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The Response of Tail Risk Perceptions to Unconventional Monetary Policy*

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Abstract

We evaluate the response of perceived tail risks in financial markets to the implementation of unconventional monetary policy by the U.S. Federal Reserve. Using information from out-of-money equity index options, we find that perceived risks decline significantly in response to both policy announcements and actual asset purchases. The announcement effects are strongest specifically for downside risk measures rather than simple measures of volatility (e.g. the VIX). The impact of actual purchases is strongest when driven by simultaneous expansion and the duration extension of the Federal Reserve's balance sheet. These effects of both announcements and purchases have been variable over time and particularly pronounced during the latest policy phases implemented in 2012, a period also coinciding with the Federal Reserve's more extensive use of forward guidance about short-term rates.

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So what are policymakers to do? First and foremost, reduce uncertainty. Do so by removing tail risks, and the perception of tail risks.

Olivier Blanchard, chief economist, IMF, *The Economist*, January 31, 2009

Even in the aftermath of the crisis, businesses, banks, and investors have been exceptionally cautious, presumably reflecting their concern about future business conditions, uncertainty about economic policy, and the perception of pronounced tail risks relating, for example, to stresses in global financial markets. I see one purpose of the Committee's accommodative policies as promoting a return to prudent risk-taking.

Federal Reserve Vice Chair Janet L. Yellen, March 4, 2013, at the National Association for Business Economics Policy Conference, Washington, D.C.

I. Introduction

There is a widespread belief that unconventional policy actions undertaken by various central banks over the past years have helped (at least partly) in alleviating some of the most immediate downside risks to financial markets and the global economy. Thus far, however, any evidence on what may be labelled the "tail risk impact" of unconventional monetary policy has been largely anecdotal. In this paper we present some quantitative evidence that unconventional monetary policy announcements and asset purchases by the U.S. Federal Reserve substantially reduced market perceptions of tail risks. Thus, the impact of unconventional monetary policy may have been broader than suggested by prior empirical studies, which have mostly focused on the effects of quantitative easing on the shape of the yield curve, asset prices, and, more recently, investors' portfolio flows.

We gauge downside risk perceptions using information gleaned from out-of-the-money (OTM) equity index (S&P500) options. Specifically, we rely on the difference between the option-implied volatilities of OTM calls and puts of the same maturity and "moneyness" (or so-called delta), often referred to as "risk reversal," as an indicator of how market participants perceive the risk of a stock market crash. In essence, this measure captures the option-implied skew in the equity return distribution (i.e. the third moment) and the associated skewness risk premium. It thus differs from the VIX (the Chicago Board of Exchange S&P500 option implied volatility index), a commonly used "fear gauge," which does not specifically capture downside risks, as it can be considered as a symmetric measure of expected volatility (the second moment).[1]

The literature on the transmission of unconventional monetary policy has been expanding rapidly in recent years. Most emphasis thus far has been on measuring the effectiveness of quantitative easing policies in affecting the shape of the yield curve (see e.g. Gagnon, Raskin, Remache, and Sack, 2011; D'Amico and King, 2012). Other papers have been broader in scope and have looked at the relevance of a variety of transmission channels by gauging the response of other asset prices, such as corporate bonds or inflation swaps (Krishnamurthy and Vissing-Jorgensen, 2011). Recent work has also started to investigate the global impact of unconventional policies, going beyond asset prices to also look directly at international capital flows (see Chen, Filardo, He, and Zhu, 2012; Fratzscher, Duca, and Straub, 2012). In line with these latter studies, the goal of this paper is to examine the broader impact of the unconventional policies, in this case on the perceptions of tail risk by market participants.

In this paper, we go beyond earlier work in two ways. First, while previous literature looked at the impact of conventional monetary policy on risk premia and some broader measures of risk appetite, we study the impact of the most recent policies, adopted since shor-term rates hit the zero-lower bound. With the scope of further easing by conventional tools exhausted, the Federal Reserve resorted to purchases of long term government and agency debt to provide further accommodation while also providing guidance about its outlook for short-term policy rates. Second, we analyze the responses in the negative tail of option-implied distribution rather than using a symmetric volatility measure such as the VIX. Specifically, we focus on the option-implied insurance premium against a sharp

[1] As depicted in Figure 4 and discussed in Section III, while risk reversals do not directly measure the probability mass in the left tail of the implied distribution they exhibit large and highly statistically significant correlation with measures available at monthly frequency that do exactly that.

drop in equity prices and how it was affected by the unconventional monetary policy announcements and asset purchases of the Federal Reserve.

Our empirical strategy is as follows. As a first step, we examine the effects of announcements and key public statements (announcements henceforth) of asset purchase programs and forward guidance via a simple non-parametric event study technique. To this end, we analyze the behavior of (tail) risk measures around 17 key announcement dates. We address small sample problems by relying on a time-series bootstrap when evaluating the statistical significance of the observed changes. As a second step, we use event study regressions in the spirit of Beber and Brandt (2006), Krishnamurthy and Vissing-Jorgensen (2011), Jiang, Konstantinidi, and Skiadopoulos (2012) and others, where we also control for drivers of risk perceptions other than monetary policy announcements. Third, we look at the impact of actual asset purchases on risk appetite and tail risk perceptions using balance sheet data of the Federal Reserve. We rely on vector autoregressions (VAR) at a weekly frequency, again controlling for prevailing macroeconomic and financial conditions when identifying the effects of unconventional monetary policy shocks. This setup also allows us to evaluate the differential impact of the Federal Reserve's purchases (or sales) of Treasury securities across various maturity baskets. Finally, we assess the impact of policy over time by studying its effects using a Bayesian time-varying parameter (TVP) VAR.[2]

Our main findings are as follows. First, event study results show that announcements associated with the Federal Reserve's unconventional policy actions significantly reduced investors' immediate perceptions of downside risks. These declines are immediate, with lower levels sustained for weeks after the announcements. While the proxies of perceived tail risks and their market hedging costs exhibit clear reactions to announcements, the VIX tends to respond with a lag, with significant changes detected only for longer announcement windows. The declines in the proxies for perceived tail risk have been large on the days of

[2]By unconventional policies we are referring to outright purchases of Treasuries, maturity extensions of the Federal Reserve's balance sheet whereby long-term purchases are accompanied by sales at the short-end, and the complementary use of forward guidance about short-term interest rates. For conciseness we refer to the Federal Reserve's large-scale asset purchase program announced in December 2008 as QE1, the program formally announced in November 2010 as QE2, the maturity extension of the Federal Reserve's balance sheet that began in September 2011 as MEP, and the fixed amount monthly purchases unveiled in September 2012 as QE3.

announcements associated with QE1 and particularly pronounced again during the Federal Reserve's operations unveiled in 2012 for the ongoing QE3 phase. To the extent that announcements during the latter part of the sample period increasingly contain guidance about future short-term rates, our findings are also consistent with simulation results of Chen, Curdia, and Ferrero (2012), who conclude that forward guidance enhances the effects of asset purchase programs. However, a direct test of the impact of forward guidance is outside the scope of this paper, since official announcements tend to contain information related to several policy measures at once.

Second, based on the VAR framework we find that actual asset purchases by the Federal Reserve had an impact on risk perceptions that goes beyond announcement effects. Following a positive shock to Treasury security holdings by the Federal Reserve, risk reversals decline significantly, with the effect peaking approximately two weeks after and sustained for more than three months. Purchases of medium- and longer-maturity bonds (maturity of five years or greater) and sales of shorter-maturity instruments (maturity less than one year) are associated with significant declines in the pricing of tail risk. This suggests that the Federal Reserve's policy of increasing the maturity of its asset holdings may have been particularly effective in curbing perceived tail risks and stimulated risk-taking. Third, our TVP-VAR results indicate that the impact of actual bond purchases by the Federal Reserve has varied over time, with the effect becoming more certain around the ongoing QE3/MEP phase. Thus, in contrast to studies that have found diminishing marginal impact of unconventional monetary policy on yields over time, we find a strong effect on proxies of tail risk perceptions during the more recent rounds of easing by the Federal Reserve, both announcements and purchases.

Evidence of monetary policy transmission to asset prices and risk-taking pre-dates the ongoing unconventional measures. A seminal paper in this context is by Bernanke and Kuttner (2005), who find a robust impact of Federal funds rate surprises on broad stock market indices. Two studies that are close in spirit to ours are Bekaert, Hoerova, and Duca (2010) and Bruno and Shin (2012). Both papers investigate the connection between conventional monetary policy and financial market volatility, as captured by the VIX. Decomposing the

VIX into a measure of uncertainty and risk aversion, Bekaert, Hoerova, and Duca (2010) provide evidence that expansionary conventional monetary policy as measured by the real federal funds rate tends to dampen investor risk aversion. Bruno and Shin (2012) find empirically that accommodative monetary policy drives down risk and leads to a pick-up of cross-border bank credit, in line with a "risk-taking channel of monetary policy" (Borio and Zhu, 2012).

The remainder of the paper is organized as follows. Section II provides a brief account of the unconventional monetary policy operations by the Federal Reserve from 2008 through 2012 and of the possible transmission channels of unconventional policies. Section III describes the empirical proxies of (tail) risk perceptions. Section IV describes the data sources. Section V presents results of the event-study results on the impact of Federal Reserve announcements. Section VI analyses the impact of actual asset purchases using structural VAR approaches. Section VII provides some further discussion and concludes.

II. Quantitative Easing Policies and Their Transmission

A. Overview of Policy Innovations by the Federal Reserve

The Federal Reserve began announcing large-scale asset purchases (LSAP) in December 2008 and started with actual purchases of government bonds and agency securities in March 2009. The stated aim of the first round of LSAP (LSAP1) was to "provide support to mortgage lending and housing markets and improve overall private credit markets." By the end of LSAP1 in March 2010, the Federal Reserve had purchased \$300 billion of longer-term Treasury securities, \$175 billion of agency debt, and \$1.25 trillion of agency mortgage backed securities (MBS). All in all, this amounted to a \$1.7 trillion increase in the Federal Reserve's balance sheet. The second round of quantitative easing (LSAP2), hinted at in Chairman Bernanke's Jackson Hole speech in August 2010 and formally announced at the November FOMC meeting, involved a further \$600 billion in purchases of longer-term Treasuries, bringing the total increase in the Federal Reserve's balance sheet to \$2.3 trillion by June 2011.

