other empirical studies have documented how expected stock market volatility, as captured by the VIX, has relevant macroeconomic effects. Bekaert et al (2013) find that looser monetary policy reduces the risk aversion component of the VIX and increases output, while Bruno and Shin (2015) shows that a decline in US dollar bank funding costs leads to an increase in bank leverage through the mitigation of volatility risk.<sup>4</sup> 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.

Expected bond and stock market volatility and the term premium

Graph 1



<sup>1</sup> Merrill Lynch Option Volatility Expectations (MOVE) index, yield curve weighted index of the normalised implied volatility on 1-month Treasury options; weekly averages. <sup>2</sup> VIX implied volatility on the S&P 500 index; weekly averages. <sup>3</sup> Decomposition of the 10-year nominal yield according to an estimated joint macroeconomic and term structure model; see Hördahl and Tristani (2014). Yields are expressed monthly in zero coupon terms.

Sources: Bloomberg; Datastream; Chicago Board Options Exchange; Merrill Lynch; BIS calculations.

A casual inspection of Graph 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).<sup>5</sup> However, other drivers, including

<sup>4</sup> 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.

<sup>5</sup> 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).



asset purchases, may be relevant. An interesting question is whether the VIX also counts. While it may be tempting to assume that only a measure of expected volatility matters for the term premium, the VIX may also be empirically relevant. For one, investors may hold diversified portfolios of bonds and equities. 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 MOVE alone, may be useful in characterising the overall attitude towards risk and the degree of uncertainty faced by bond investors.

To study the interaction between the term premium, expected volatilities and monetary policy, we rely on the estimation of VAR models to identify different shocks. Variables include a measure of the 10-year term premium,<sup>6</sup> the MOVE and the VIX volatility indicators, broker-dealer leverage, a measure of the monetary policy instrument and an indicator of economic conditions. We estimate separate VAR models for the pre-crisis and post-crisis periods using different time frequencies: a quarterly model for 1988Q1–2007Q4, which combines quarterly sampled and quarterly averaged variables, and a weekly model for 2008M1–2013M12. We estimate a distinct model for the post-crisis period because the standard policy instrument, the federal funds rate, has been mostly unchanged at zero while policymakers have relied on large-scale asset purchases to influence long-term interest rates. Moreover, the transmission mechanism and the effects of expected volatility on the term premium may have changed significantly.

Our main findings can be summarised as follows. First, an unexpected loosening of monetary policy – through a cut in the fed funds rate pre-crisis or an increase in bond purchases post-Lehman – typically leads to a decline in both expected stock and bond market volatilities as well as in the 10-year term premium. However, there is a key difference between the two periods. While conventional monetary policy easing boosts economic activity pre-crisis, unconventional monetary policy post-crisis is found to have no statistically significant real impact, despite having a sizeable negative effect on the term premium.<sup>7</sup> This finding, which is still preliminary and needs to be confirmed by further analysis, casts some doubt on the ultimate effectiveness of quantitative easing in the United States. Moreover, unlike in the pre-crisis period, financial intermediaries' leverage (proxied by the net position of primary dealers in US Treasuries) declines in response to asset purchases, suggesting a reduced importance of the market-making role for bond traders in US Treasury markets. Second, the expected equity volatility is found to be more important than bond market volatility. Unlike the VIX, an innovation to the MOVE leads to little or no change in the term premium and has no statistically significant effect on other variables, both pre- and post-crisis. By contrast, an innovation to the VIX has a significant but opposite-sign effect on the term premium. During the pre-crisis period, a shock to the VIX leads to a concomitant rise in the MOVE, a contraction of economic activity, a fall in broker-dealer leverage and a rise in the term premium. On

<sup>6</sup> The measure of the 10-year term premium is based on a model by Hördahl and Tristani (2014).

<sup>7</sup> Impulse responses suggest that a 1% increase in Federal Reserve asset purchases (equivalent to 23.4 billion USD) reduced the US 10-year term premium by 4 basis points over a period of 12 months. A 10-time increase in Fed purchases will mean a \$234 billion, which amounts to 40 basis points, decline in the term premium, consistent with findings in other studies.

the contrary, post-crisis, an innovation to the VIX is associated with a drop in the term premium, suggesting a flight to quality or a shift from riskier assets into relatively safer Treasury bonds (perhaps through stronger capital inflows). These results remain robust regardless of whether we use alternative identification mechanisms or variables.

The remainder of this paper is organised as follows. Section 2 describes the empirical model used to investigate the impact of monetary policy actions. Section 3 presents main results. Section 4 reports robustness tests. Section 5 concludes.

## 2. Empirical model and data

We first estimate a quarterly VAR model using data over a longer time period until 2007 to examine the effect of conventional interest rate policy and later shift to a weekly high frequency model to investigate the impact of Federal Reserve asset purchases. Our VAR model, estimated for the US economy, includes the following basic set of variables: an indicator of economic activity, CPI inflation, the fed funds target rate, global risk aversion (stock volatility), broker-dealer leverage, bond market volatility, and the US term premium.

We consider shocks to economic conditions as purely exogenous by ordering them first, which means business cycle shocks do not respond contemporaneously to shocks to policy decisions or other endogenous variables in the model, with a recursive sequencing of the contemporaneous restrictions. The recursive ordering structure (Cholesky factorisation) means that, contemporaneously, the first variable in the ordering is not affected by shocks to the other variables, but shocks to the first variable affect the other variables; the second variable affects the third and the fourth ones, but it is not affected contemporaneously by them, and so on. All variables are, however, related to each other through their lags as determined via optimal lag length selection criteria. The Cholesky decomposition is used to identify the VAR and the ordering of the endogenous variables. Although we experimented with alternative orderings, the results are qualitatively similar. The short-run relationship between the VAR residuals (or unexpected shocks) and the structural shocks (which are exogenous and uncorrelated with each other) can be defined as follows:

$$Ae_t = Bu_t \text{ where } E[uu'] = I,$$

where  $u_t$  is the vector of structural shocks, and A and B are the matrices that set the linear relationship between the structural shocks and the VAR residuals,  $e_t$ . We include a constant exogenously in the VAR. As  $e_t$  is the vector of VAR residuals and  $u_t$  is the vector of structural shocks, the above model is consistent with these short-run restrictions in a recursive order exactly-identified form as follows:

$$\begin{bmatrix} e_{ry} \\ e_{in} \\ e_{mp} \\ e_{ev} \\ e_{le} \\ e_{bv} \\ e_{tp} \end{bmatrix} = \begin{bmatrix} a_{11} & 0 & 0 & 0 & 0 & 0 & 0 \\ a_{21} & a_{22} & 0 & 0 & 0 & 0 & 0 \\ a_{31} & a_{32} & a_{33} & 0 & 0 & 0 & 0 \\ a_{41} & a_{42} & a_{43} & a_{44} & 0 & 0 & 0 \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} & 0 & 0 \\ a_{61} & a_{62} & a_{63} & a_{64} & a_{65} & a_{66} & 0 \\ a_{71} & a_{72} & a_{73} & a_{74} & a_{75} & a_{76} & a_{77} \end{bmatrix} \begin{bmatrix} u_{ry} \\ u_{in} \\ u_{mp} \\ u_{ev} \\ u_{le} \\ u_{bv} \\ u_{tp} \end{bmatrix}$$

where  $e_{y_t}$  is the residual from the economic activity equation,  $e_{in_t}$  is from the CPI inflation equation,  $e_{mp_t}$  is from the unconventional monetary policy equation,  $e_{ev_t}$  from the equity volatility or global risk aversion equation,  $e_{le_t}$  denotes the residual from the leverage equation,  $e_{bv_t}$  comes from the bond volatility equation, and  $e_{tp_t}$  is from the term premia equation.

This structure allows us to identify the following:

The economic activity equation being ordered first suggests that positive economic conditions can help minimise volatility in both stock and bond markets in a contemporaneous sense. Easy monetary conditions can, however, aid output recovery which can be captured through lagged effects. CPI inflation is ordered next as it is standard in the structural vector auto-regression (SVAR) literature, followed by the policy reaction function. Equity volatility or global risk aversion can react contemporaneously to changes in economic conditions, inflationary expectations, and interest rate shocks. Equity volatility can depend counter-cyclically on economic conditions and negatively on the degree of policy intervention. Leverage depends not only on global risk aversion, monetary policy stance, and general economic conditions in a contemporaneous sense, but also on other variables such as bond market uncertainty and term premia, in a lagged sense. Finally, bond market volatility depends on the above variables contemporaneously, and term premia depend on bond volatility along with all the other variables (counter-cyclically on real economic conditions and negatively on policy).

The benchmark VAR is estimated with the above 7 variables. We use the industrial production index and the ADS index constructed by Aruoba et al (2009) as indicators of US economic activity in quarterly and weekly models, respectively. The ADS index, computed and released by the Federal Reserve Bank of Philadelphia, combines a large number of high and low frequency information to track US business conditions on a real time basis, and has therefore become a key indicator to gauge the state of the US economy on a high frequency basis. Long-term bond yields can be represented by either the spot 10-year US Treasury yield or an estimate of the US term premium taken from Hördahl and Tristani (2014). US monetary policy is measured by the fed funds target rate up to 2007 and Federal Reserve asset purchases for the period following the 2008 crisis, when the fed funds rate hit the zero lower bound.

As regards financial intermediaries' role in monetary transmission, following Bruno and Shin (2015) we represent the balance sheet capacity of global banks by US broker-dealer leverage from the US flow of funds. Unfortunately, however, this series is available only at quarterly frequency. For the weekly model, therefore, we proxy broker-dealers' leverage by the net position of primary dealers in the US Treasury market, measured as the difference between their long and short positions. As noted by Adrian and Fleming (2005), primary dealers often undertake offsetting spot and forward transactions that have zero implication for their net financing position but have major consequences for their exposure to risks arising from future price movements. By implication, net positions of primary dealers that include their forward positions are likely to be a better indicator of risk-taking than a simple leverage that measures capital at risk for a given set of financing. Data on net positions are taken from the weekly releases on primary dealers' financing and positions by the Federal Reserve Bank of New York.

The implied bond volatility in the US Treasury market is measured by the MOVE index, while the stock volatility is measured by the VIX index of implied volatility from options on the S&P 500 index. The VIX is a model-free volatility index, measuring

investor fear due to its negative relationship with S&P 500 return dynamics, which justifies its use as a proxy for market risk and volatility. Like the VIX, the MOVE index is an average implied normal volatility for constant forecast horizon of one month. However, the MOVE is not model-free 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 the market participants.

## Statistical properties of variables

Appendix 1 provides descriptive statistics of the main variables. A key finding is that both the VIX and the MOVE do not follow the standard assumption of normality, suggesting that there are regimes of high and low volatility. Moreover, the shape of the term premia is multi-modal, raising the issue of multiple equilibria and therefore the possibility that Fed policies may have different impacts at different levels of term premia. We confirm this hypothesis by estimating a quantile regression of VIX, MOVE and term premia on the federal funds rate. These bivariate regressions indicate that bond volatility is more affected by the fed funds rate when volatility is high but is less affected when volatility is low. In the empirical model we pursue this hypothesis through a time-varying parameter VAR model.

Next we undertake the stationarity tests on all variables. The augmented Dickey-Fuller (DF) test suggests that four variables are stationary while the other four are of order 1 ( $I(1)$ ) or non-stationary. Allowing for a single structural break in the level and trend of each series, we follow the procedure of Zivot and Andrews (ZA, 1992), in order to estimate one endogenous break under the alternative hypothesis of stationarity. Most series turn out to be stationary when applying the ZA test with break at least at the 10% level of significance for the sample period starting in 2008.

We also consider Lumsdaine and Papell (1997) and the Lagrange Multiplier (LM) unit root test developed by Lee and Strazicich (2003), with two endogenous breaks under the null and the alternative hypothesis of stationarity. The results of the Lee-Strazicich test with two endogenously determined structural breaks indicate the rejection of the null of unit root of most variables, except Fed holdings series, which appear to have a unit root even if we allow for two breaks (intercept and trend). We also considered Fed holdings as a percentage of GDP, but the series still remained non-stationary. This is primarily because the series does not change frequently, but when it changes it behaves like a jump variable. Therefore, the pattern of non-stationarity is not similar to a standard non-stationary series. The estimated break locations can make a difference to the test results in small samples. It is for this reason that the LM tests can be slightly more powerful than the DF version tests. Regardless of the order of integration, Sims et al (1990) show that the OLS estimates of a VAR model in levels are still consistent. The optimal lag selection is found to be 3 for the VAR model (see Tables A2 and A3 at the end of the paper).

## 3. Results from VAR models

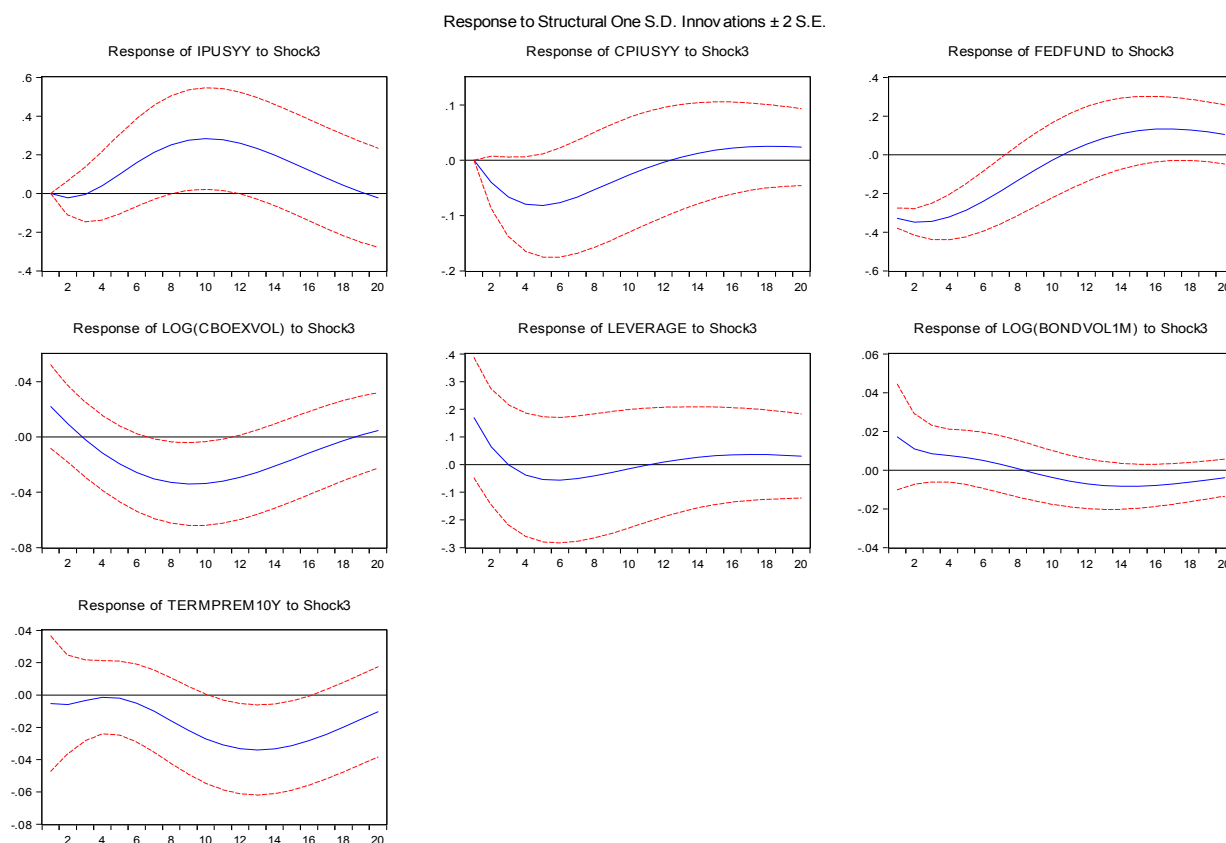
### The pre-crisis period

We start with impulse response functions for the pre-2008 crisis period when monetary policy was not constrained by the zero lower bound. We use the Federal

Reserve’s traditional policy instrument, the target federal funds rate, as the indicator of US monetary policy stance. Graphs 2 and 3 show the impulse responses from a structural one standard deviation shock to monetary policy, stock volatility and bond volatility. (We report expansionary policy shocks in order to be consistent with Fed asset purchase shocks, to be reported later).

Quarterly expansionary MP shock (a cut in fed funds rate)

Graph 2



Notes: Responses are for a negative shock (or a cut) in the fed funds rate denoted as ‘shock3’ (ie, one S.D. Innovations  $\pm$  2 S.E., which is 95% confidence interval bands); IPUSYY is industrial production growth (economic activity indicator), CPIUSYY is CPI inflation, FEDFUND is Fed Funds target rate (conventional pre-crisis monetary policy instrument), CBOEXVOL is the equity volatility or global risk aversion, LEVERAGE denotes leverage, BONDVOL1M refers to bond volatility, and TERMPREM10Y is the term premia.

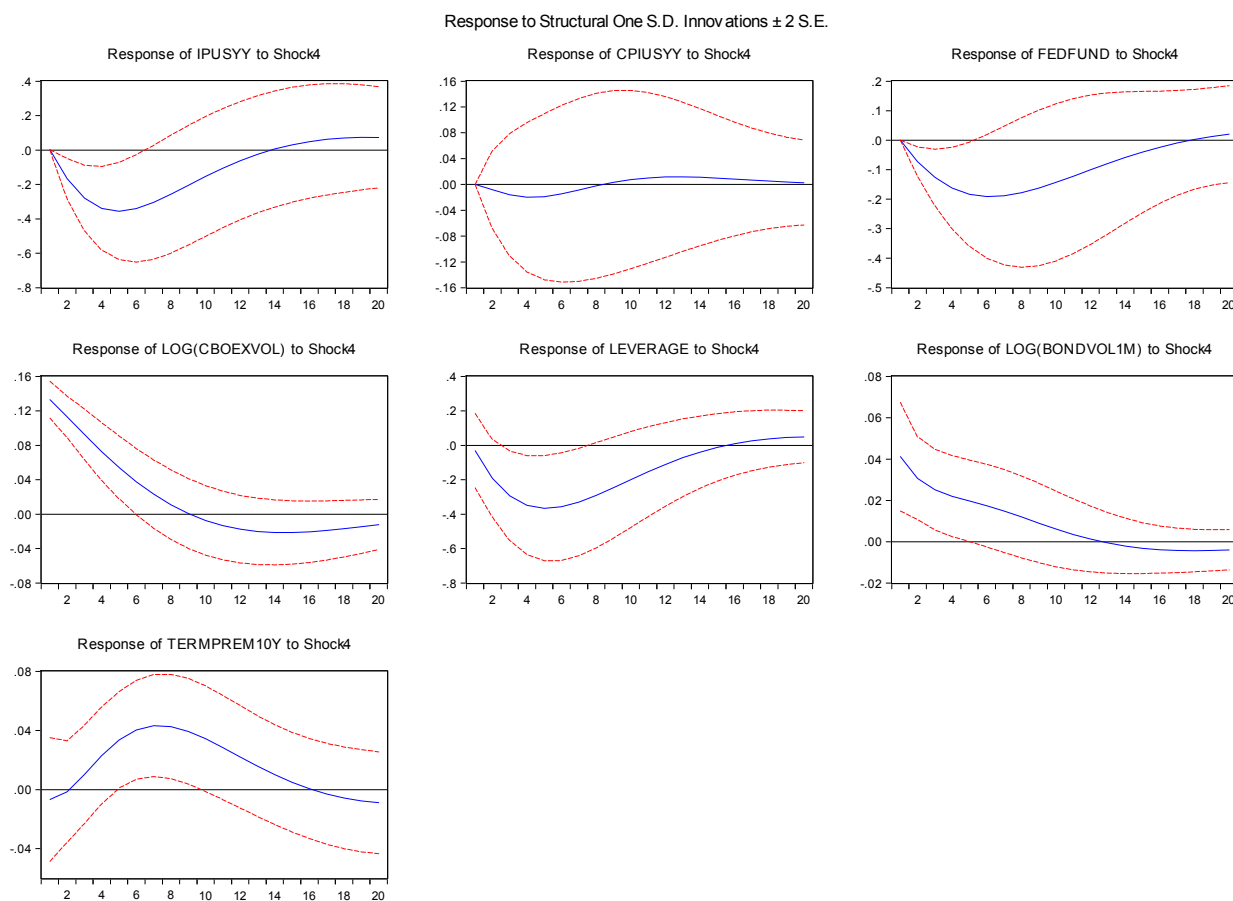
The results are consistent with Bekaert et al (2013) in that tighter US monetary policy is associated with an increase in risk aversion – here captured by the VIX – and a weakening of US economic activity. As shown in the second lower panel of Graph 2, an expansionary monetary shock leads to lower stock volatility with a lag of two quarters, and the impact reaches a peak after 9 quarters, which is roughly comparable to the 20-40 months reported by Bekaert et al (2013). Although we use the VIX in our benchmark exercise, 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 from the VIX. The conditional variance is obtained from a GARCH(1,1), which is the simplest and most robust of the family of volatility models.<sup>8</sup>

<sup>8</sup> As a check, we performed the same decomposition of the VIX as in Bekaert et al (2013). The VIX can be decomposed into a conditional variance measure and a variance risk premium. The former is

Broker-dealer leverage increases following the monetary shock, although the impact dies down steadily and remains insignificant. Even though the response of bond volatility is not significant, expansionary US monetary policy leads to statistically and economically significant effects on the US term premium after about 10 quarters. US industrial production expands after a lag of 8 quarters, and the impact peaks around same time as the VIX.

Quarterly VIX shock

Graph 3



Notes: Responses are for a positive shock in the VIX or an increase in global risk aversion denoted as 'shock4' (ie one S.D. Innovations  $\pm$  2 S.E., which is 95% confidence interval bands); IPUSYY is industrial production growth (economic activity indicator), CPIUSYY is CPI inflation, FEDFUND is Fed Funds target rate (conventional pre-crisis monetary policy instrument), CBOEXVOL is equity volatility, LEVERAGE denotes leverage, BONDVOL1M refers to bond volatility, and TERMPREM10Y is the term premia.

Graph 3 shows responses in the opposite direction, that is, when the economy is hit by a shock to the VIX. It is clear that the shock has a sizeable negative effect on broker-dealer leverage, which declines up to 6 quarters, creating a powerful feedback loop to other financial markets and the economy more generally, as reported by Bruno and Shin (2015). Not only does the shock lead to a jump in bond volatility, but it is also followed by higher US term premia and a large decline in economic activity within 6 quarters. As shown by the lower panel of Graph 3, the Federal Reserve

normally interpreted as a predictable measure of uncertainty, while the latter is normally interpreted as being more closely related to investors' risk aversion. In our VAR exercises, replacing the VIX with either one of its two components leads to roughly similar results (not presented here in order to save space, but available upon request from the authors). Note, though, that the focus of Bekaert et al (2013) was not the term premium or bond price volatility.

responds to the shock by lowering the fund target rate until economic activity has been fully stabilised.

Impulse responses from a positive shock to implied bond volatility are reported in Graph A3 in the appendix. The shock is generally much more short-lived than that to implied equity volatility (lasting no more than 2-3 quarters, whereas that to equity volatility persists for over a year). The shock does have a statistically significant positive impact on the term premium, but this does not last beyond the initial quarter. Given its very short-lived impact on the term premium, it is no surprise that the shock to implied bond market volatility does not have much impact on either the stock market or monetary policy.

## The post-crisis period

The pre-crisis results suggest that one of the channels through which monetary policy works is through the VIX, confirming the results of Bekaert et al (2013). It is therefore important to assess whether, after the global financial crisis, large-scale asset purchases have similar stabilising effects on market volatility as standard monetary policy operations before the crisis.

Since November 2008, the Federal Reserve has carried out four rounds of asset purchases under the Large-Scale Asset Purchase (LSAP) programme.<sup>9</sup> The first round focused on mortgage-backed securities and agency debt and was later expanded to include long-term Treasury bonds. The consensus in the literature is that the programme achieved its intended effect of lowering long-term interest rates and reducing deflation risk after the fed funds rate hit the zero lower bound (Gagnon et al (2011), D'Amico and King (2012), Krishnamurthy and Vissing-Jorgensen (2011) and Chadha et al (2013)). Others studies have reached similar conclusions by focusing on the counter-factual evidence as to how US output and inflation would have evolved had the Federal Reserve not undertaken such purchases (Del Negro et al (2011), Chung et al (2012) and Chen et al (2012)).

A potential shortcoming of the existing empirical studies is – as mentioned in the introduction – that they do not explicitly address the role of risk aversion or uncertainty, and hence do not consider the role of market volatility in the determination of term premium. One implication is that the failure to include risk and uncertainty channels can lead to either underestimation or overestimation of the impact of unconventional policies. For example, central bank asset purchases may reduce investors' perception of macroeconomic risk and uncertainty or improve their risk tolerance, stabilising market volatility and long-term interest rates.