While the Federal Reserve's statements gave no clear guidance on the intended direct effect of LSAPs on asset prices, this changed with the maturity extension program MEP, which was supposed to "put downward pressure on longer-term interest rates and help make broader financial conditions more accommodative." With the economic outlook deteriorating again by mid-2011, the FOMC decided to provide further policy accommodation at its September 2011 meeting. Specifically, the Federal Reserve proceeded to extend the maturity of its existing asset holdings, that is, to finance purchases of long-term Treasury bonds with sales of an equal amount of short-term notes, keeping the size of the balance sheet unchanged but increasing the duration of its asset holdings. The initial target for the MEP, also referred to as "Operation Twist," involved the sale of $400bn of Treasuries with maturity one year or less and a purchase of securities with an average time to maturity of ten years. There were also large purchases at the very long end (30 years) which accounted for roughly 21% of the amounts outstanding. In June 2012, the Federal Reserve announced further MEP with additional purchases of $267 billion of even longer average maturity, financed by selling bonds with 1-3 year maturity. In total the balance sheet stood at $2.8 trillion by the end of Q3 2012.[3] Figure 1 shows the composition of the Federal Reserve's treasury holdings broken down into four maturity baskets.

– Insert Figure 1 about here –

In September 2012, the Federal Reserve switched to a combination of policies, extending the maturity of its Treasury holdings while also conducting large scale purchases of MBS. For the first time, the FOMC did not commit to a pre-specified limit, but specified the pace of monthly purchases, of $40 billion and $45 billion of MBS and Treasury securities respectively, until the situation in labor markets improved sufficiently. Such a conditionality

[3]To prevent a gradual decline in balance sheet size through repayments of MBS, a reinvestment policy was introduced. In August 2010 the Federal Reserve announced reinvestment of mortgage principal payments into Treasuries, representing roughly an additional $180 billion increase in Treasuries held outright in total. Then, in September 2011, FOMC announced the decision to reinvest principal payments of MBS back into MBS.

signalled to markets the willingness of the Federal Reserve to provide insurance against possible adverse states of the world.

A complementary tool once short-term rates hit the zero-lower bound has been forward guidance. Specifically, the Federal Reserve began employing forward guidance for the federal funds rate target of 0 to 25 b.p. in its December 2008 FOMC meeting, stating that "weak economic conditions are likely to warrant exceptionally low levels of the federal funds rate for some time." The Committee then changed the language from "for some time" to "for an extended period" at its March 2009 meeting. At its August 2011 meeting, the FOMC changed "for an extended period" to "at least through mid-2013" then to "at least through 2014" at the January 2012 meeting. Finally, the FOMC adopted a threshold based forward guidance at the December 2012 meeting, indicating the 0 to 25 b.p. target range as appropriate as long as unemployment rate remains above 6.5% and inflation expectations are well anchored. Such increasingly explicit guidance may have signalled a stronger commitment to keep interest rates low for long, thus anchoring expectations of future short-term rates. Since these statements were usually a part of broader announcements by the Federal Reserve, which also included information about its asset purchase program, the results in this paper, especially event studies of announcement effects, are likely picking up joint impact of both quantitative easing and forward guidance.

B. Transmission Channels in the Existing Literature

Since the Federal Reserve began with its unconventional policy actions in late 2008, there has been a growing body of empirical literature to analyze its transmission effects. The primary focus has been on announcements of new open market operations and the subsequent purchases, and how successful these were in bringing down longer-term bond yields (Gagnon, Raskin, Remache, and Sack, 2011; Krishnamurthy and Vissing-Jorgensen, 2011; D'Amico and King, 2012). Some literature, especially more recent papers, have also focused on the impact of forward guidance and expected path of future short-term rates.

The theoretical motivation for the transmission of unconventional policies has mostly revolved around the so-called "signalling" and "portfolio balancing" channels. According to the signalling channel, asset purchases (and even mere announcements) can signal commitment to monetary stimulus, thereby lowering the expected path of future short-term rates (see Eggertsson and Woodford, 2003). According to the portfolio rebalancing channel, announcements and actual purchases of government bonds can trigger portfolio rebalancing, as investors who have preferences for bonds of specific maturities or safety characteristics ("preferred habitat investors") shift into close substitutes to the securities being purchased.

Using event studies, Gagnon, Raskin, Remache, and Sack (2011) provide evidence that yields of longer-dated Treasuries and MBS yields fell more than shorter-dated bonds (in total, a 91 b.p. impact for ten-year compared to 34 b.p. for two-year Treasury yields).[4] They attribute most of the reduction in long-term Treasury yields to a reduction in the term premium, which in turn had broader repercussions on other risky bonds, as investors targeting a certain risk/return profile were induced to buy bonds with greater duration and/or higher credit risk.[5]

Others have challenged the dominance of the portfolio rebalancing channel in the transmission of the Federal Reserve asset purchases to changes in interest rates. Using event studies, Bauer and Rudebusch (2011) find that changes in expectations of future path of monetary policy (e.g. short-term rates) account for approximately an equal proportion in the decline in longer-term yields as term premium compression. On this basis, they argue for a more direct forward guidance about future policy rate targets, which the Federal Reserve has subsequently adopted. Kiley (2012) in turn estimates an empirical macro model to show that movements in expected short-term interest rates have a greater impact on real economic activity than movements in the term premium. Similarly, simulating a

[4]Krishnamurthy and Vissing-Jorgensen (2011) and Christensen and Rudebusch (2012) also document large announcement effects. Krishnamurthy and Vissing-Jorgensen (2011) find for instance that ten-year agency debt, 30-year MBS yields, and Baa corporate bond index yields dropped by 164, 116, and 68 basis points respectively around LSAP1 announcements. The effects for LSAP2 were measured to be smaller: 25, 27, and 17 basis point declines for ten-year Treasuries, ten-year agency debt, and Baa corporate bonds respectively.

[5]In fact, by the end of 2012 estimates for the nominal term premium in ten-year Treasury bonds ranged from approximately -50 to -140 basis points, based on the Federal Reserve and BIS term structure models respectively. See D'Amico, Kim, and Wei (2010) for the model underlying Federal Reserve estimates and Hoerdahl and Tristani (2012) for the BIS model.

DSGE model, Chen, Curdia, and Ferrero (2012) find that forward guidance substantially enhances the impact of asset purchases on both output and inflation, and that the boost is increasing in the length of such commitment.[6] A comprehensive set of arguments for the importance of guidance relative to asset purchases alone are outlined by Woodford (2012).

The literature also looks at the impact of actual purchases (as opposed to the mere announcements) in the context of the two channels outlined above. Using a panel regression approach, D'Amico and King (2012) estimate that the Federal Reserve's purchases of $300 billion in Treasuries during QE1 lowered 10-year yields (15-year yields) in total by 30 b.p. (50 b.p.), which they attribute to a so-called stock effect. In addition, they assign another 3 to 4 b.p. reduction to a flow effect on days when actual purchases took place. Similarly, Meaning and Zhu (2012) estimate that a 1% increase in the ratio of Federal Reserve's Treasury holdings to the amount outstanding reduces yields by 20 b.p. for 10-year bonds.[7] Hancock and Passmore (2012) estimate a pricing model for MBS yields in a structural cointegration framework. Their results confirm that the stock of the Federal Reserve Treasury holdings has a significant impact on MBS yields, which they interpret as evidence in support of the portfolio rebalancing channel. Wright (2012) uses both a structural Vector Autoregression (VAR) approach and an event study to find that the effect on yields is relatively short-lived, with a half-life of about two months.[8]

Broader transmission of unconventional policies. While initial studies of the transmission channels of asset purchases have mostly focused on the yields on government bonds, agency MBS, or their close substitutes, recent work has started to look at the broader transmission to other assets and markets. Krishnamurthy and Vissing-Jorgensen (2011), for instance, analyze the response of corporate bond yields, credit default swap (CDS)

[6] These authors attribute relatively low impact of asset purchases to smaller than expected market segmentation between short- and long-term government bonds, a necessary ingredient for portfolio rebalancing channel to work.

[7] Maturity swaps through the Federal Reserve's MEP have been found to have an impact on yields of a similar magnitude as outright purchases of long-term bonds (see, for example, Meaning and Zhu, 2011; Ehlers, 2012; Hamilton and Wu, 2012).

[8] Joyce, Lasaosa, Stevens, and Tong (2011) find similar evidence for the UK. The evidence is more mixed for the impact of the Federal Reserve's MBS purchases (Hancock and Passmore, 2011; Stroebel and Taylor, 2012).

spreads, swaption-implied volatility and inflation swap rates to shed light on various transmission channels.[9] Gambacorta, Hofmann, and Peersman (2012) impose an identifying sign restriction in their VAR framework when assessing the impact of unconventional monetary policy shocks on output and detect a significant decrease in the VIX in response to a positive Federal Reserve balance sheet shock. These studies are related to our paper in that they assess the repercussions of central banks' unconventional policies on option-implied volatility and other risk measures.

C. Transmission via Tail-Risk Perceptions

The impact of central bank asset purchases on the pricing of downside risks is implicit in theories emphasizing monetary policy transmission via intermediary balance sheets. The transmission mechanism is related to the "risk-taking channel" of conventional monetary policy, a term coined by Borio and Zhu (2012), who identify monetary policy transmission via financial intermediary balance sheets and risk spreads, a link confirmed by Adrian and Shin (2010) and Adrian, Estrella, and Shin (2010). The beginning of this literature predates the ongoing unconventional policies by the Federal Reserve. These authors therefore focus on the transmission of *conventional* policy measures, i.e. changes in short-term policy rates, to the broader economy via financial intermediary balance sheets. Our study, by contrast, is specifically interested in evaluating the impact of recent *unconventional* measures on risk appetite and perceived tail risks. A theoretical framework that provides guidance in the context of unconventional policies has been proposed by Brunnermeier and Sannikov (2012). In their model, central bank purchases can serve as insurance against tail events, if accompanied by clear communication and a commitment device conditional on future states of the world. In their framework, the central bank can signal its commitment to redistribute tail risk (that is, to fight against the inefficient redistribution generated by an adverse shock) at some future date. Forward guidance about short-term rates, in

[9] Some studies also look at broader transmission internationally: to other advanced economies (see e.g. Neely, 2010; Bauer and Neely, 2012), spillover effects across regions (e.g. Peng, 2011, in the context of Asian markets), and across a number of assets and emerging market economies (Chen, Filardo, He, and Zhu, 2012).

turn, can interact with financial leverage to support risk appetite of funded balance sheets by lowering the costs of maturity transformation (see, for example, Adrian, Moench, and Shin (2013) a possible channel). This, in turn, can have an immediate effect on market expectations and pricing of downside risks.

III. Empirical Proxies for (Tail) Risk Perceptions

We rely on proxies of tail risk perceptions computed from option prices on the SP&500 index. Besides these, we also consider some other well-known measures of volatility. Figure 2 shows the time-series of the SP&500, the VIX, and realized volatility.

– Insert Figure 2 about here –

Risk reversals. We focus on a measure of the cost of hedging against downside risk, which is generally referred to as the risk reversal. Risk reversals are typically expressed as the difference between the implied volatility (IV) of an out-of-money (OTM) call and the IV of an OTM put of the same moneyness and maturity:

$$x\delta RR = IV^{x\delta}_{Call} - IV^{x\delta}_{Put}, \tag{1}$$

where δ, an option's delta, indicates the sensitivity of the value of the option to the price of the underlying. We consider risk reversals for two degrees of moneyness in our analysis, 25δ options (OTM) and 10δ options (deep OTM). If the risk-neutral return distribution is symmetric, the implied volatility of the OTM call is the same as the IV of the OTM put. Risk reversals only take on non-zero values if the risk-neutral distribution of equity returns is skewed. If the risk-neutral return distribution is negatively (positively) skewed, the IV of the OTM put is higher (lower) than the IV of the call. Since equity return distributions are typically negatively skewed, risk reversals tend to be negative on average, as out-of-money puts have a higher likelihood of being exercised than out-of-money calls, meaning that their price (or IV) is higher.

In essence, what we are looking at here is the shape of the volatility "smirk" (in derivatives jargon) and how it changes around unconventional monetary policy measures.[10] Risk reversals are particularly elevated when the market price of hedging against extreme downside risk is high, making them a useful indicator of how the market perceives crash risk. Figure 3 shows the time series of $25\delta RR$ and $10\delta RR$, expressed as absolute values, during our sample period.

– Insert Figure 3 about here –

Importantly, although risk reversals measure option-implied skew and the skewness risk premium rather than the probability mass in the negative tail of the implied distribution itself, these simple proxies exhibit high and statistically significant correlation with more direct measures of tail risk. However, because these more precise measures require more granular information to construct the entire option-implied and statistical densities, they tend to be available at lower frequencies only, which renders them unsuitable for the analysis pursued in this paper. Figure 4 shows scatter plots and a least-squares fit of risk reversals (monthly averages) with the negative tail risk measure based on Tarashev, Tsatsaronis, and Karampatos (2003) and Tarashev and Tsatsaronis (2006). $25\delta RR$ exhibits a correlation coefficient of 0.8745 significant at 1% and higher and the further OTM $10\delta RR$ exhibits a marginally higher correlation coefficient 0.8863, also significant at 1% and higher. This corroborates the use of risk reversals as a suitable proxy for capturing the tail risk in equity markets.

– Insert Figure 4 about here –

Realized and implied volatility. For comparison purposes we also look at two other measures of risk, namely realized volatility and implied volatility. The former is a proxy for the actual volatility of equity returns and is computed from historical high-frequency (intraday) returns (e.g. Andersen, Bollerslev, Diebold, and Labys, 2003). We rely on realized

[10]Risk reversals have frequently been employed as gauges of crash risk in other strands of the literature, e.g. the literature on carry trades (Brunnermeier, Nagel, and Pedersen, 2009; Farhi, Fraiberger, Gabaix, Ranciere, and Verdelhan, 2009).

volatility computed from squared continuously compounded returns on the S&P500 index over five minute intervals.[11] The time series is taken from the Oxford-Man Institute of Quantitative Finance Realized Library. For implied volatility we rely on the VIX, which is often regarded as the "fear gauge" (Whaley, 2000). The way it is constructed by CBOE ensures that it is a risk-neutral expectation of return volatility of the S&P500 index. These two volatility measures differ from the ones above as they do not focus on the downside risk of large negative price movements, and thus can be considered as symmetric measures of risk.

IV. Data

Indicators of unconventional monetary policy. Table I describes the data, sources, and transformations. We measure the stance of the Federal Reserve's unconventional monetary policy in two ways. First, we rely on announcements of the different policies during various episodes, commonly referred to as QE1, QE2, MEP and MEP/QE3. We supplement announcement dates analyzed by previous research (Gagnon, Raskin, Remache, and Sack, 2011; Wright, 2012; Ehlers, 2012; Fratzscher, Duca, and Straub, 2012) with additional announcements related to MEP and QE3 policy phases. Table II lists the announcement dates and provides some further details on the content of each announcement.

– Insert Table I and Table II about here –

Our second measure is based on the actual amounts of Treasury debt held on the Federal Reserve's balance sheet. Here, we are studying whether there is an impact of the actual purchases per se, i.e. going beyond the effect of the actual announcements. We obtain data on the amounts of Treasury securities and agency MBS held in the Federal Reserve System Open Market Account (SOMA) at weekly frequency for various maturities.

[11] We also experimented with other measures of realized volatility, in particular an RV measure that is robust to microstructure noise based on the realized kernel approach of Barndorff-Nielsen, Hansen, Lunde, and Shephard (2008). Using this alternative measure, we obtain only negligible differences in the results.

Other data sources. Option-implied volatilities for different deltas to construct our tail risk proxies are obtained from Bloomberg. We rely on these data to construct the $10\delta RR$ and $25\delta RR$ introduced in Section III. Our measure of implied volatility relies on the VIX. The measures of realized volatility are obtained from the Oxford-Man Library.[12] Finally, we proxy for financial conditions using returns on the S&P500 and proxy for macroeconomic conditions at a weekly frequency by relying on a measure of U.S. economic surprises from Citigroup.

V. Effects of QE Announcements on Tail Risk Perceptions

A. Non-Parametric Event Study

We now provide an empirical assessment of the impact of unconventional monetary policies on market perceptions of (tail) risk. We start with a simple event study, measuring the response of our risk gauges to the announcements of the policies. Looking at the impact of announcements follows the tradition set by prior work studying the effect of QE announcements on the shape of the yield curve (e.g. Krishnamurthy and Vissing-Jorgensen, 2011; Gagnon, Raskin, Remache, and Sack, 2011, among others). Specifically, we compare the average level of our risk gauges over an event window of 5 and 10 trading days before and after each announcement.[13] Overall, we consider 17 announcements related to the policies of the U.S. Federal Reserve during the QE1, QE2, MEP and QE3/MEP episodes. The announcements are listed in Table II.

– Insert Figure 5 about here –

[12]See Heber, Lunde, Shephard, and Sheppard (2009) for details on the construction of these data.

[13]Our empirical research design here is similar (but not identical) to so-called "volatility event studies", (See e.g. Mayhew, 1995, for a review). While the exact methods in these event studies often differ, the general idea in much of this literature is to assess if the variability of equity prices changes before and after the event, with the ultimate goal of assessing the volatility impact of the event (Clayton, Hartzel, and Rosenberg, 2003). Some further examples of this line of literature are Bailey (1988), Isakov and Perignon (2001) and Bhagat, Brickley, and Loewenstein (1987).

Figure 5 illustrates the results of this empirical exercise. It shows the average levels of $10\delta RR$ and $25\delta RR$, implied volatility, and realized volatility over a period of 22 days before and after the announcement dates, *aggregated* across all 17 events. For ease of exposition, we also report the average levels of the different indicators over the 22-day pre- and post-announcement window.[14]

We observe a significant drop in the hedging costs of downside risk following Federal Reserve announcements over the 22 trading days following the announcements. On average across all events, 25- and $10\delta RR$ on the S&P500 decline by approximately 2 percentage points, from 9 to 7 and from 15 to 13 respectively. It is also interesting to note that the largest reaction of our risk measures does not occur on the day of the announcement. As suggested by Figure 5 it takes some time for the news to be fully reflected in market prices. The overall fall in implied volatility (e.g. the VIX, bottom-left panel) also appears to be sizeable, but the behavior of implied volatility around the announcements appears less starkly driven by the announcements themselves. Also note that, contrary to the option-implied measures, realized volatility tends to pick up on announcement days. This is consistent with higher market activity and turnover due to portfolio rebalancing in reaction to the announcements. As realized volatility is a somewhat noisier measure, it is also harder to assess the significance of the fall in realized volatility on subsequent days compared to the pre-announcement period.

The next question is whether the change in the levels of risk gauges following Federal Reserve announcements is statistically significant. We rely on a bootstrap approach for inference, as asymptotic theory may be of little help due to the relatively small number of observations we are dealing with. We adopt a time series bootstrap method, the stationary bootstrap by Politis and Romano (1994), which preserves the dependencies in the data. We re-sample the time-series under the null of no relation between the event and our risk proxies. The average block length in the bootstrap is chosen to be 30 days and the number

[14] Observed changes around announcement dates are robust to transforming the variables into logarithms, see Appendix Figure 10.

of bootstrap replications is set to 5,000.[15] The major goal in this bootstrap experiment is to assess the frequency with which we would see drops in the risk measures of similar (or greater) magnitude under the null in the artificially generated bootstrap samples. In technical terms, what we compute here is a bootstrap p-value, allowing us to judge the statistical significance of the results.

Table III tabulates the results for different event windows together with bootstrap*p-values*. We find that the tail risk gauges based on risk reversals exhibit statistically significant declines (at the 10% level) under all specifications. The evidence is strongest for the the 10-day pre- and post-announcement window. For this case, we see relative drops of tail risk perceptions by about 8% and 10%, for the $10\delta RR$ and $25\delta RR$, respectively. These changes are significant at the 5% level in both cases based on the bootstrap*p-values*. While the symmetric volatility measures (IV and RV) also tend to fall following the announcements, the evidence for a significant change is much weaker from a statistical perspective. Declines in realized volatility are marginally statistically significant (at the 10% level) only when longer (22-day) post-announcement windows are considered. Overall, these findings suggest that Federal Reserve announcements of unconventional monetary policy seem to have had their strongest effect on market perceptions of downside risk.

– Insert Table III about here –

To assess the degree to which particular phases of unconventional monetary operations drive these results, we also repeat the event study separating between various phases of the policies. This seems important as the objectives and circumstances of the Federal Reserve policies were quite different across various regimes. We thus distinguish between announcements related to QE1, QE2, MEP, and the latest combined phase of MEP and QE3.

It is clear from this table that most of the significant declines in tail risk perceptions occurred around QE1 (first announced in November 2008, implemented in March 2009

[15] A fairly large block length seems reasonable as it preserves the long memory properties of time series such as IV and RV. We also experimented with smaller block lengths with no major changes to the results.

and phased out starting November 2009) and around the ongoing QE3/MEP phase (with further maturity extension announced in June 2012 and monthly MBS purchases announced in September of 2012). $25\delta RR$, for instance, declined by approximately 17% in relative terms in the QE1 period (10-day window). The fall was even stronger during the ongoing QE3/MEP phase, with a relative decline of about 28%. Furthermore, unlike the later programs, QE1 is also associated with statistically significant declines in both implied and realized stock market volatility.

Announcements related to QE2 and MEP, by contrast, were not associated with significant declines in the readings of risk reversals. A possible explanation for this is that 2011 period corresponded to a broad-based increase in financial market tensions driven by the intensification of the crisis in the euro zone. Hence, by all accounts the Federal Reserve was in the midst of "leaning against the wind" when it made the first rounds of announcements related to the MEP in September 2011.[16]

In sum, large declines in tail risk perceptions registered around announcements related to the QE1 phase. The effects of subsequent announcements associated with QE2 and "Operation Twist" (Maturity Extension Program (MEP)) policy phases were more subdued. Federal Reserve announcements, once again, have been curbing tail risk perceptions substantially in 2012 during the on-going phase of QE3.