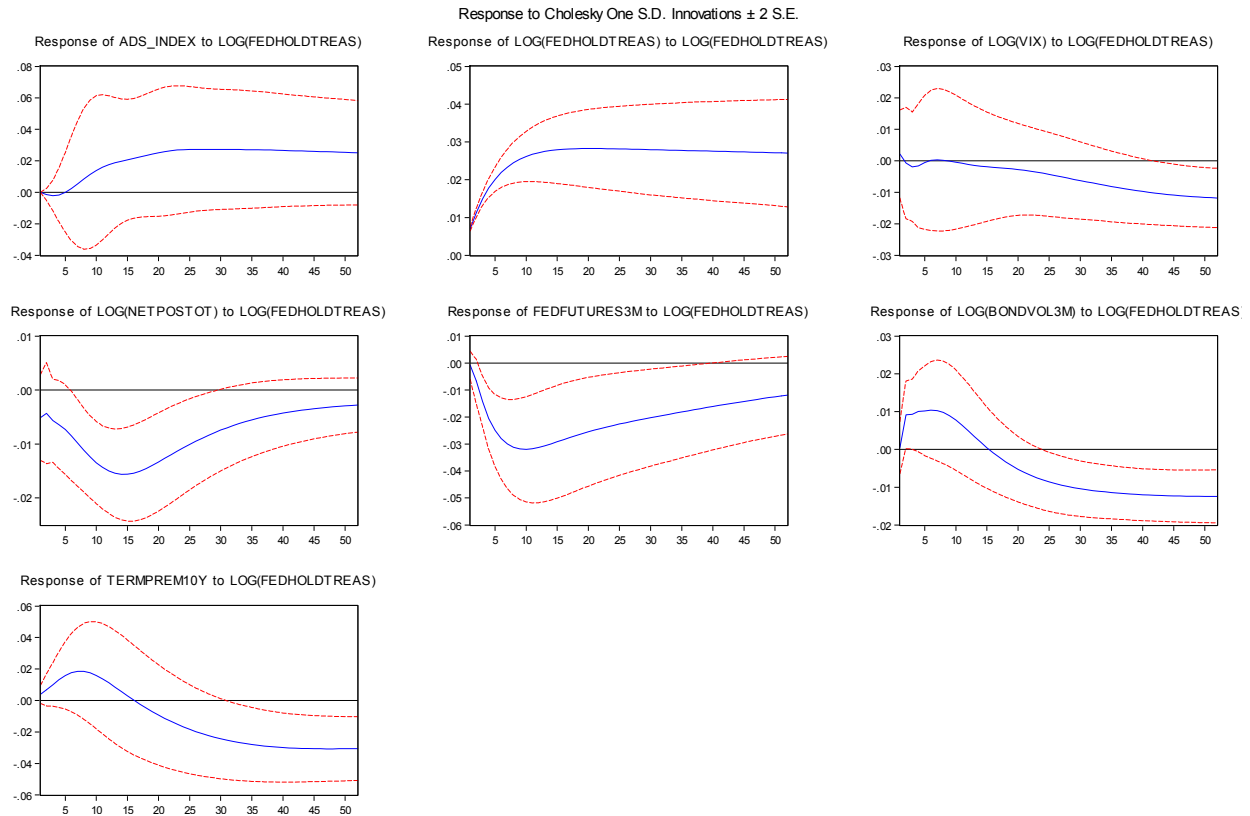
To address this issue, we turn to a weekly VAR model. We retain the original ordering of variables but replace industrial production, the fed funds rate, and broker-dealer leverage with the ADS index, Fed asset purchases and the net position of primary dealers, respectively. We introduce 3-month fed funds futures as an additional variable to control for the fact that the Federal Reserve's forward guidance policy may lead to contamination of the estimated impact of asset purchases on bond yields. We order the 3-month fed funds future as our fifth variable before bond volatility and the term premium. Bond volatility therefore contemporaneously

<sup>9</sup> Borio and Disyatat (2010) discuss the differences among the various forms of unconventional monetary policy, characterising the wide range of central bank responses as balance sheet policies.

depends on four other variables in the VAR (namely the ADS index, fed holdings, the VIX, and fed futures).

## Weekly asset purchase shock

Graph 4



Notes: Responses are for a positive shock in FEDHOLDTREAS (one S.D. Innovations  $\pm$  2 S.E. which is 95% confidence interval bands); ADS\_INDEX is an index of economic activity, FEDHOLDTREAS is Fed holdings of US Treasury securities (post-crisis monetary policy instrument), VIX is equity volatility, NETPOSTTOT denotes leverage, FEDFUTURES3M denotes Fed funds futures reflecting forward guidance, BONDVOL3M refers to bond volatility, and TERMPREM10Y is the term premia.

Graph 4 shows that the stabilising effects of Fed asset purchases on bond volatility come with a lag, similar to what Bekaert et al (2013) and Bruno and Shin (2015) find. The impact is persistent and long-lasting, leading to a substantial reduction in bond term premia over a period of one year. In terms of quantitative estimates, the impact of a one per cent increase in asset purchases (equivalent to US\$23.4 billion in US long-term Treasuries using data as of end-April 2014) will lead to 1.7% decline in bond volatility in a year's time (response to a one SD shock=0.012 / SE of asset purchase=0.007), which is equivalent to 104 basis points in the 3-month MOVE index. Similarly, for term premia, the effect of this asset purchase is stronger, with a 4.4% decline (0.031/0.007) implying only 4 basis points if we consider the maximum value of term premia (0.9385) over the post-crisis sample.

The fact that the shock leads to a significant reduction of the expected path of future short rates suggests that Fed asset purchases may have also been effective by providing signals to market participants about the future stance of monetary policy. While stock volatility declines following higher asset purchases by the Federal Reserve, the response is insignificant and much weaker than that for bond volatility. This is in line with Arnold and Vrugt (2010) and Ulrich (2014), who show that uncertainty about the future course of monetary policy is the key determinant of

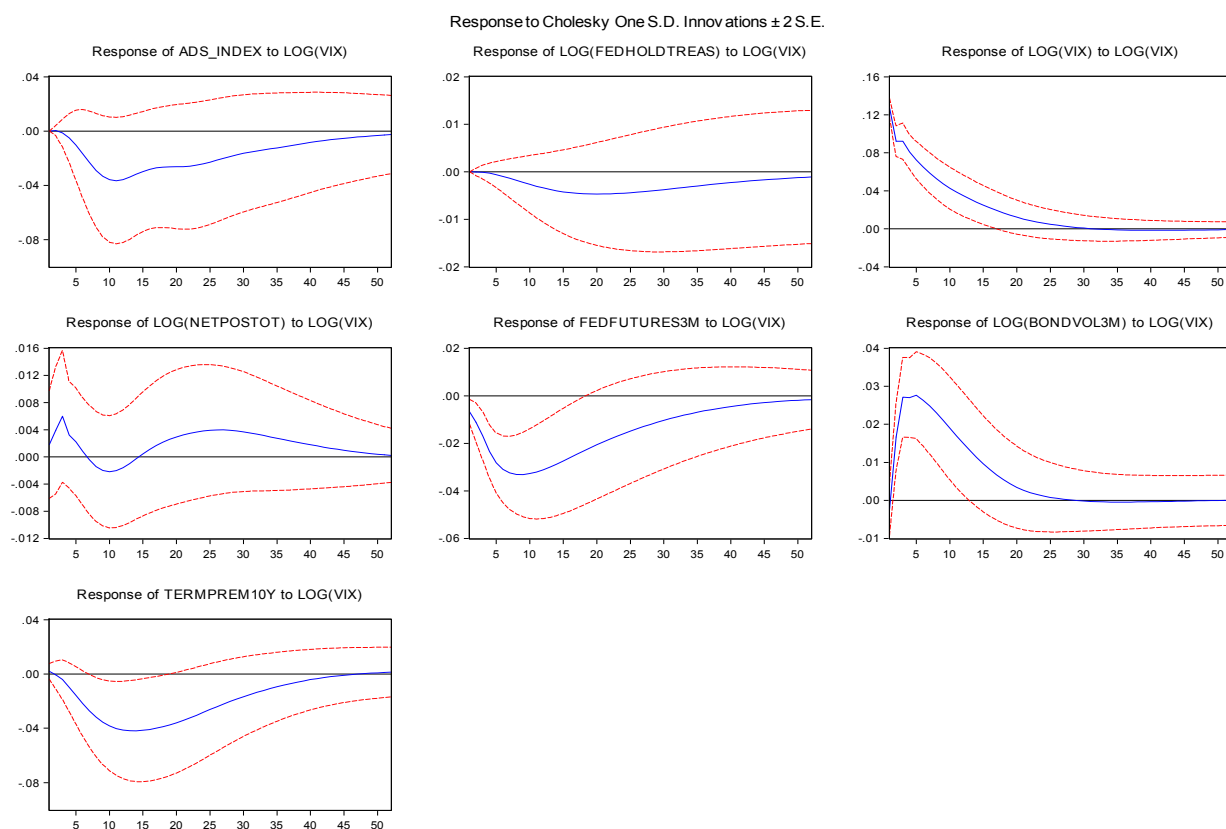


Treasury bond volatility across all maturities. The impact on volatilities and term premia is very much delayed – it takes about 40 weeks for asset purchases to have a statistically significant impact on VIX. Although the initial impact on bond market volatility and the term premium is positive, they are insignificant. Higher Fed purchases also seem to lead to an increase in economic activity, although the responses are not significant.

Surprisingly, however, the net position of primary dealers declines following additional asset purchases by the Federal Reserve. This stands in contrast to the procyclical response of bank leverage to changes in short-term interest rates in the pre-crisis period. One explanation for this unexpected result is that the Federal Reserve may have replaced the market-making role of bond traders in the Treasury market. Adrian et al (2013) show that, after declining sharply in the wake of the 2008 crisis, both gross and net leverage of primary dealers remained very subdued, suggesting that these market players had already been adjusting their risk exposures even as the Federal Reserve embarked on its asset purchase programme. Another potential interpretation is that primary dealers are more sensitive to changes in short-term rates than to changes in the Federal Reserve balance sheet, which arguably did not carry much information about the future stance of US monetary policy.

Weekly VIX shock

Graph 5



Notes: Responses are for a positive shock in the VIX - an increase in global risk aversion, (one S.D. Innovations  $\pm$  2 S.E. which is 95% confidence interval bands). The variables are defined in the same way as in Graph 4.

Graph 5 shows that there is a high correlation between VIX (equity) and Move (bond) volatility as reflected in the response of bond volatility to a positive shock in stock market volatility. A rise in volatility leads to a reduction in the expected future

path of short-term rates and a lower term premium, while responses of other variables including Fed asset purchases are not significant. Results from a bond volatility shock are reported in Graph A4 in the appendix. This shows that the shock has no significant effect on other variables. Since the variable is an indicator of policy decisions, the shock itself does not matter as it has little effect on asset purchases.

In sum, it is quite clear that despite the short rate being constrained by the zero lower bound, the Federal Reserve's policy action in the form of higher asset purchases has been able to reduce the long-term interest rate through term premium. Expansionary unconventional monetary policy shocks also tend to lower bond market volatility.

#### 4. Robustness checks

In this section we report a number of robustness checks. First, we consider an over-identified SVAR model where we test whether only market volatility shocks (bond and equity) drive term premia. To do so, we make an assumption that the term premium has no immediate impact on both monetary policy shocks and leverage shocks (as shown in the specification below). This also means monetary policy and leverage shocks have no contemporaneous effect on term premia. If this assumption does not get rejected, the only remaining variables influencing term premia will be market volatilities and demand shocks. Thus, we impose a zero restriction on either  $a_{37}$  or  $a_{73}$ . Similarly, the way to identify the leverage shock from the term premia shock is to impose a restriction that affects the value of either  $a_{57}$  or  $a_{75}$ . We deal with this by imposing restrictions that those two variables in the last row of the recursive matrix have no immediate effect on term premia in the pre-crisis model ( $a_{73} = 0$  and  $a_{75} = 0$ ).

$$\begin{bmatrix} e_{ry} \\ e_{in} \\ e_{mp} \\ e_{ev} \\ e_{le} \\ e_{bv} \\ e_{tp} \end{bmatrix} = \begin{bmatrix} a_{11} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ a_{21} & a_{22} & 0 & 0 & 0 & 0 & 0 & 0 \\ a_{31} & a_{32} & a_{33} & 0 & 0 & 0 & a_{37}(=0) & 0 \\ a_{41} & a_{42} & a_{43} & a_{44} & 0 & 0 & 0 & 0 \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} & 0 & a_{57}(=0) & 0 \\ a_{61} & a_{62} & a_{63} & a_{64} & a_{65} & a_{66} & 0 & 0 \\ a_{71} & a_{72} & a_{73}(=0) & a_{74} & a_{75}(=0) & a_{76} & a_{77} & 0 \end{bmatrix} \begin{bmatrix} u_{ry} \\ u_{in} \\ u_{mp} \\ u_{ev} \\ u_{le} \\ u_{bv} \\ u_{tp} \end{bmatrix}$$

This over-identified model fits the data reasonably well and the over-identifying restrictions are not rejected. In other words, these two restrictions have no important effect on the results, suggesting that both bond and equity volatilities can have an immediate impact on term premia shocks, along with shocks in economic activity. The LR test for this over-identification is:  $\chi^2(2) = 0.466791$  (p-value = 0.7918). The non-rejection of the restrictions suggests that market volatilities drive term premia, and the impulse responses in the restricted model remain the same as before.

We impose the same set of restrictions on the post-crisis weekly model, namely that term premia shocks are driven by market volatilities and economic conditions and that monetary policy and leverage shocks have no immediate impact ( $a_{72} = 0$  and  $a_{74} = 0$ ). The LR test for this over-identification is:  $\chi^2(2) = 1.757063$  (p-value = 0.4154). This strategy of over-identification does not alter the benchmark impulse responses in the figures in the previous section.

Second, we check that our results are robust to using different variables. We find that results about the impact of a Federal Reserve asset purchase shock remain robust to using alternative variables to the term premium (10-year spot rate or a 5-year forward 10-year rate), to using total Fed holdings or Fed holdings as a percentage of GDP, or the 3-month (or 1-month / 12-month) fed funds futures rate, to using the ADS index or a surprise activity index, and to whether we drop bond or stock market volatility from the model. We also check the sensitivity of the results by using a measure of policy uncertainty index replacing the ADS index. Our main results remain robust even with alternative variables and after removing leverage, or both leverage and fed funds futures, from the VAR, although in the latter case the responses suggest that fed funds futures expectations do play a role in reflecting the effect of market volatility. In this 5-variable case, removing leverage and fed funds futures, the negative impact of an asset purchase shock on VIX turns significant in 32 weeks (eight months, as in Bekaert et al (2013)), while the dampening impact on bond volatility turns significant in 22 weeks (five months), and for term premia the negative effect becomes significant in 28 weeks (seven months). In this 5-variable case, the impact on the ADS index turns significant and positive in nine weeks.