B. *Regression-Based Evidence*

The regression setup largely follows Beber and Brandt (2006), Vahamaa and Aijo (2011) and Jiang, Konstantinidi, and Skiadopoulos (2012), where changes in the specific measure of risk are regressed on dummy variables that take a value of one during the event window and a value of zero otherwise. The controls include contemporaneous (log) stock returns ($SP500$), lagged U.S. economic conditions as proxied via changes in the Citi Economic Sur-

[16] As Wright (2012) point out, QE2 may have been largely anticipated, noting, for example, that the Federal Reserve surveyed primary dealers for their estimates of the possible size of QE2 in late October 2010. However, we do not find a significant impact even though we also include Chairman Bernanke's August 2010 Jackson Hole speech in which he mentioned further purchases of long-term Treasuries as a potential policy option. The muted reaction (if any) measures of (tail) risk perceptions are thus in line with the insignificant reaction to QE2 announcements in the bond markets documented by previous literature.

prise Index ($USECON$), and the lagged dependent variable to assess the marginal effect of the announcement. Following Krishnamurthy and Vissing-Jorgensen (2011), we assign statistical significance based on the *F-test*for the null that the coefficients on the QE dummies are jointly equal to zero. Based on the results of these regressions, we further report the cumulative abnormal effect of the announcements, aggregated over the event window and across announcements. In addition to a 2-day event window (the announcement day and the following day), we cover 3- and 5-day windows.

– Insert Table IV about here –

Table IV reports the results. In addition to the cumulative announcement effect we also report the sum of the coefficients on the announcement dummies.[17] The results show a statistically significant decline in perceived tail risk around unconventional monetary policy announcements by the Federal Reserve during 2-, 3-, and 5-day announcement windows. The cumulative "abnormal" changes in the VIX are also negative around the announcements, but are only deemed statistically significant for the longer 5-day window. Furthermore, the impact in the units of volatility is larger for measures of extreme crash risk. Taking the results over the 2-day announcement window as an example, the cumulative "abnormal" changes are: -10.3 for $10\delta RR$, -6.7 for $25\delta RR$, -3.8 for IV. Thus, the reaction by the VIX is more muted compared to the tail risk proxies. This suggests that the transmission of policy announcements to volatility measures originated from investors' repricing extreme downside risks rather than from the overall level of volatility per se. Also, in line with the results of the previous section, while the announcements tend to reduce the negative skew of the implied distribution of returns, realized volatility actually goes up. This possibly reflects a pick-up in market activity and trading due to portfolio rebalancing in response to the event and is consistent with existing literature on announcement affects. A rise in realized volatility, while large immediately following the announcements (70.1 for

[17] We omit reporting the coefficients on controls for brevity. Overall, while coefficients on lagged changes in economic conditions tend to be insignificant, coefficients on contemporaneous returns are highly significant and large. This confirms the tight relationship between S&P500 returns and realized volatility as well as proxies of (tail) risk computed from option prices. Complete regression results are available from the authors upon request.

2-day window) is followed by declines as the announcement window is expanded to 3 and 5 days. Such impact on realized volatility is consistent with existing event study literature.

Taken together, the event study exercises convey two main messages. First, announcements associated with the Federal Reserve's unconventional monetary policy worked to ameliorate investor expectations associated with extreme downside risks rather than simply reducing implied volatility generally. Second, this effect is particularly large for the latest QE3/MEP phase of the Federal Reserve's operations unveiled in 2012.

VI. Impact of Actual Asset Purchases

Our next objective is to characterize the effect of the actual asset purchases by the Federal Reserve on proxies of tail risk. The data on Treasury security holdings in the SOMA account of the Federal Reserve are available at weekly frequency, therefore in what follows t denotes a week rather than a day. Following studies with a similar focus to ours, e.g. Bekaert, Hoerova, and Duca (2010) and Bruno and Shin (2012), the econometric framework is a standard structural fixed parameter VAR. Later on, we then extend this setup to allow for time-varying parameters in a Bayesian VAR setting.

A. Impulse Response Analysis: Fixed Parameter VAR

The baseline structural VAR can be written

$$\boldsymbol{A}\mathbf{y}_t = \boldsymbol{\Gamma}\mathbf{y}_{t-1} + u_t, \tag{2}$$

and $\boldsymbol{A}$ is a 4×4 matrix with full column rank and $E(u_t u_t') = I$. The variables modeled in the system are defined via the 4×1 vector

$$\mathbf{y}_t = \begin{pmatrix} USECON_t \\ TREAS_t^m \\ SP500_t \\ RISK_t^i \end{pmatrix},$$

where $TREAS_t^m$ denotes week t minus week $t-1$ changes in Treasury debt holdings by the Federal Reserve (in millions USD) in maturity basket m: >10 years, 5-10 years, 1-5 years, and <1 year. Our main interest lies in the effects of the underlying structural shocks u_t on our main variables of interest, that is, market perceptions of tail risk. We start by estimating the model given by Equation (2) in reduced form:

$$\mathbf{y}_t = \boldsymbol{B}\mathbf{y}_{t-1} + \boldsymbol{A}^{-1}\Sigma\epsilon_t,\ \epsilon_t \sim N(0, I), \tag{3}$$

where $\boldsymbol{B} = \boldsymbol{A}^{-1}\Gamma$, and Σ is a 4×4 diagonal matrix collecting the the standard deviations of the structural shocks. For identification, six restrictions have to be imposed. We rely on a standard Cholesky decomposition of the variance matrix of the shocks. The benchmark ordering assumes an order of exogeneity that goes from economic conditions ($USECON$) to purchases by the Federal Reserve ($TREAS$) to financial conditions ($SP500$) to our proxies of (tail) risk ($RISK$). The main guiding principle in this ordering is that the business cycle variable is more sluggish in its response to high-frequency financial market dynamics, and so are changes in the Federal Reserve balance sheet. By contrast, our measures of equity returns and risk gauges are allowed to be affected instantaneously by business cycle shocks as well as unconventional monetary policy shocks.[18]

– Insert Figure 6 about here –

Baseline results. We focus on the impulse response analysis for the following system, concentrating on the effect of purchases of Treasuries with maturity greater than 5 years

[18] The results are robust to an alternative ordering of variables in the VAR system. Figure 11 in the Appendix shows impulse responses with $RISK$ considered exogenous to $SP500$.

on 10δ risk reversals: $\mathbf{y}_t = [\ USECON_t,\ TREAS_t^{>5-years},\ SP500_t,\ RISK_t^{10\delta RR}]'$, where $USECON_t$ and $TREAS_t^{>5-years}$ enter the system in first differences, $SP500_t$ in log differences, and $RISK_t^{10\delta RR}$ in levels.[19] The number of autoregressive lags is set to one.[20] We estimate the four-variable VAR model using weekly data from the week of 9 January 2008 to that of 26 September 2012. Figure 6 illustrates 90% confidence bands of impulse responses computed via bootstrap simulation. First, looking at the left-hand panels, a positive one standard deviation shock to changes in U.S. economic conditions, $USECON$, tends to have a positive impact on S&P500 returns, with the effect sustained for about two weeks. It also leads to an immediate reduction in market participants' tail risk perceptions, as measured by the 10δ risk reversal. Moving to the right-hand panels, we see that positive shocks to Federal Reserve purchases are associated with higher S&P500 returns, with the effect largest one week following the Federal Reserve balance sheet shock. Most importantly, positive shocks to the Federal Reserve's holdings of medium- and long-term Treasury debt exhibit a statistically significant impact on tail risk perceptions. The effect is largest one week following the Federal Reserve balance sheet shock, and is sustained for 12 weeks. Thus, the VAR impulse responses show that it is not only the announcements that matter for curbing tail risk perceptions, but that the actual Federal Reserve purchases tend to have the significant and sustained effect of alleviating downside risk perceptions in financial markets. The sustained impact of actual Federal Reserve balance sheet shocks is noteworthy because it suggest that transmission of policy may be taking place through balance sheets of financial intermediaries, whereas the significance of announcement effects alone is not enough to rule out only a short-lived market impact due to the effect on expectations.

Maturity structure of the Federal Reserve balance sheet. We are further interested in the effects of Federal Reserve purchases across different maturity segments of the

[19] The subsequent results are robust to using first differences for measures of $RISK_t^i$ as well as percent changes for $TREAS_t^m$. Also, using percent changes rather than dollar differences for Federal Reserve holdings of Treasuries, $TREAS_t^m$, would bias results in our favor, as due to the growing size of the Federal Reserve's balance sheet an equal amount of purchases would translate into increasingly smaller percentage change relative to the total stock, thus attributing greater impact to a given percentage change in Treasury bond holdings towards the latter part of the sample.

[20] Lag length is chosen based on the Akaike Information Criterion.

Treasury securities purchased. Here we differentiate between maturities of >10 years, 5-10 years, 1-5 years, and <1 year. Figure 7 shows the results, where we again consider $10\delta RR$ as our measure of risk. These results indicate that Federal Reserve purchases of Treasuries at the very long end (maturity of 10 years or greater) lead to the most significant reduction in downside risk perceptions (top panels). Purchases of Treasuries with maturity between 5-10 years also reduce perceived tail risk, but at lower levels of statistical significance. Shocks to purchases of lower duration assets (1-5 years) essentially have no effect. In contrast, a positive shock to the Federal Reserve's holdings of short-term bonds and notes increases market perception of risk (bottom panel). This likely captures the impact of the "Operation Twist" (MEP) programme, in which the Federal Reserve has been buying long-duration assets financed by selling short-duration securities. Since sales at the short-end automatically accompanied the purchases at the long-end, these results alone do not distinguish between the duration effect and the stock effect of long-term bond holdings. Nonetheless, the balance sheet policies of the Federal Reserve were influential in alleviating market perceptions of downside risks also during the MEP programme.

– Insert Figure 7 about here –

Time-varying impact. Previous literature and the event study results of Federal Reserve announcement effects on risk measures suggest that the effect of unconventional monetary policy on market perceptions of risk might be changing over time. Although market reactions to actual purchases would differ from the ones to one-time announcements of new policy measures, we could still expect to see variation in the effects of actual purchases across various phases of the Federal Reserve's unconventional monetary policy. Studies that have looked at bond yields and portfolio flows find significant time-variation in policy impact. For example, Krishnamurthy and Vissing-Jorgensen (2011) find that QE2 had a significantly smaller impact on yields compared to QE1 while Fratzscher, Duca, and Straub (2012) find a differential policy association with bond and equity fund flows. Krishnamurthy and Vissing-Jorgensen (2011) attribute the greater impact of QE1 on yields of various assets to additional risk premium and liquidity channels operative during that phase. Therefore, market perceptions of extreme downside risks may have also reacted differently to QE1, QE2, and subsequent phases.