Third, we check the results are robust to using the decomposition of the VIX into a variance risk premium – or proxy for investors' risk aversion (implied variance minus conditional variance) and conditional variance – or proxy for uncertainty (Bekaert et al (2013)). In Bekaert et al (2013), the responses of key macroeconomic variables included in the study – namely CPI, PPI, IP and the real interest rate – to risk aversion and uncertainty shocks were significant, whereas the macro shocks themselves did not have any statistically significant impact. The focus of Bekaert et al (2013), however, was not on the long-term rate (or the term premia or bond market volatility). With these bond market variables in the post-crisis period, we are able to establish a robust dampening impact of asset purchase policy on the long-term interest rate, showing a term premia channel of monetary policy transmission, although the impact of bond volatility shocks remains neutral in the fixed-coefficient VAR, which can become more noticeable in a time-varying VAR setting. Given that the series is stationary, the bond volatility shock may not persist for long, and hence the variability of the response at different points in time needs to be computed to better understand the impact of bond volatility shocks.

Fourth, we check alternative identification through sign-restriction VAR using the weekly model (see Appendix 2). We impose two sign restrictions to identify a term premium shock and three sign restrictions to identify a bond volatility shock, and four restrictions to identify a Fed asset purchase shock. The results of sign-restriction VAR do not alter our benchmark findings. Not only are these restrictions accepted, but they also help confirm our main result that Fed asset purchase shocks have significant and economically meaningful effects on bond price volatility and the term premium.

### Time-varying parameter structural VAR approach

As a further robustness check, we also examine whether the findings obtained from the fixed-coefficient VAR models remain qualitatively valid once we allow for time

variation in the coefficients.<sup>10</sup> Specifically, we estimate a time-varying parameter structural vector auto-regression (TVP-SVAR) using the methodology suggested by Primiceri (2005). In the TVP-VAR model, all parameters are assumed to follow the first-order random walk process, thus allowing for both a temporary and permanent shift, along with stochastic volatility. Consider the TVP-VAR model with stochastic volatility as:

$$y_t = c_t + \sum_{j=1}^p B_{j,t} y_{t-j} + u_t \text{ where } u_t \sim N(0, \Omega_t)$$

where  $y_t$  is the  $k \times 1$  vector of observed variables, and  $B_{j,t}$  refers to  $k \times k$  matrices of time-varying coefficients and  $\Omega_t$  is a  $(k \times k)$  time-varying covariance matrix. The disturbance  $u_t$  is a  $k \times 1$  structural shock, and we specify the simultaneous relations of the structural shock by recursive identification, assuming that  $A$  is a lower-triangular matrix with elements  $a_{ij}$ , and the diagonal elements equal to one, and  $\Omega_t = A_t^{-1} \Sigma_t \Sigma_t' A_t^{-1}$ . Therefore, this model has two sets of time-varying 'coefficients':  $B_{j,t}$  and  $a_{ij}$  and a stochastic volatility model for the diagonal elements  $h_{it}$ . We have undertaken this procedure both in RATS and by using Nakajima (2011) TVP-VAR code in MATLAB.

Our TVP-SVAR includes real output growth, the real fed funds rate (nominal rate minus CPI inflation), bond volatility and equity volatility over the sample period 1988Q2 to 2013Q3 (see Graph A7a). We keep it as a 4-variable VAR, as a large number of variables makes it too computationally intensive. Moreover, the main variables of interest are bond volatility and the real fed funds rate (which captures the effect of inflation). We had to rely on the real fed funds rate as the key policy variable due to unavailability of Fed asset purchase data over a long time span covering the pre-crisis period. The variables are ordered from relatively exogenous to fully endogenous variables. Since this recursive order of variables is a strong restriction in conventional SVAR models, it is important to consider the changes in volatility in TVP-VAR model. This permits to check responses at different points in time. Graph A7a shows that bond market volatility oscillates around a flat trend and does not show any persistence, at least until 2004, while equity volatility shows persistent oscillation. In contrast, in the more recent part of the sample, bond market volatility displays more persistent fluctuation. The change in the behaviour of this variable is one of the things that we intend to capture using a TVP-VAR model.

We first show impulse response functions at four different time points: 2003:Q3, 2006:Q3, 2008:Q3, and 2013:Q3. We classify the first two points as low volatility periods and the last two as high-volatility periods. The first point clearly belongs to the "Great Moderation" and the second to the famous "Greenspan Conundrum", when higher fed funds rate were accompanied by a flattening in the US Treasury yield curve. In the last two high volatility periods, the Fed introduced three rounds of QE: the first round (QE1) in 2008, the second round (QE2) in 2010 and the third round (QE3) in 2012.

Graphs A7b and A7c show that most of the variation can be attributed to a shift in coefficients rather than the variance of the residuals. Moreover, volatility appears to be non-stochastic for a large part of the sample period. Graphs A8a-A8d present the impulse response results for the above four time points and Graph A9a the

<sup>10</sup> In order to address the common problem that the observed historical economic relationships may have changed following the recent crisis, Baumeister and Benati (2013) use a time-varying parameter structural VAR model (TVP-VAR) showing that fixed-coefficient models estimated using the past two decades of data lead to underestimation of the macroeconomic effects of yield spread compression achieved by the Federal Reserve asset purchases since November 2008.

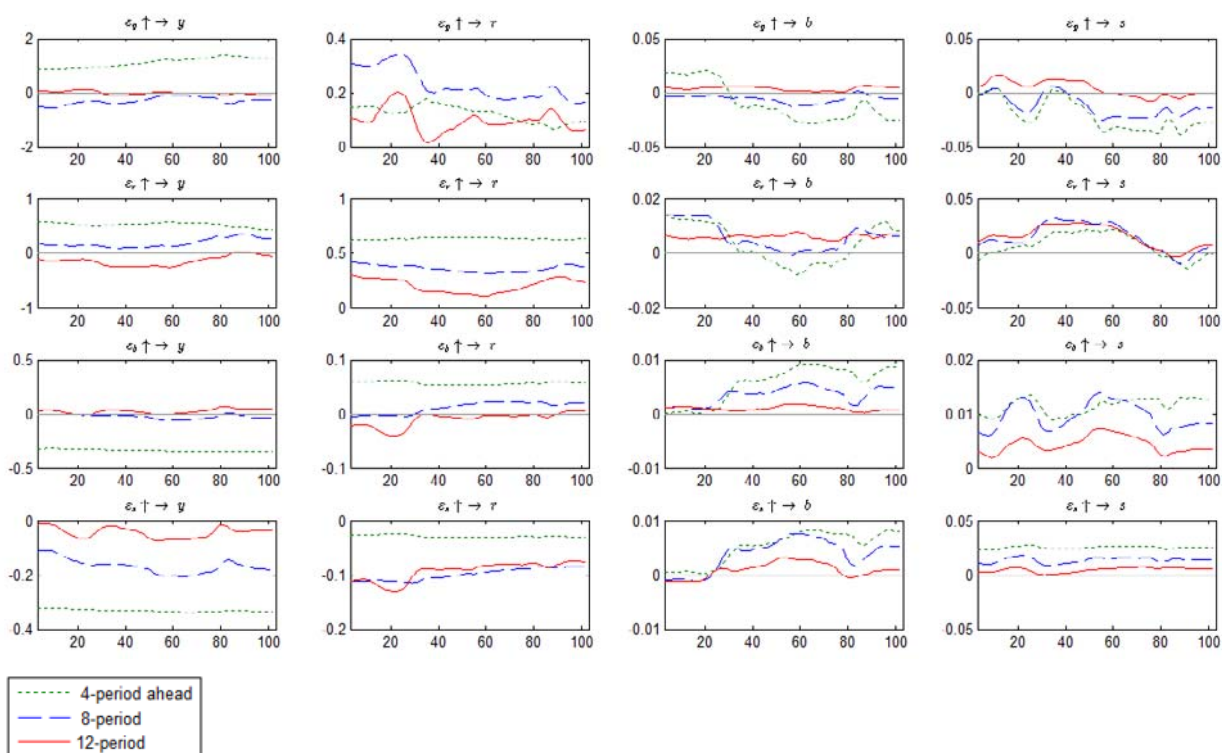
posterior estimates of simultaneous relations, corresponding to the lower triangular elements in the Cholesky decomposition of the variance-covariance matrix.

Graph A9a shows that the coefficients have changed post-crisis. The sensitivity of the time-varying coefficients suggests that negative demand shocks lead to higher bond and stock volatility in a contemporaneous sense. Moreover, the time-varying contemporaneous coefficient of the real interest rate on bond and stock volatilities has changed from negative to positive in the post-crisis period, which suggests that low real rates of return simultaneously increase both volatilities in the post-crisis regime. This means that the effect of monetary policy in the post-crisis period (lower real rate) leading to higher stock and bond market volatilities is offset via Fed asset purchase shocks that contribute to a lower term premium. Even in a time-varying sense, bond volatility shocks are positively related to stock volatility across both regimes.

The only noticeable difference is the time-varying nature of reduced form coefficients in TVP-VAR, as shown in Graph A9a (A-inverse coefficients) as opposed to the recursive VAR analysis. As the structural A matrix remains the same over time, the time-varying reduced form coefficients make the impact of structural shocks different over time as in the above figure.

Time-varying impulse responses with the above 4-variable VAR

Graph 6



Notes: y, r, b, and s denote output growth, real interest rate, bond volatility and stock volatility respectively. Rows refer to the effect of each shock, with the first row denoting demand shock, the second row denoting a shock in real interest rate, and so on.

The impulse responses are computed at all points in time using the estimated time-varying parameters. The impulse responses at different time-points show that the responses to market volatility (both bond and stock) shocks are significantly different from zero, although the responses were insignificant in the constant VAR

model. The output responses for a stock volatility shock stay negative for the entire sample period (1988Q2-2013Q3), while for bond volatility the output response fluctuates over time (Graph 6). A shock to bond volatility has a positive impact on stock volatility (Graph 6: 3rd row, 4th column), whereas a stock volatility shock has a contractionary real effect (Graph 6: 4th row, 1st column). In that sense, a bond volatility shock has an indirect effect, but it does not have any direct real effect (Graph 6: 3rd row, 1st column). This is consistent with our benchmark responses. In the very short term (4 periods ahead), bond volatility has a negative real effect, but in terms of the 8- to 12-period ahead response, the impact is not prominent. In this time-varying set-up, bond volatility shocks seem to matter in influencing term premia to the extent they influence real interest rates and stock market volatility, as in Graph 6 (2<sup>nd</sup> row).

Also, there are significant interactions between the real fed funds rate and market volatilities over time, although they are not significantly different from zero (see Graph A9b). The impact of a shock to the real fed funds rate on bond volatility remains negative. The correlation between the two volatilities remains. The finding that the real effects of both market volatilities are significant in this time-varying set-up does suggest that both bond and equity volatilities matter for the real economy. This finding is in line with Cover (2011), who finds credit risk shocks explaining declines in output during 2008 and 2009.

To sum up, the TVP-VAR model indicates significant variation of the impulse responses over time as well. Shocks to both bond and equity market volatilities did have a negative effect. Furthermore, for most shocks, we observe the direction of the impulse responses being similar, although the magnitudes of the responses are different. The comparison across different identification schemes makes our findings reliable and robust.

## 5. Conclusion

In this paper we have studied the interaction between the term premium, expected market volatility and monetary policy. This interaction has not received much attention in the literature, and our paper aims at filling 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) and Bruno and Shin (2015)). Yet little analysis seems to have been carried out to understand the response and influence of monetary policy on bond market volatility and 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 of a break at the time of the Great Financial Crisis in 2008. Both before and after the crisis, monetary policy easing tends to reduce the term premium. But, post-crisis, the fall in the term premium does not appear to boost economic activity, unlike in pre-crisis times. Even financial intermediaries' leverage behaves differently. Contrary to the pre-crisis period, bond dealers' leverage declines in response to an expansionary (unconventional) monetary policy surprise, suggesting a reduced importance of market-making in Treasury markets.

Another interesting finding is that stock market volatility is more important than bond market volatility. This is true both pre- and post-crisis. A shock to the MOVE has little impact on the term premium and no statistically significant effects on other variables. Moreover, time-varying coefficient VAR analysis shows that the effects of shocks to the MOVE are unstable over time. By contrast, shocks to the VIX have a clear sizeable impact on the term premium and other variables, but the sign of the impact has changed since the crisis. Pre-crisis, a shock to the VIX leads to a rise in the MOVE, a contraction of economic activity, a fall in broker-dealers' leverage and a rise in the term premium. By contrast, after the crisis, an innovation to the VIX leads to a fall in the term premium, possibly associated with a flight to quality or a portfolio shift towards relatively safer assets.

The empirical responses found in our paper can be consistent with several mechanisms. Hence, future research could focus on building structural models that can explain these findings and the changes that have occurred with the financial crisis.

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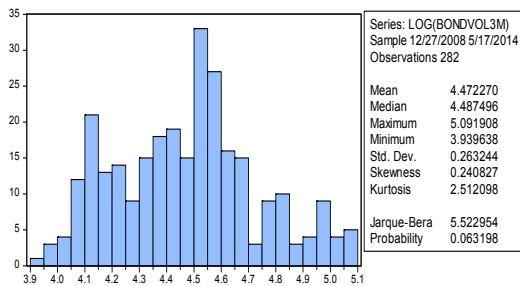
## Appendix 1: Descriptive statistics and preliminary results from quantile regression

Given the focus of the paper, in Graph A1 we show the standard descriptive statistics of bond and stock market volatility in log levels (with the histograms). It is important to note that the skewness statistics for both series diverge from zero, suggesting that both volatilities do not follow symmetric distribution. Positive skewness means that the distribution has a long right tail, and since the kurtosis remains below 3, the distribution is peaked (leptokurtic) relative to the normal. The Jarque-Bera (JB) test statistic measures the difference of the skewness and kurtosis of the series with those from the normal distribution. The reported JB p-value for log of VIX suggests the rejection of the null hypothesis of a normal distribution at the 1% significance level. The JB test of normality is rejected for log of the VIX, but the normality test can only be rejected at the 10% level of significance for log of the MOVE index.

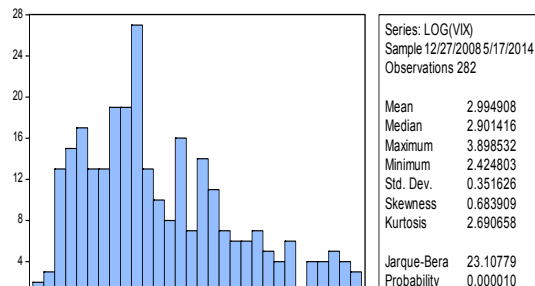
The distribution and test of normality

Graph A1

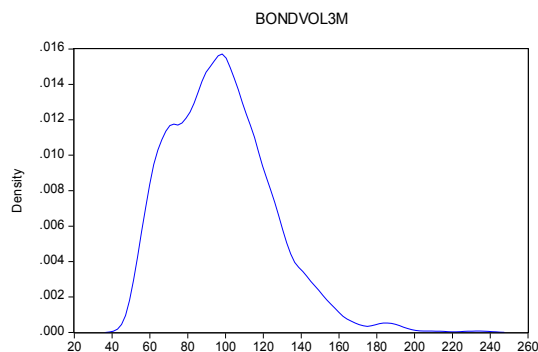
Bond volatility histogram



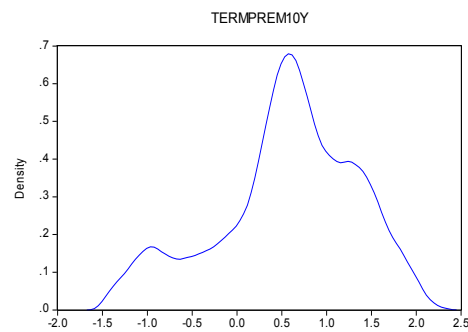
Equity volatility histogram



Bond volatility (kernel density distribution)

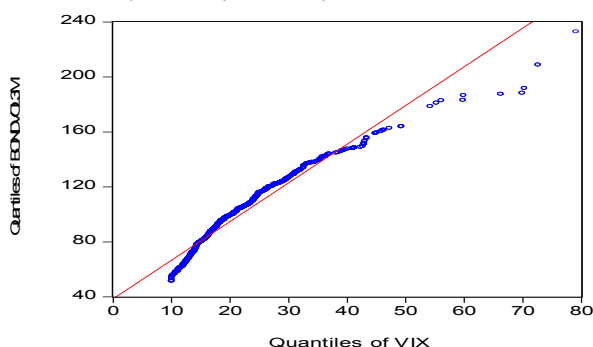


Term premia (kernel density distribution)

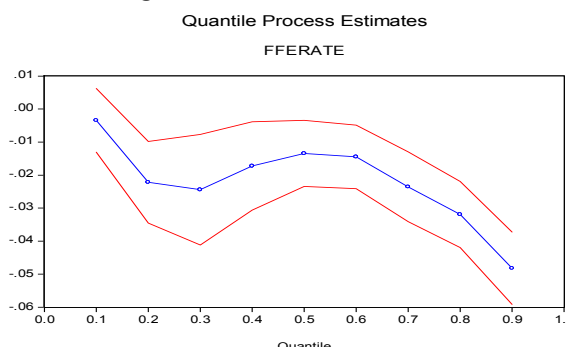


These characteristics suggest that empirical estimation may present an uncertain bias if we follow the traditional analysis under the assumption of normality. The kernel density graph for bond volatility also displays the density not having a normal shape, which suggests that there are high and low volatility regimes, and Fed policy may have differential effects depending on the volatility regime. Looking at term premia density, it is quite clear that the shape of the distribution is multi-modal, raising the issue of multiple equilibria. It also highlights the possibility that at higher levels of term premia, the impact of the Fed rate is lower in reducing term premia.

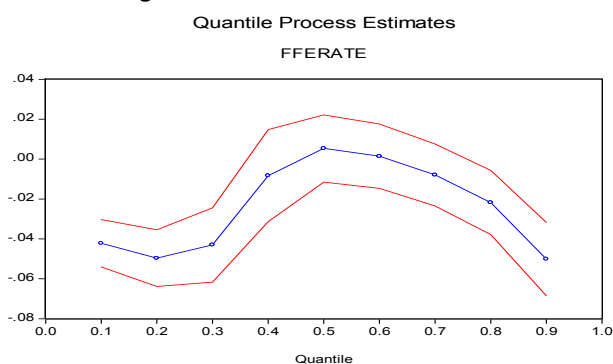
Quantile-quantile plot (empirical distribution)



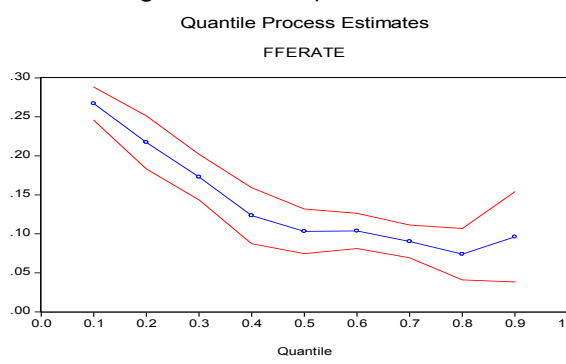
Quantile regression of Bond Vol on Fed rate



Quantile regression of VIX on Fed rate



Quantile regression: term premia on Fed rate



The empirical quantile distribution plots the quantiles of bond volatility against the quantiles of equity volatility. If the distributions of the two series are the same, the QQ-plot should lie on a straight line. As shown in the figure above, they are clearly different at the high end, which explains a possible decoupling that has been observed in recent years. But for most of the sample period, both series seem to have co-moved. This suggests that there is clearly a need for quantile estimation for bond volatility as the unconditional distribution is not normal.

Koenker and Bassett (1978) first proposed quantile regression as an extension of the classical OLS estimation of approximating the conditional mean located at the centre of the distribution to different conditional quantile functions, thereby fully representing the distribution with the estimated coefficients being insensitive to outliers (also see Koenker and Hallock (2001)). In the quantile regression plots in Graph A2, at higher quantiles of conditional distribution of bond volatility, which is the case during the post-crisis sample when the interest rate is zero-bound, the impact of the Fed rate on bond volatility is lower. This implies that the volatility has been minimised at the top end of the distribution via the asset purchase programme.

As shown in Graph A2, there are different responses at different points of the conditional distribution of bond volatility. The bivariate quantile regression results indicate that bond volatility was more affected by the Fed target rate when the bond volatilities were high, but they were less affected by Fed policy when the volatilities were low. Given the negative relationship between Fed rate and bond volatility, higher Fed rate is more effective in lowering volatility when bond volatility is high, which means the zero-bound Fed rate can increase volatility that can only be lowered by other instruments such as LSAP. Therefore the LSAP programme might have had a

role to play in this regard, which requires further empirical investigation. Although quantile regression considers the conditional distribution of bond volatility (dependent variable), it fails to consider the time-varying properties of the independent variable (fed funds rate). Therefore we cannot use this bivariate approach to describe the current scenario where interest rate is near zero. In what follows we put these preliminary findings to formal empirical examination through VAR models. The bivariate quantile regression is simply used as a type of descriptive analysis to understand the effect of the policy rate on volatility at different segments of the distribution of volatilities in order to motivate our VAR analysis in the next section. There is clearly a negative relationship between the policy rate and bond volatility (also the VIX and term premia).

## Appendix 2: Robustness with respect to sign restriction VAR

In this appendix, we undertake an alternative identification using the weekly model, with two shocks being identified jointly using sign-restriction VAR. In addition to the above recursive traditional identification strategy, we adopt a sign restriction method (Uhlig (2005)) which is robust to non-stationarity of series including breaks. Although the zero restrictions may appear ad-hoc, they are useful in considering statistical properties of the data. Within the sign-restrictions approach, we can make use of serious theoretical considerations and identify different types of underlying disturbances, namely term premia and bond volatility shocks jointly or Fed asset purchase and bond volatility jointly. We apply sign restrictions to the above VAR with six variables.

We impose two sign restrictions to identify a term premia shock and three sign restrictions to identify a bond volatility shock, and four restrictions to identify a Fed asset purchase shock (monetary easing) as a robustness check. The restrictions are shown in Table A2. First, we jointly identify a bond volatility shock alongside a term premia shock, in order to check any inter-linkage between Treasury market and bond volatility. Then we also jointly identify bond volatility and Fed asset purchase shocks to corroborate our earlier evidence whether the asset purchase policy has influenced market expectations and stabilised market volatilities.

The first two shocks are: term premia shock and asset purchase shock. The shocks are defined as follows: while a term premia shock refers to an increase in term premia and bond volatility, the asset purchase shock means a decline in term premia and a decline in bond volatility. The shocks have been identified correctly as the term premia shock does lead to an increase in bond volatility whereas the asset purchase shock leads to a reduction in bond volatility. Although we only impose these restrictions for two weeks, they sustain for a very long time span, as shown in the responses (see Graphs A5a and A5b).

In addition, we also identify a bond volatility shock first and then asset purchase shock (see Graphs A6a and A6b). The bond volatility shock is defined as one which leads to an increase in stock volatility and a decline in fed futures expectations. Fed funds rate normally declines following an increase in market volatility and therefore Fed futures may decline. Fed futures may also decline in response to positive bond volatility shocks. These restrictions are accepted but the shock has no strong effect on economic conditions, term premia, or asset purchases. However, the impact of an asset purchase shock remains the same in this alternative identification as in the benchmark recursive identification case.

Identifying sign restrictions

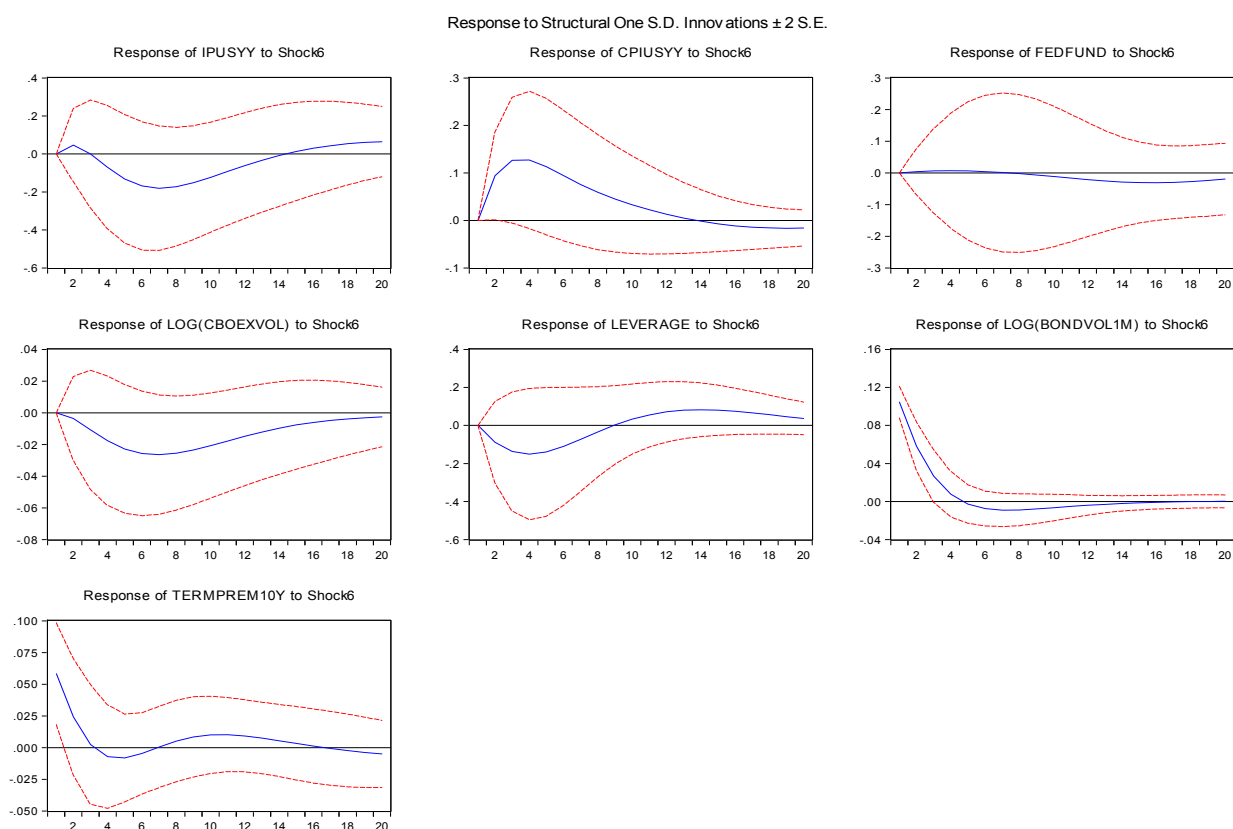
Table A1

	Economic conditions	Term premia	Fed asset purchase	Fed funds futures	Bond volatility	Stock volatility
Term premia shock (positive)	?	+	?	?	+	?
Fed asset purchase shock (positive)	+	-	+	?	-	?
Bond volatility shock (positive)	?	?	?	-	+	+