As a first pass, we repeat the baseline VAR on time subsamples, designating weekly observations from March to November 2009 as QE1, November 2010 to June 2011 as QE2, and October 2011 to September 2012 (cut-off month for our sample period) as QE3/MEP. Figure 8 shows the associated impulse responses of 10δ risk reversals to a one standard deviation shock to the Federal Reserve's holdings of Treasuries with 5-year maturity or greater. The results point at considerable variation across policy phases: the response of $10\delta RR$ to a $TREAS^{>5yr}$ shock shows a significant but transitory decline during the QE1 phase (with the effect dissipating within 2 weeks), insignificant or mixed results for the QE2 phase, and a significant and highly persistent decline in measured risks during the QE3/MEP phase. In fact, the impulse responses based on the latter subsample bear the most similarity to the pooled VAR result reported in Figure 6, suggesting that the aggregate finding of the significant reduction in risk perceptions in response to the Federal Reserve's asset purchases may be driven primarily by the latest policy phases.

– Insert Figure 8 about here –

The results based on subsample estimates using the fixed parameter VAR have several shortcomings, however. First, the power of the test is significantly reduced due to the lower number of observations within each time sample. Second, the volatility of the underlying variables, such as S&P500, varied considerably during this period and should be accounted for in the time-varying setup. Finally, due to the low number of observations for the latest round of fixed amount monthly purchases, unveiled in September 2012, MEP and QE3 have been lumped together as one policy phase, whereas alternative techniques, such Time-Varying Parameter Bayesian VAR, would make it possible to extract marginal information from each successive observation in the sample.

B. Time-Varying Parameter Bayesian VAR

We rely on the methodology developed by Primiceri (2005) and applied by Nakajima (2011) to estimate the evolution of the relationship between unconventional monetary policy and pricing of downside risk over time. Consider the time-varying parameter Bayesian VAR (TVP-VAR) model with stochastic volatility:

$$\mathbf{y}_t \;=\; \mathbf{y}_{t-1}\boldsymbol{\beta}_t + A_t^{-1}\Sigma_t\,\varepsilon_t, \quad t = s+1, \ldots, n, \tag{4}$$

where the coefficients $\boldsymbol{\beta}_t$, and the parameters A_t, and Σ_t are all time-varying. Following Primiceri (2005), let $\boldsymbol{a}_t = (a_{21}, a_{31}, a_{32}, a_{41}, \ \ldots, a_{k,k-1})'$ be a stacked vector of the lower-triangular elements in A_t and $\boldsymbol{h}_t = (h_{1t}, \ldots, h_{kt})'$ with $h_{jt} = \log \sigma_{jt}^2$ capturing the variance of ϵ_{jt}, for $j = 1, \ldots, k$, $t = s+1, \ldots, n$, where k is the number of variables. We assume that the parameters in equation (4) follow driftless random walk processes

$$\begin{aligned} \boldsymbol{\beta}_{t+1} &= \boldsymbol{\beta}_t + u_{\beta t}, \\ \boldsymbol{a}_{t+1} &= \boldsymbol{a}_t + u_{at}, \\ \boldsymbol{h}_{t+1} &= \boldsymbol{h}_t + u_{ht}, \end{aligned} \qquad \begin{pmatrix} \varepsilon_t \\ u_{\beta t} \\ u_{at} \\ u_{ht} \end{pmatrix} \sim N\left(0, \begin{pmatrix} I & O & O & O \\ O & \Sigma_\beta & O & O \\ O & O & \Sigma_a & O \\ O & O & O & \Sigma_h \end{pmatrix}\right),$$

for $t = s+1, \ldots, n$, where $\boldsymbol{\beta}_{s+1} \sim N(\mu_{\beta_0}, \Sigma_{\beta_0})$, $\boldsymbol{a}_{s+1} \sim N(\mu_{a_0}, \Sigma_{a_0})$ and $\boldsymbol{h}_{s+1} \sim N(\mu_{h_0}, \Sigma_{h_0})$. The variance and covariance structure for the innovations of the time-varying parameters are governed by the parameters collected in the matrices Σ_β, Σ_a and Σ_h, where Σ_a and Σ_h are diagonal matrices.

We estimate the four-variable TVP-VAR model using weekly data from the week of 9 January 2008 to that of 26 September 2012, thereby examining the time-varying nature of the impact of the Federal Reserve's purchases of long-term Treasury securities on market participants' valuation of downside risk while controlling for the prevailing macroeconomic and financial conditions. The selection of variables is the same as for the baseline results in the previous subsection.

We set the number of lags to one following fixed parameter VAR. We assume that Σ_β is a diagonal matrix following Nakajima (2011). The following priors are assumed for each i-th diagonal element of the covariance matrices:

$$(\Sigma_\beta)_i^{-2} \sim \text{Gamma}(2, 0.01),\ (\Sigma_a)_i^{-2} \sim \text{Gamma}(2, 0.01),\ (\Sigma_h)_i^{-2} \sim \text{Gamma}(2, 0.01).$$

For the initial state of the time-varying parameter, rather flat priors are set; $\mu_{\beta_0} = \mu_{a_0} = \mu_{h_0} = 0$, and $\Sigma_{\beta_0} = \Sigma_{a_0} = \Sigma_{h_0} = 10 \times I$. To compute the posterior estimates, we draw $M = 10{,}000$ with the initial 1,000 samples discarded as burn-in. See Nakajima (2011) for the details of prior specification and for the Bayesian MCMC parameter sampling procedure.

– Insert Figure 9 about here –

Figure 9 reports time series of one-period ahead impulse responses from the TVP-VAR model. We focus on time-variation of one-period ahead impulse responses because the response of $10\delta RR$ to a shock to the Federal Reserve's balance sheet shock is largest one week afterwards according to the fixed-parameter VAR analysis. Since the coefficients are time-varying, the impulse responses are calculated at each date over the sample period. The shock size for the responses is set equal to the time-series average of the stochastic volatility of each series over the sample period. Impulse responses are calculated for each draw of the MCMC with the current draw of the parameters, and afterwards credible intervals of the responses are computed.[21] In Figure 9 we report the means of generated

[21]Sample autocorrelation and posterior densities for Σ_a, Σ_b, and Σ_h suggest stable sample paths and low sample autocorrelations, indicating that the sampling method efficiently produced samples from the posterior distribution.

impulse responses along with the credible intervals.[22]

Our main result concerns the bottom right-hand panel of Figure 9. It corroborates our earlier findings of a significant impact of unconventional monetary policy shocks on tail risk perceptions. In the panel, the variation of means over time points to a time varying effect of purchases. Around the period of QE1, we see a substantial downward impact on tail risk perceptions as measured by $10\delta RR$. However, the effect becomes muted in the period around QE2. Moreover, the uncertainty about the size of the effect is large during this period, as indicated by the widening of the credible intervals. Most notably, the response of risk reversals becomes larger again around the period of introduction of MEP, and the uncertainty about its effect is substantially diminished. Negative posterior means and the narrowing of the uncertainty bounds point to the effectiveness of the ongoing QE3/MEP phase of the Federal Reserve's unconventional policies, as the maturity extension of the Federal Reserve's balance sheet is accompanied by further expansion. Furthermore, to the extent that the Federal Reserve's use of forward guidance and communication of unemployment targets may have enhanced the effect of MEP and of QE3 (see for example (Chen, Curdia, and Ferrero, 2012)) by making clear its commitment to support the recovery, this may further explain why the effect on proxies of tail risk perceptions becomes stronger in 2012.

We can discuss the relationship in other sets of variables more clearly by investigating the contemporaneous impulse responses in (see Appendix Figure 12). A positive shock to U.S. economic conditions is associated with higher S&P500 returns, although the association is fairly variable over time. A positive shock to the Federal Reserve's holdings of long-term Treasury securities (>5-year maturity) is associated with higher stock market returns towards the second half of the sample period in late 2010 and 2011. Not sur-

[22]Following Primiceri (2005) and Nakajima, Kasuya, and Watanabe (2011), we rely on 68% credible intervals when interpreting the results of the impulse response analysis with the TVP-VAR model. The credible interval at each sample period allows us to quantify the uncertainty of the size of response at a particular point in time. As Nakajima, Kasuya, and Watanabe (2011) point out, the uncertainty of the posterior distribution for the impulse response in the TVP-VAR model tends to be larger than that of the constant parameter VAR model. A caution for readers less familiar with Bayesian statistics is that, unlike the frequentist approach, which quantifies the uncertainty in terms of a confidence interval based on the probability of committing a Type 1 error in a hypothesis test, credible interval in Bayesian statistics conveys the probability of observing an outcome around the posterior mean.

prisingly, there is a strong and significant negative association between a positive shock to S&P500 returns and option-implied downside risk perceptions. The time-varying estimates of structural shock volatility to each variables also have a ready economic interpretation (see Appendix Figure 13), broadly supporting our model choice. As the figure shows, stock market volatility peaked in October 2008, and has been declining since, albeit with some adverse movement in early 2011. Macroeconomic volatility started declining in mid-2011, and this decline has been accompanied by a pick-up in shocks to the Federal Reserve's balance sheet, indicating an aggressive monetary stance. The latest phases of unconventional policy also appear to be associated with lower volatility of shocks to 10-delta S&P500 risk reversals, which has returned to pre-crisis levels, although the uncertainty of the estimates remains high.

VII. Conclusions

A common, yet hitherto unproven, narrative is that unconventional monetary policy actions such as the various rounds of asset purchases by the U.S. Federal Reserve were instrumental in curbing perceptions of tail risks in the economy. In this paper, we rely on the information in option prices to investigate whether such a transmission channel is indeed operational.

We show via both event studies of announcement effects and VAR analysis of the impact of actual purchases that proxies of perceived tail risks in financial markets decline significantly in response to the Federal Reserve's unconventional policies. Parametric and non-parametric event study techniques show that options-based measures of tail risks decline significantly (by around 10% over a 10-day window) around announcements of unconventional monetary policy. The effects are strongest and appear first specifically in the proxies for downside risk perceptions (e.g. risk reversals) rather than in simple measures of volatility (e.g. the VIX). We also find a significant flow effect of asset purchases by the Federal Reserve, which further contributed to a re-pricing of the option-based tail risk gauges. This impact comes on top of any knock-on effects associated with positive feedback from stock prices, which also tend to rise in response to such measures. We detect such significant effect of unconventional policies on tail risk perceptions during the QE1 phase and a particularly strong effect again during the ongoing MEP/QE3 phase, while the effect in the QE2 period was more muted.

One way of thinking about these results is in terms of a transmission mechanism suggested by Brunnermeier and Sannikov (2012, 2013), whereby central bank purchases can provide insurance against tail events, if accompanied by clear communication and a commitment to condition policy actions on future states of the economy. For example, purchases of long-duration assets and term premia compression would enhance search for yield motives on the one hand while generating capital gains for holders of such assets on the other.[23] The transmission to the market price of risk may also operate through the balance sheets of financial intermediaries (see, for example, Adrian, Moench, and Shin, 2013) whose risk bearing capacity may be further enhanced (via lower costs of maturity transformation) with a commitment to keep short-term rates low. This, in turn, can change the valuation of downside risks across a range of assets and is likely to show up in broad measures, such as S&P500 index options. More broadly, our results support the notion that central bank asset purchases and communication can play a significant role in affecting market expectations and asset prices. Well-designed central bank balance sheet policies, backed by clear commitment and conditionality, can contribute to an elimination of coordination failures and reduce perceived disaster risks, and hence may diminish the likelihood of self-fulfilling risk panics (Bacchetta, Tille, and van Wincoop, 2012).