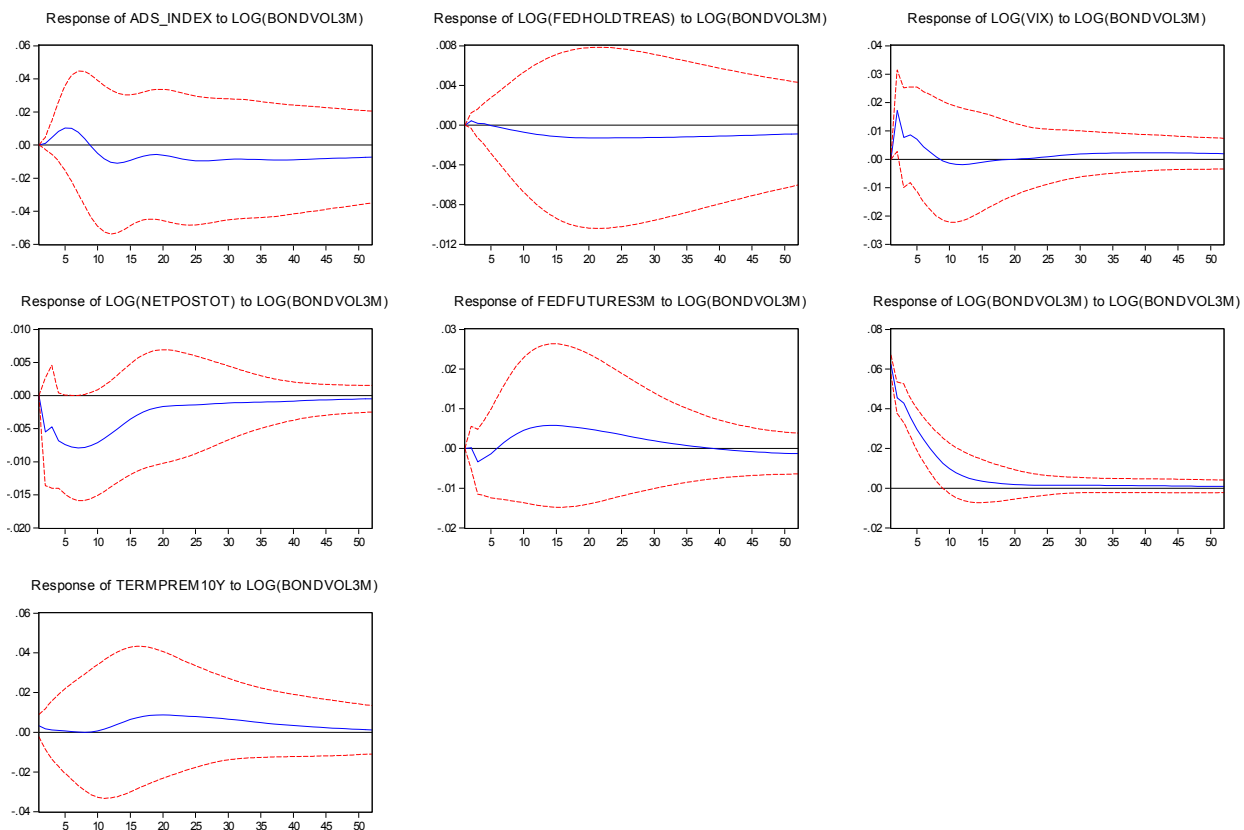
Our results with regard to the effect of a Fed asset purchase shock show that it contributed to lowering term premia and bond volatility. With regard to the effect on economic conditions, an LSAP shock has a positive impact on economic activity (see Graph A5b). This is also consistent with the finding in Baumeister and Benati (2013), who explore the macroeconomic effects of a spread shock defined as a shock that leaves the policy rate unchanged via large asset purchases, and find that such unconventional monetary policy actions have averted significant risks both of deflation and of output collapses. The three shocks are displayed in Graphs A6d-e over the period 2008-2010.

Quarterly MOVE shock

Graph A3

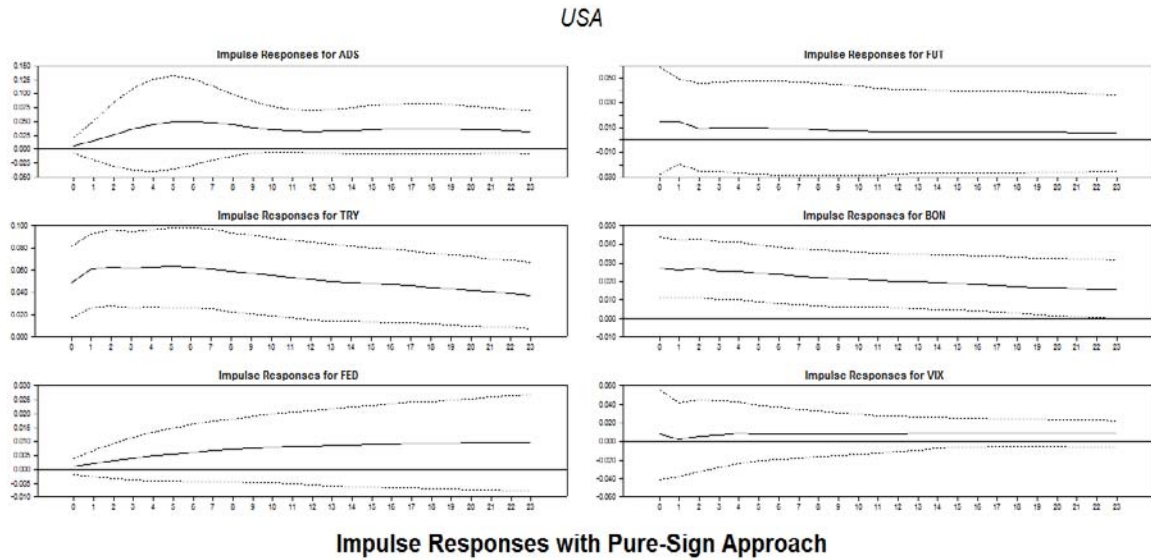


Response to Cholesky One S.D. Innovations  $\pm 2$  S.E.



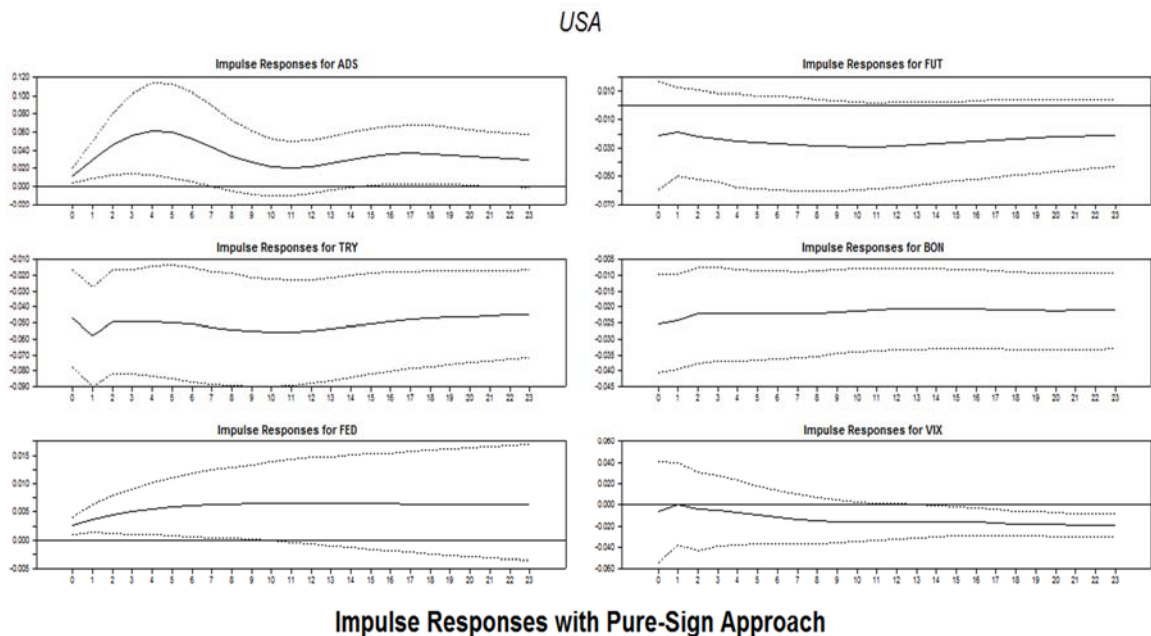
Term premia shock using sign restrictions (+term premia, +bond volatility) (joint identification of two shocks – term premia and fed purchase)

Graph A5a



Fed asset purchase shock (+Fed policy, –bond volatility, –term premia, +economic condition)

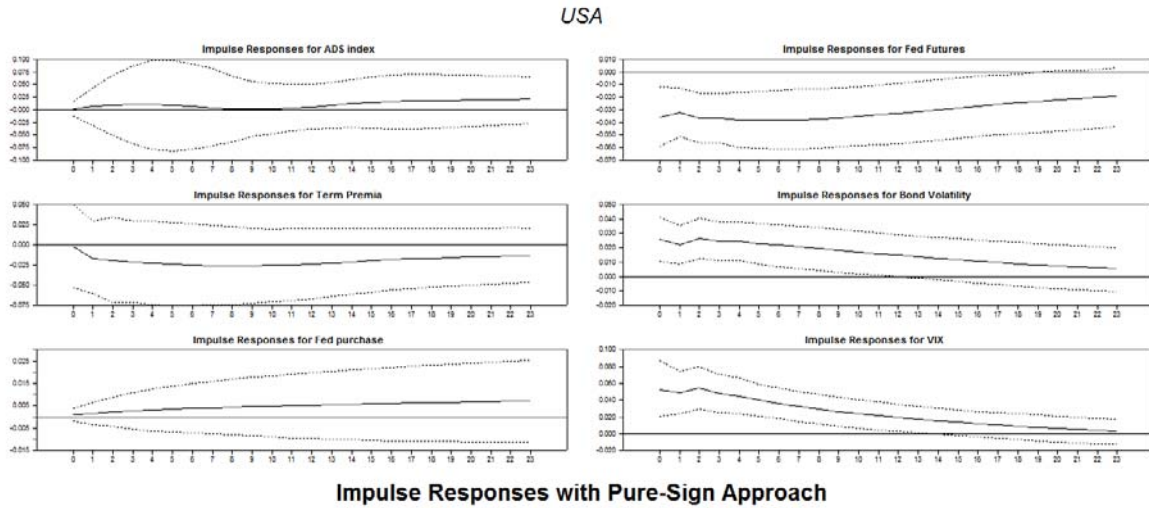
Graph A5b





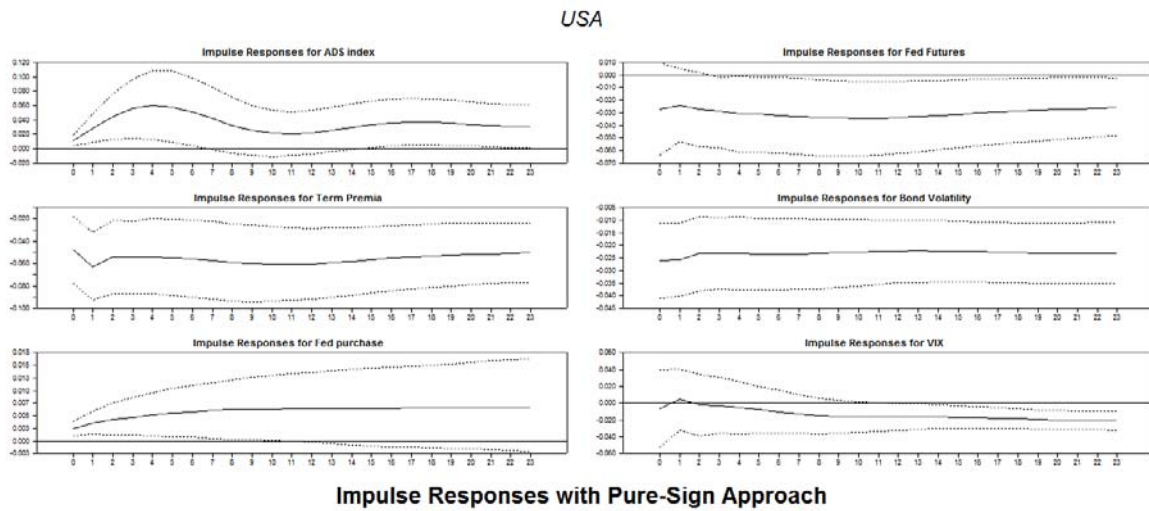
Bond volatility shock using sign restrictions (+bond volatility, –fed funds futures, +vix) (joint identification of two shocks – bond volatility and fed purchase)

Graph A6a



Fed asset purchase shock (+Fed policy, –bond volatility, –term premia, +economic condition)