[23] In fact, BIS (2012) shows evidence that monetary policy response during the 2008 to 2010 period supported the rebuilding of banks' capital base.

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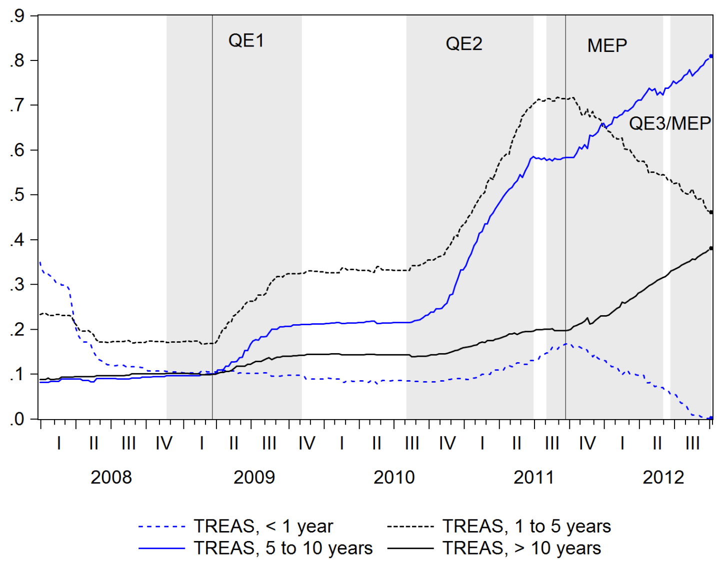
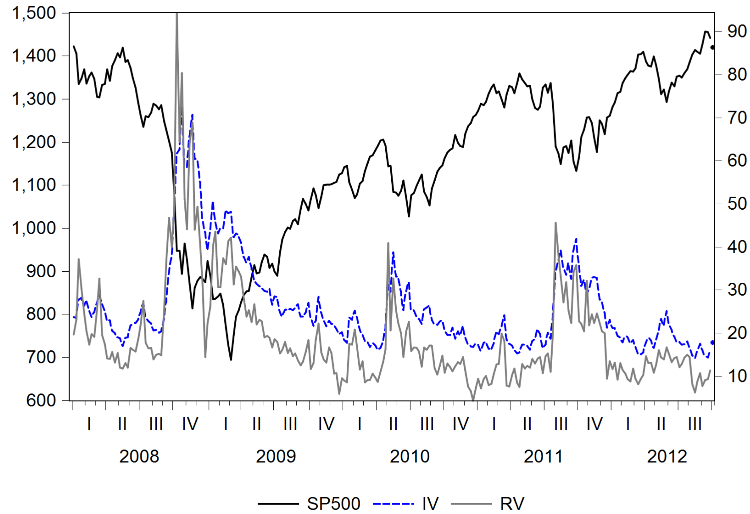
Figures and Tables

Figure 1. Maturity Breakdown of the Federal Reserve's Treasury Debt Holdings



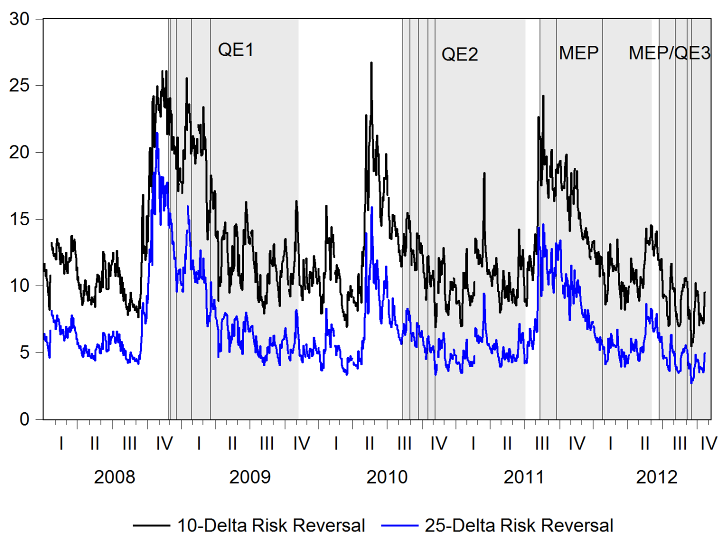
Notes: The Figure shows the maturity breakdown of Treasury debt security holdings in the Federal Reserve System Open Market Account (SOMA), expressed in USD billions.

Figure 2. Volatility and Equity Prices



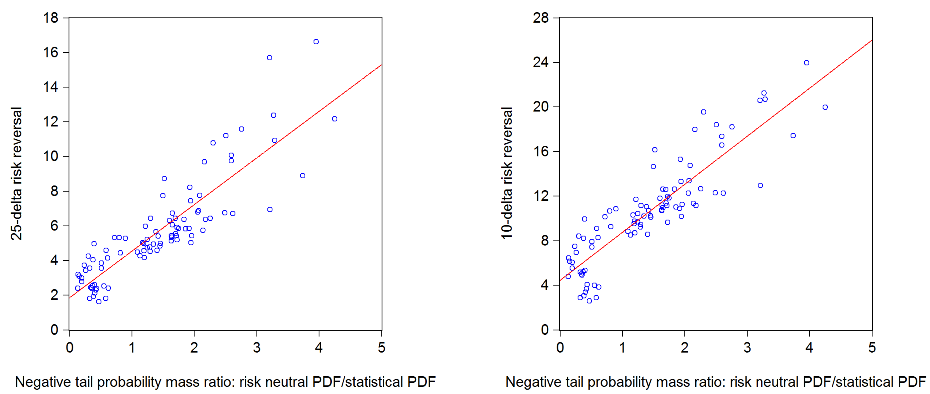
Notes: U.S. equity prices (left axis, S&P500 Index) plotted against implied volatility measured by the VIX (IV) and realized volatility (RV) (right axis, in %, p.a.).

Figure 3. Measures of Tail Risk



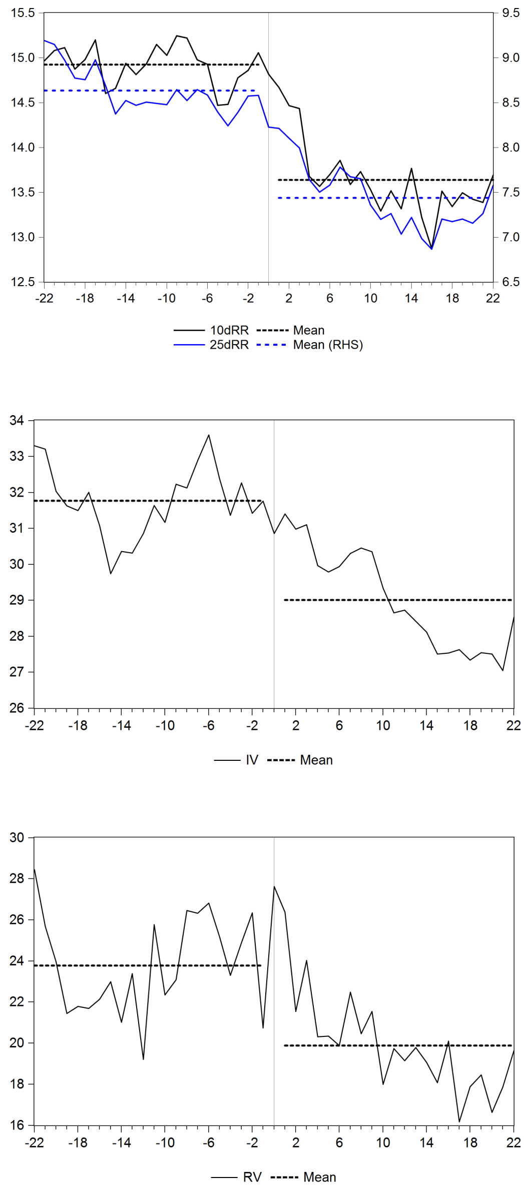
Notes: Tail risk gauges, as measured by 10-delta and 25-delta risk reversals. Risk reversals are typically expressed as the difference of implied volatility (IV) of an out-of-money (OTM) call and the IV of an OTM put of the same "moneyness" and maturity. We consider risk reversals for two degrees of moneyness in our analysis, 25δ options (OTM) and 10δ options (deep OTM). Because of negative skew in equity prices, OTM puts tend to be more expensive than OTM calls, hence risk reversals values are negative. For ease of exposition, we work with absolute values of risk reversals, hence the series in the figure and in the estimation are positive. Vertical lines indicate Federal Reserve asset purchase and "forward guidance" announcements and related speeches (see Table II).

Figure 4. Correlation of Risk Reversals and PDF-Based Tail Risk Measures (Monthly)