Graph A6b

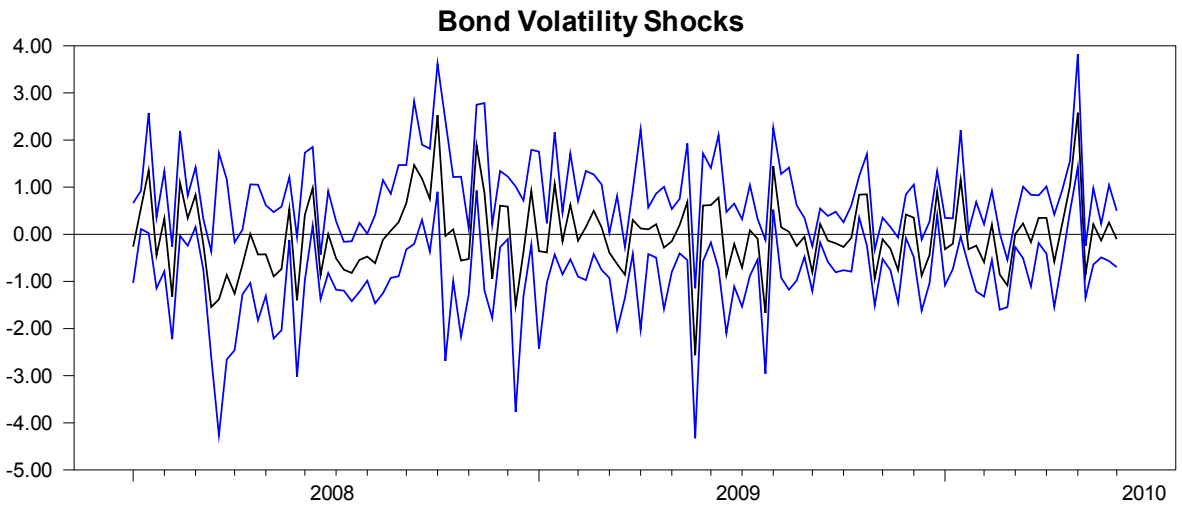


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Bond volatility shocks using sign restrictions (+bond volatility, -fed funds futures, +VIX) during 2008-2010

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Graph A6c

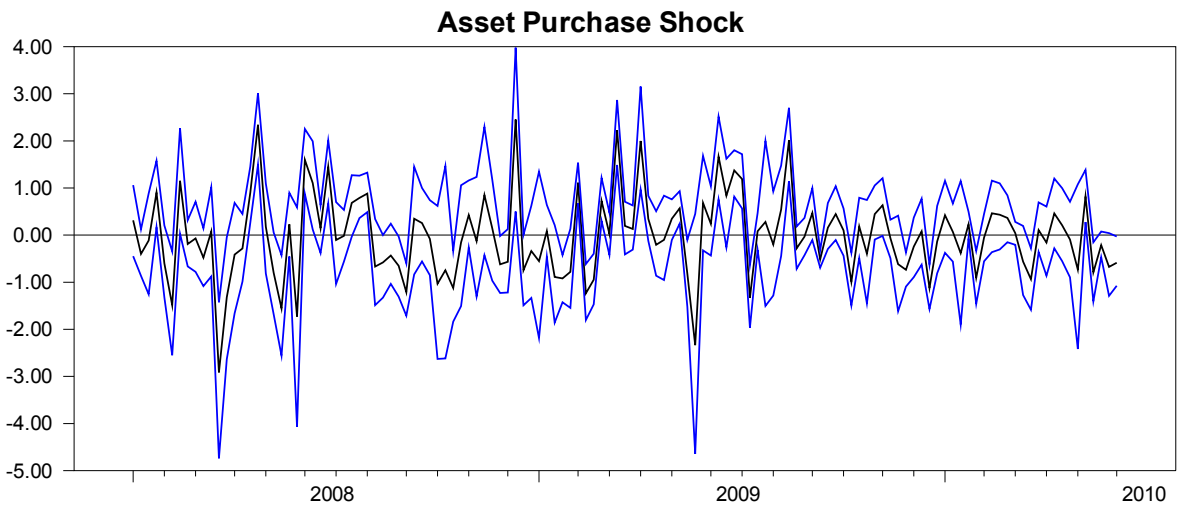


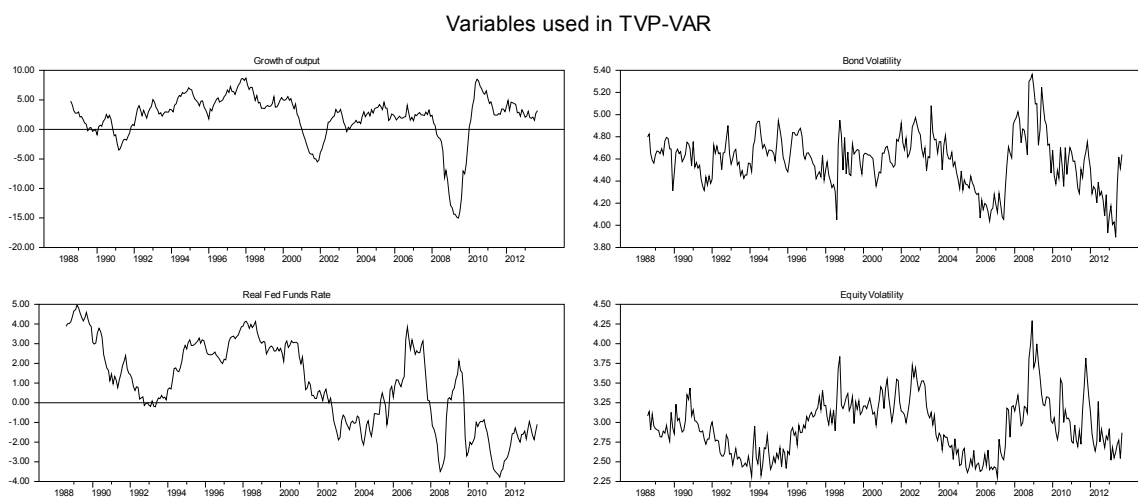
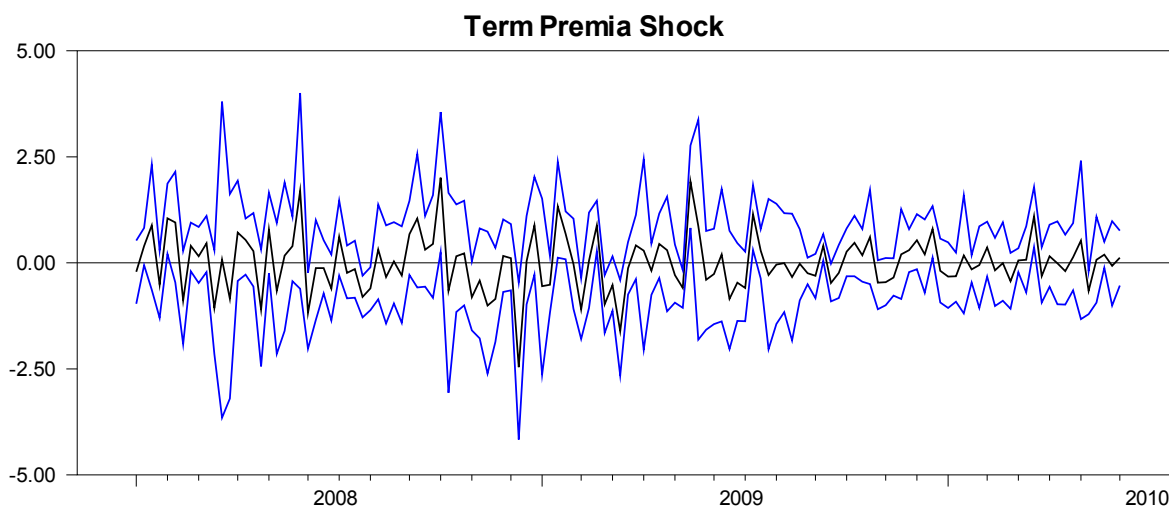
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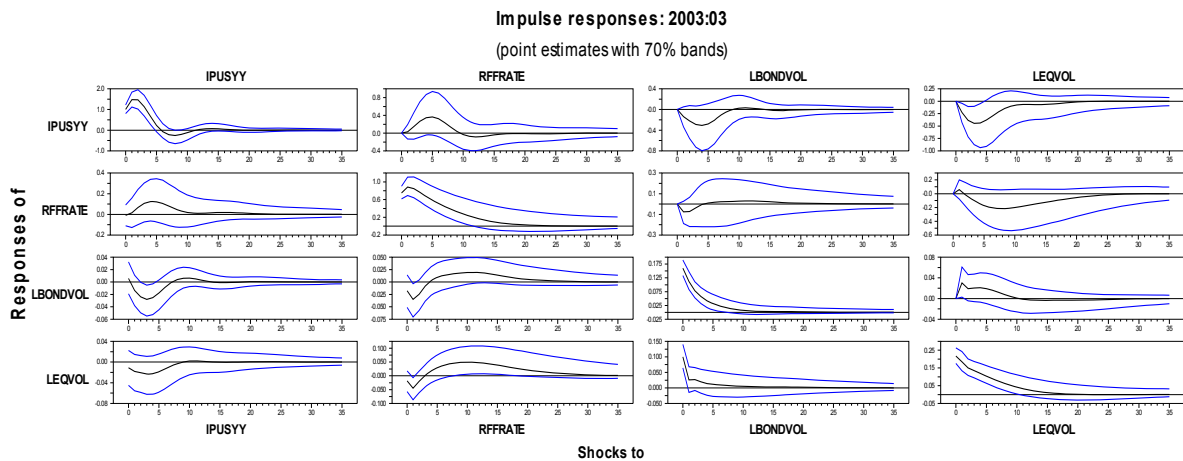
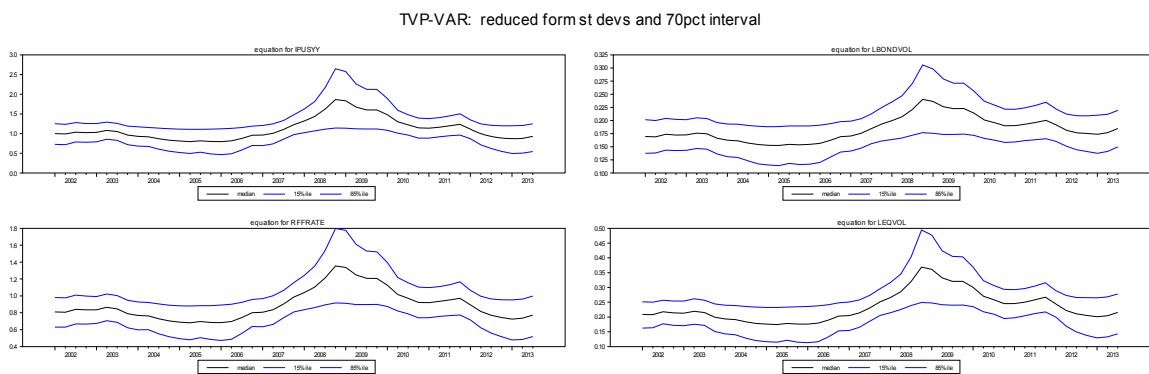
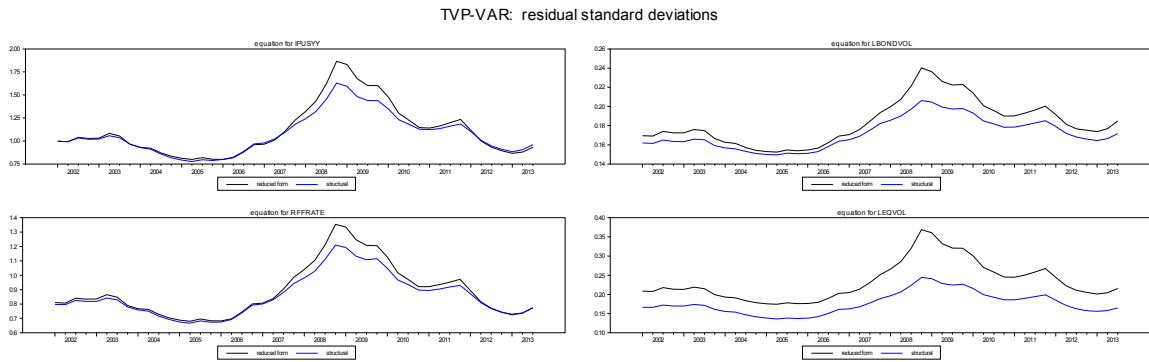
Fed asset purchase shock (+Fed policy, -bond volatility, -term premia, +economic condition)

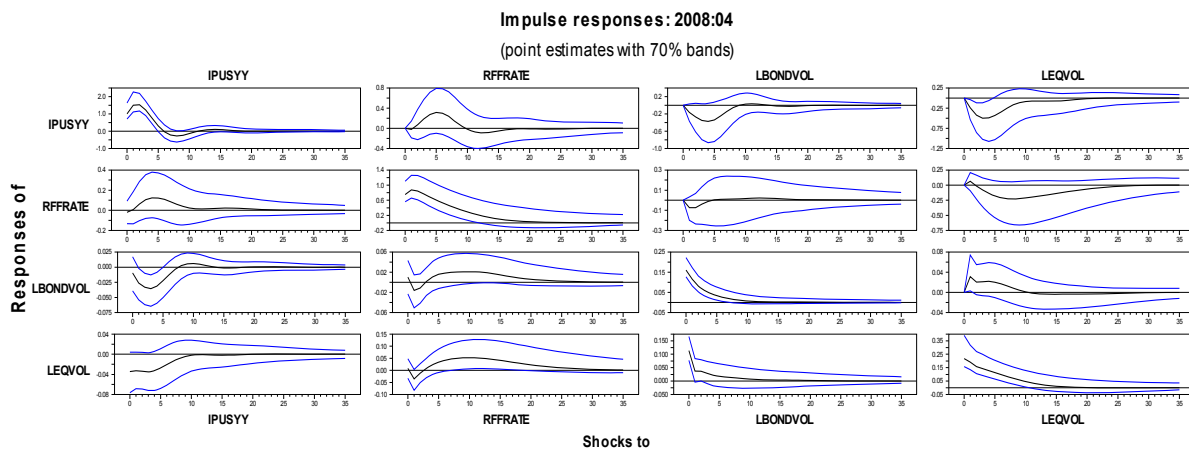
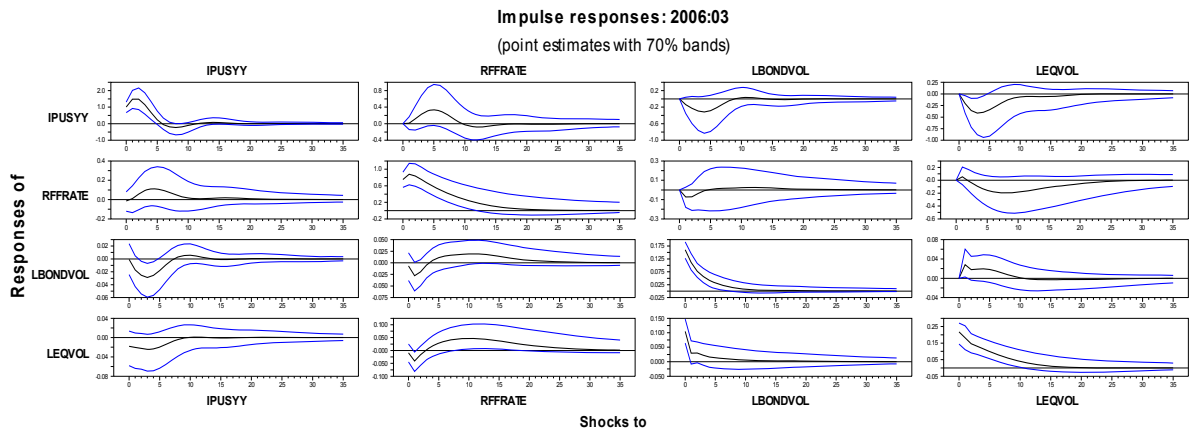
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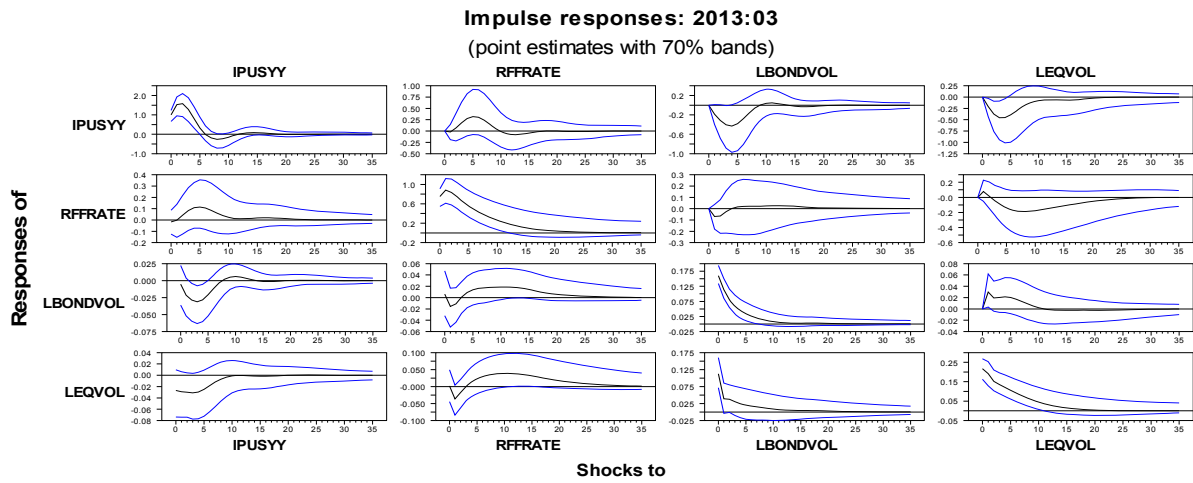
Graph A6d



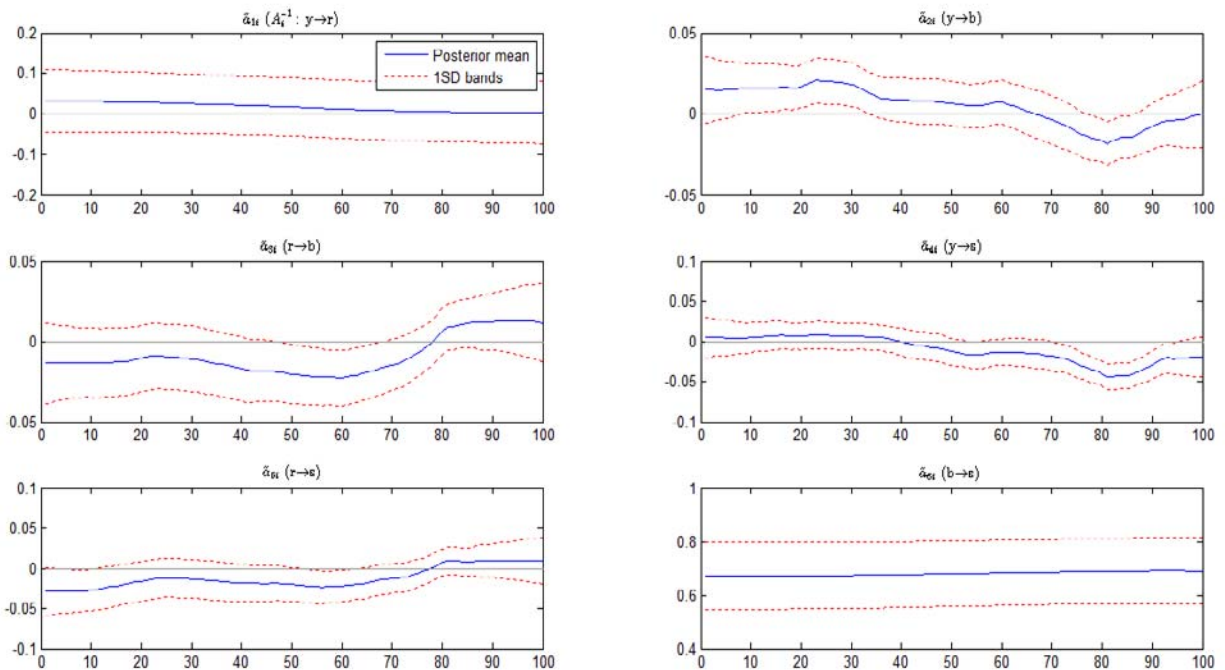








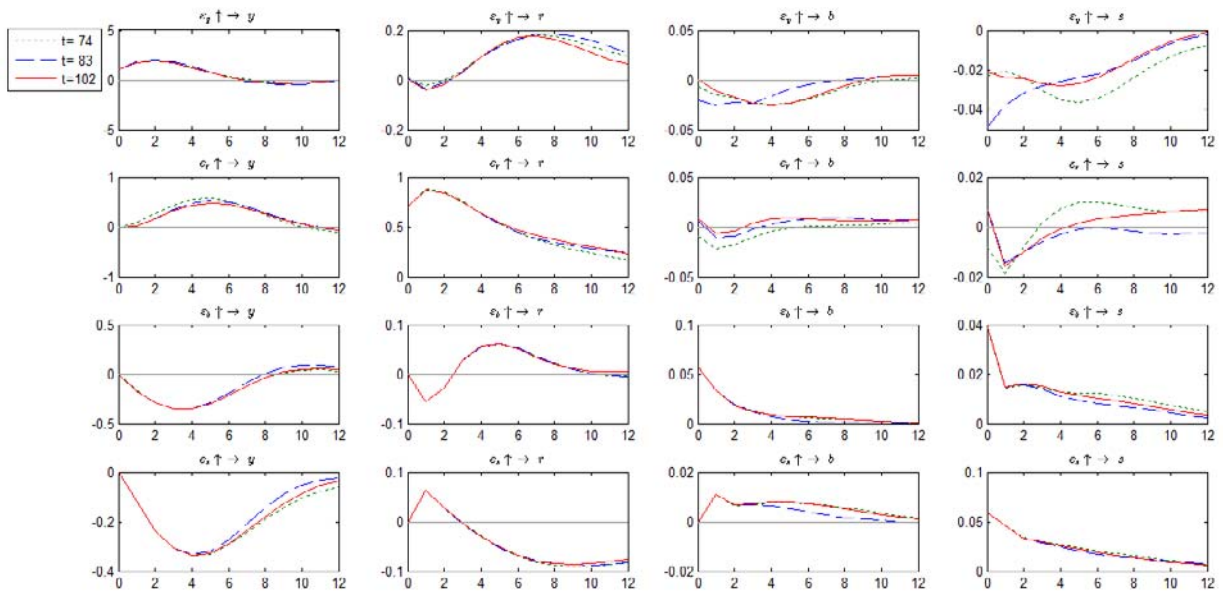
Time-varying contemporaneous effect of structural shocks based on recursive identification



Notes: y, r, b, and s denote output growth, real interest rate, bond volatility and stock volatility respectively. X-axis represents quarters starting from 1988Q2 to 2013Q3 (102 quarters in total).

Time-varying impulse responses at 2006Q3 (t=74), 2008Q4 (t=83), and 2013Q3 (t=102)

Graph A9b



Notes: y, r, b, and s denote output growth, real interest rate, bond volatility and stock volatility respectively. Rows refer to the effect of each shock. The responses at all points in time can be seen in Graph A9a. Specifically, we also plotted the responses at t=30 (1995Q3), t=60 (2003Q1), and t= 90 (2010Q3), and we found similar responses. They can be obtained from the authors.

## Unit root tests

Table A2

	DFGLS	KPSS	Zivot-Andrews	Lumsdaine-Papell	Lee-Strazicich
ADS_Index	-1.6316*	0.9645**	-5.6149** [2009:03:20]	-4.9562 [2008:05:09 2009:06:12]	-6.9525** [2009:02:13 2010:06:25]
TREASYLD10Y	-0.6919	1.5485**	-5.1495** [2011:07:29]	-5.3524 [2011:07:01 2013:04:19]	-4.7505** [2011:07:29 2013:06:07]
TERMPREM10Y	-1.0216	1.4343**	-4.3781 [2011:06:17]	-6.7316** [2011:06:10 2013:04:12]	-5.5926** [2011:07:29 2013:05:24]
FEDHOLDTREAS	1.5200	2.0717**	-3.7862 [2008:03:21]	-4.8551 [2008:03:14 2010:11:12]	-2.7524 [2011:01:14 2012:04:20]
FEDFUTURES3M	-0.1098	1.0475**	-5.72850** [2008:08:08]	-6.8314** [2008:09:19 2010:04:16]	-3.8321* [2008:10:31 2012:03:09]
BONDVOL3M	-2.0009**	1.7147**	-4.9114* [2008:12:19]	-4.4992 [2009:08:07 2011:11:18]	-6.8025** [2008:11:14 2010:05:07]
VIX	-3.1172**	1.0799**	-5.2402** [2009:03:13]	-4.8656 [2008:08:22 2009:10:02]	-5.7260** [2008:11:07 2009:07:10]

Notes:

DFGLS and KPSS tests are known as Dickey-Fuller test with GLS detrending, and the Kwiatkowski, Phillips, Schmidt, and Shin test respectively. The DFGLS test involves estimating the standard ADF test equation with the GLS de-trended data as opposed to the original series. The KPSS test differs from other unit root tests in the sense that the time series is assumed to be trend-stationary under the null. The optimal lag length in the DF-GLS test is 6, which has been automatically selected by the lag selection criteria. Zivot-Andrews (ZA) test allows for structural break in both intercept and trend.

\* and \*\* denote rejection of the null at 10% and 5% level of significance respectively. The asymptotic 10% critical values are: DFGLS: -1.6160 (with constant); KPSS: 0.3470 (with constant). Under KPSS test, the null is stationary. ZA Critical Values are -5.57 and -5.08 for 1% and 5% respectively. Numbers in brackets are the estimated structural breaks based on the ZA test. Lumsdaine-Papell Unit Root Test critical values are -6.7400 (1% sig level), -6.1600 (5% sig level) and -5.8900 (10% sig level). Critical values of the endogenous two-break LM unit-root test at 10%, 5% and 1% level of significance are -3.504, -3.842 and -4.545 respectively from Table 2 Lee and Strazicich (2003: 1084).



## VAR Lag Order Selection Criteria

Table A3

Lag	LogL	LR	FPE	AIC	SC	HQ
0	-781.3908	NA	7.63e-05	4.708927	4.765980	4.731675
1	2095.888	5651.182	2.92e-12	-12.37059	-12.02827	-12.23410
2	2540.151	859.2638	2.37e-13	-14.88115	-14.25356	-14.63092
3	2695.970	296.7084	<b>1.08e-13*</b>	<b>-15.66449*</b>	<b>-14.75164*</b>	<b>-15.30053*</b>
4	2709.588	25.52287	1.16e-13	-15.59633	-14.39822	-15.11863
5	2728.609	35.08196	1.20e-13	-15.56053	-14.07716	-14.96909
6	2760.768	58.34784	1.15e-13	-15.60340	-13.83476	-14.89822
7	2790.301	52.69888*	1.13e-13	-15.63054	-13.57663	-14.81162
8	2808.845	32.53689	1.17e-13	-15.59189	-13.25272	-14.65923

Notes: \* indicates lag order selected by the criterion; Endogenous variables: TREASYLD10Y ADS\_INDEX LOG(VIX) LOG(BONDVOL1M) LOG(FEDHOLDTREAS); LR: sequential modified LR test statistic (each test at 5% level); FPE: Final prediction error; AIC: Akaike information criterion; SC: Schwarz information criterion; HQ: Hannan-Quinn information criterion.

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