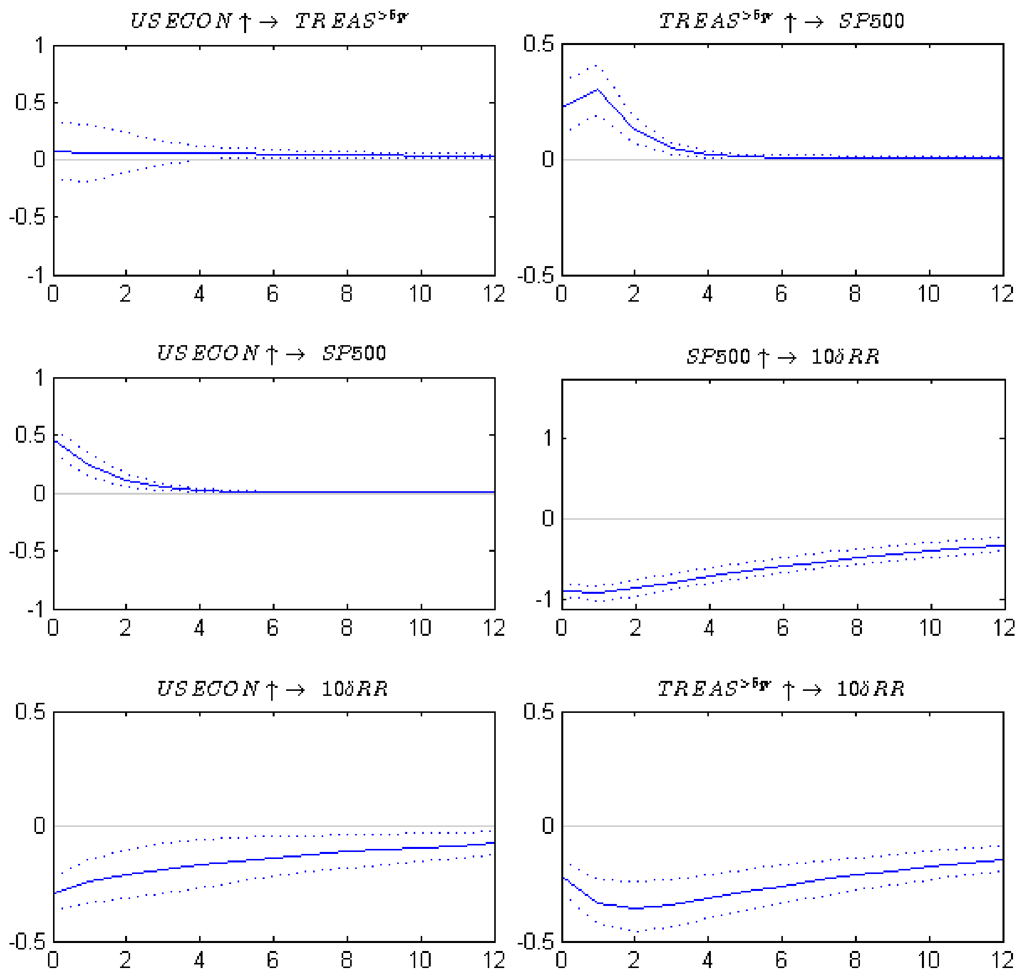
Notes: The Figure shows scatter plots and a least-squares fit of risk reversals (monthly averages) with the negative tail risk measure based on Tarashev, Tsatsaronis, and Karampatos (2003). The tail risk premium parameter is calculated to match each month's difference between left-tail probability mass based on risk neutral and statistical densities. *Left:* 25-delta risk reversals ($25\delta RR$), correlation coefficient 0.8745 with p-value of 0.0000; *Right:* 10-delta risk reversals ($10\delta RR$), correlation coefficient 0.8863 with p-value of 0.0000. Sample period: January 2005 to February 2013.

Figure 5. Impact of Federal Reserve Policy Announcements on Risk Perceptions



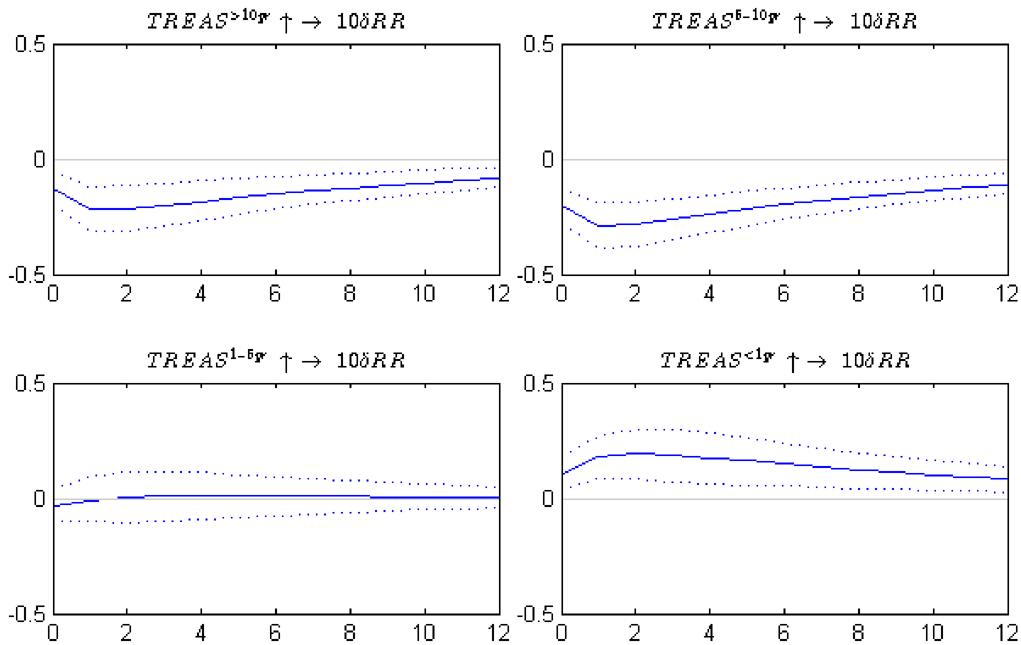
Notes: Average readings of 10- and 25-delta risk reversals ($10\delta RR$ and $25\delta RR$), implied volatility (IV), and realized volatility (RV) 22 days before and after the 17 announcement dates associated with the Federal Reserve's unconventional monetary policy measures, as indicated in Table II.

Figure 6. Impact of Federal Reserve Purchases on Risk Perceptions



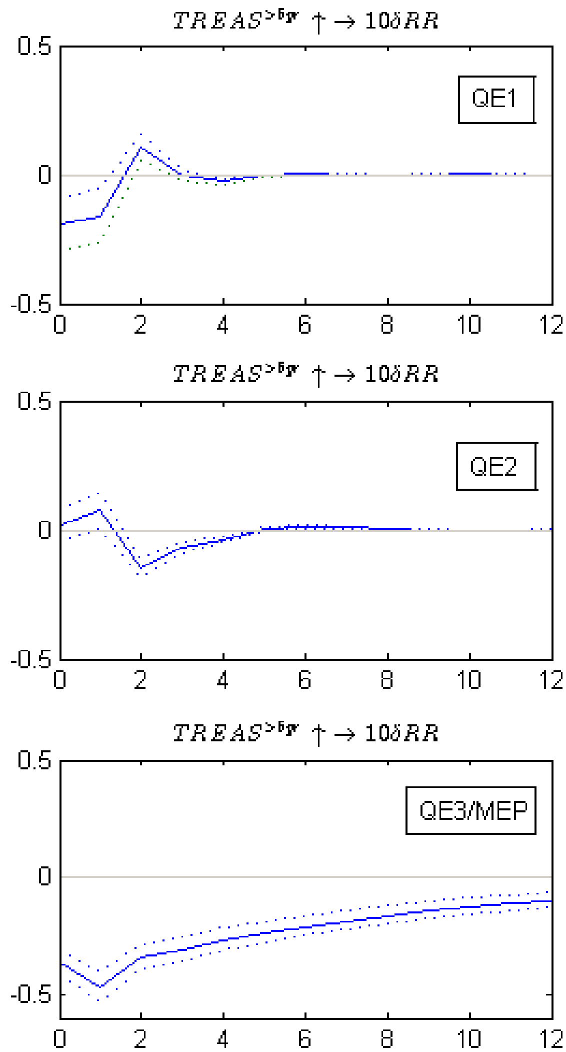
Notes: Impulse responses and 90% Monte-Carlo (MC) confidence bands of the the following VAR system: $\mathbf{y}_t = [\,USECON_t$, $TREAS_t^{>5yr}$, $SP500_t$, $RISK_t^{10\delta RR}]'$; where $USECON_t$ and $TREAS_t^{>5-years}$ enter the system in first differences, $SP500_t$ in log differences, and $RISK_t^{10\delta RR}$ in levels. The number of autoregressive lags is set to one with lag length chosen based on the Akaike Information Criterion. Confidence bands computed based on 10,000 MC samples after discarding first 1,000 as burn-in. We estimate the four-variable VAR model using weekly data from 9 January 2008 to 26 September 2012.

Figure 7. Impact of Federal Reserve Purchases on Risk Perceptions: by Maturity of Purchases



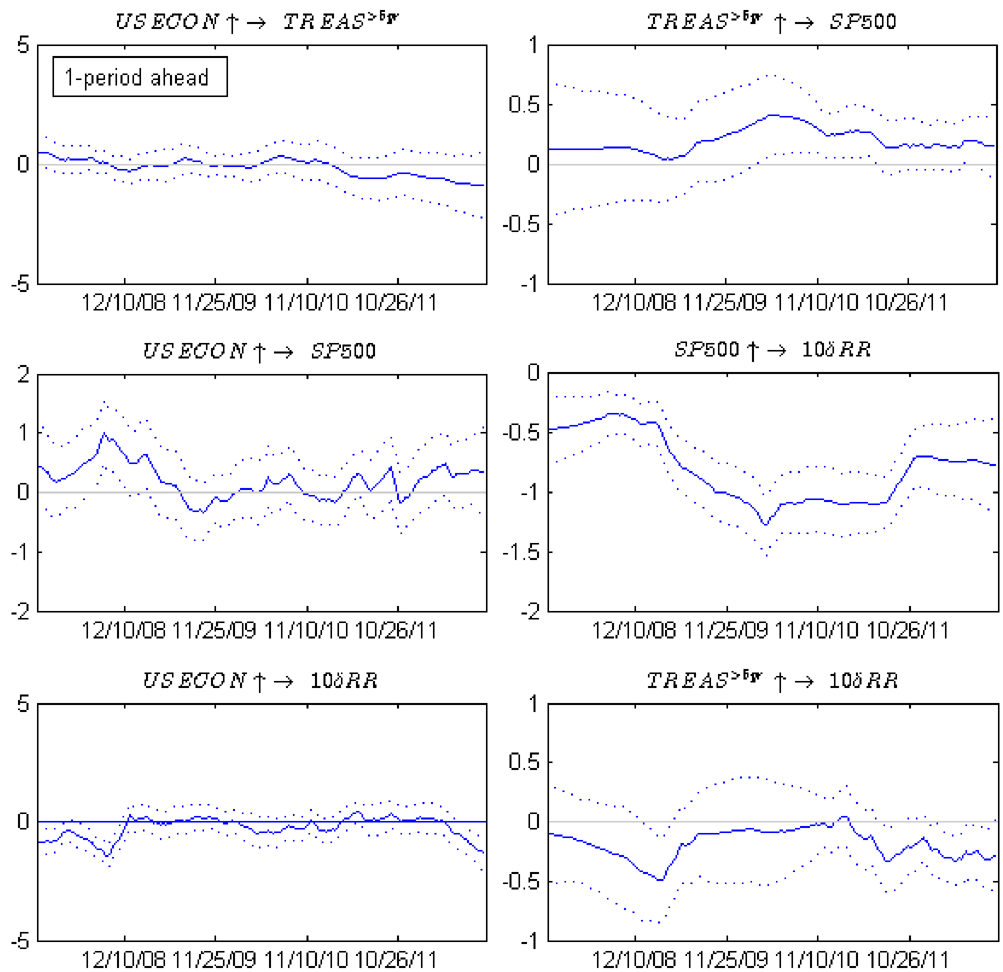
Notes: Impulse responses and 90% Monte-Carlo (MC) confidence bands of the the following VAR system: $\mathbf{y}_t = [\, USECON_t$, $TREAS_t^m$, $SP500_t$, $RISK_t^{10\delta RR}]'$ based on four alternative models: $m > 10-years$, $10 > m > 5-years$, $5 > m > 1-year$ and $m < 1-year$. $USECON_t$ and $TREAS_t^m$ enter the system in first differences, $SP500_t$ in log differences, and $RISK_t^{10\delta RR}$ in levels. The number of autoregressive lags is set to one with lag length chosen based on the Akaike Information Criterion. Confidence bands computed based on 10,000 MC samples after discarding first 1,000 as burn-in. We estimate the four-variable VAR model using weekly data from 9 January 2008 to 26 September 2012.

Figure 8. Impact of Federal Reserve Purchases on Risk Perceptions: by Policy Phase



Notes: Impulse responses and 90% Monte-Carlo (MC) confidence bands of the the following VAR system: $\mathbf{y}_t = [\,USECON_t$, $TREAS_t^{>5yr}$, $SP500_t$, $RISK_t^{10\delta RR}]'$; where $USECON_t$ and $TREAS_t^{>5-years}$ enter the system in first differences, $SP500_t$ in log differences, and $RISK_t^{10\delta RR}$ in levels. The number of autoregressive lags is set to one with lag length chosen based on the Akaike Information Criterion. Confidence bands computed based on 10,000 MC samples after discarding first 1,000 as burn-in. We estimate the four-variable VAR model using weekly data. QE1: March 2009 to November 2009; QE2: November 2010 to June 2011; QE3/MEP: October 2011 to September 2012.

Figure 9. Time-Varying Impact of Federal Reserve Purchases on Risk Perceptions: Week-1



Notes: Time series of 1-period ahead time-varying parameter Bayesian (TVP) VAR impulse responses with 68% credible interval bands. The Figure shows TVP-VAR impulse responses of the following system: $\mathbf{y}_t = [\, USECON_t,\ TREAS_t^{>5yr},\ SP500_t,\ RISK_t^{10\delta RR}]'$; where $USECON_t$ and $TREAS_t^{>5-years}$ enter the system in first differences, $SP500_t$ in log differences, and $RISK_t^{10\delta RR}$ in levels. The number of autoregressive lags is set to one following the fixed parameter VAR procedure. We estimate the four-variable TVP-VAR model using weekly data from 9 January 2008 to 26 September 2012.

Table I. Description of Variables

Variables:	Units:	Transform:	Frequency:	Source:
Monetary policy:				
Announcements	0 or 1		daily	Gagnon et al (2011), Wright (2011)
Fed Treasury holdings:				Ehlers (2012), Fratzscher et al (2012)
< 1-year	USD billions	first diff.	weekly	Federal Reserve System
1 to 5-year	USD billions	first diff.	weekly	Open Market Account (SOMA)
5 to 10-year	USD billions	first diff.	weekly	
>10-year	USD billions	first diff.	weekly	
Economic and financial conditions:				
Citi Economic Surprise Index	Diffusion index, -50 to +50	first diff.	daily/weekly	Citigroup Inc.
S&P500	Simple index	log diff.	daily/weekly	Bloomberg
Volatility and tail risk:				
Realized volatility	$\sqrt{RV(5min) \times 22 \times 12} \times 100$	first diff.		Oxford-Man Institute of Quantitative Finance
1-month implied volatility	VIX	level	daily/weekly	
25-delta risk reversal	$IV_{Call}^{25\delta} - IV_{Put}^{25\delta}$	$\times -1$, level		Bloomberg
10-delta risk reversal	$IV_{Call}^{10\delta} - IV_{Put}^{10\delta}$	$\times -1$, level.		

Sample: 2 January 2008 - 6 November 2012.

Table II. Overview of Federal Reserve Announcements of Unconventional Monetary Policy

Date	Phase	Announcement details
25/11/2008	QE1	Purchase of $100bn of agency debt and $500bn of agency MBS; Evaluation of the benefits of purchasing longer-term Treasury securities.
1/12/2008	QE1	Speech by Chairman Bernanke about an expansion of QE. Bernanke mentions that the Federal Reserve could purchase long-term Treasuries.
16/12/2008	QE1	Lower target range of federal funds rate to 0 - 25bp; Evaluation of the benefits of purchasing longer-term Treasury securities.
28/1/2009	QE1	FOMC statement about an expansion of QE. The Federal Reserve is ready to expand agency debt and MBS purchases, as well as to purchase long-term Treasuries.
18/3/2009	QE1	Purchase up to $300bn in Treasuries and additional $750bn of agency MBS bringing total purchases to $1.25tr; Increase in holdings of agency debt to $200bn.
10/8/2010	QE2	Reinvestment of MBS principal into Treasuries; Low rates for an extended period likely.
27/8/2010	QE2	Expansion of QE. Bernanke mentions potential policy options for further easing, including additional purchases of long-term securities.
21/9/2010	QE2	Maintain reinvestment policy. Low rates for an extended period likely.
15/10/2010	QE2	Speech by Chairman Bernanke on expansion of QE. The Federal Reserve is prepared to provide additional accommodation if needed to support the economic recovery.
3/11/2010	QE2	Purchase of a further $600bn of longer-term Treasuries.
9/8/2011	MEP	Prepared to adjust securities holdings as appropriate, low federal funds rate at least until mid-2013
21/9/2011	MEP	Announcement of the Maturity Extension Programme (MEP). Reinvestment of agency MBS and agency debt principals into agency MBS.
25/1/2012	MEP	Low federal funds rate at least until late 2014; prepared to adjust securities holdings as appropriate.
20/6/2012	MEP	Announcement of additional Maturity Extension Programme; low federal funds rate at least until late 2014.
1/8/2012	MEP	Committee will closely monitor incoming information and provide additional accommodation as needed.
31/8/2012	QE3 MEP	Bernanke speech – Discusses merits of unconventional monetary policy at Jackson Hole Conference, Wyoming.
13/9/2012	QE3 MEP	FOMC announces new policy of purchasing additional agency mortgage-backed securities at a pace of $40 billion per month. MEP continued.

Sources: Board of Governors of the Federal Reserve System; Gagnon, Raskin, Remache, and Sack (2011); Wright (2012); Ehlers (2012); and Fratzscher, Duca, and Straub (2012).

Table III. Risk Measures around Policy Announcements: Non-Parametric Analysis

Event Window	Risk Measure	ALL	QE1	QE2	MEP	QE3/MEP
5-5 day	$10\delta RR$	-0.565	-0.973	-0.241	0.076	-1.753
		[0.170]	[0.056]	[0.34]	[0.561]	[0.002]
	$25\delta RR$	-0.547	-1.398	-0.152	0.251	-0.974
		[0.087]	[0.003]	[0.336]	[0.734]	[0.013]
	IV	-1.193	-4.548	-0.201	1.692	-0.817
		[0.193]	[0.01]	[0.429]	[0.863]	[0.267]
	RV	-1.565	-9.541	2.324	3.312	0.450
		[0.162]	[0.000]	[0.706]	[0.754]	[0.469]
10-10 day	$10\delta RR$	-0.982	-2.110	-0.260	0.014	-1.889
		[0.068]	[0.002]	[0.349]	[0.515]	[0.004]
	$25\delta RR$	-0.757	-2.102	-0.136	0.385	-1.126
		[0.065]	[0.000]	[0.391]	[0.799]	[0.011]
	IV	-1.758	-6.377	-0.154	1.862	-0.962
		[0.129]	[0.001]	[0.442]	[0.860]	[0.252]
	RV	-3.049	-12.774	1.138	3.094	0.305
		[0.062]	[0.000]	[0.520]	[0.669]	[0.391]

Notes: The Table reports changes of risk measures around announcements of unconventional monetary policy. The entries in the table report the difference in the mean risk measure after and before the event, averaged across the different events. ALL means that the differences in the mean around the different announcement dates are averaged across all 17 events, whereas the other entries report the differences in mean averaged across the events of the indicated policy phases. Bootstrap p-values are reported in brackets and are based on the stationary bootstrap by Politis and Romano (1994).

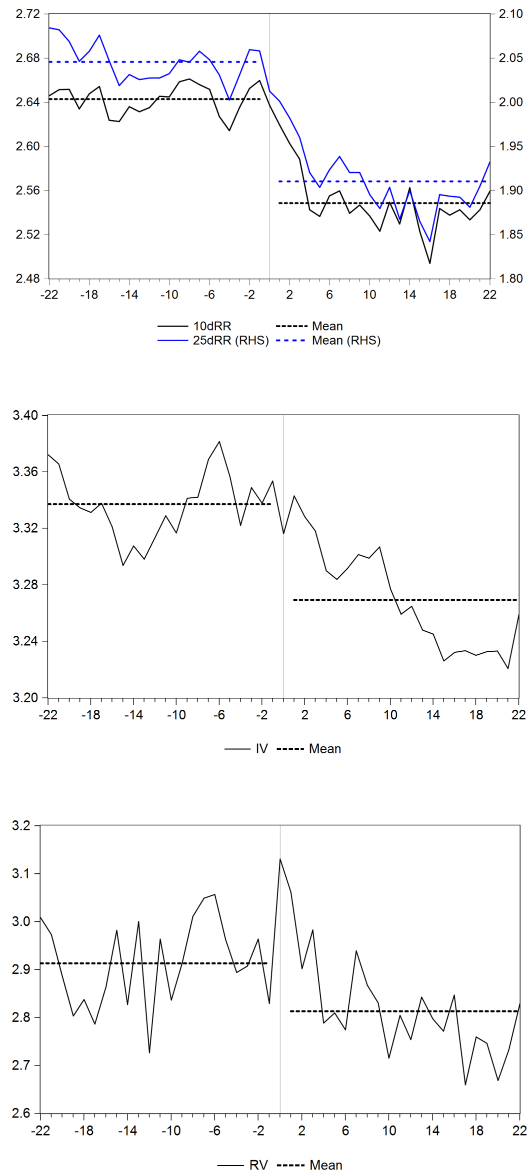
Table IV. Announcement Effect for 2-, 3-, and 5-day Event-Windows, Cumulative Changes, and Joint Coefficient Significance Tests; Entire Sample Period

Event Window	Dependent variable:	10δ RR	25δ RR	IV	RV
2-day	Cumulative abnormal change	-10.270	-6.695	-3.785	70.100
	$\sum$ Announcement dummies	-0.805 ***	-0.538 **	-0.292	5.830 **
	p-value	[0.009]	[0.053]	[0.842]	[0.022]
	F-stat	4.732	2.956	0.171	3.827
	R-squared	0.294	0.365	0.689	0.205
3-day	Cumulative abnormal change	-11.991	-8.592	-7.797	-4.190
	$\sum$ Announcement dummies	-0.960 **	-0.702 *	-0.622	-0.120 ***
	p-value	[0.019]	[0.084]	[0.827]	[0.001]
	F-stat	3.321	2.225	0.297	5.678
	R-squared	0.295	0.366	0.69	0.215
5-day	Cumulative abnormal change	-12.056	-8.215	-11.380	-37.739
	$\sum$ Announcement dummies	-2.080 ***	-0.415 ***	-0.831 **	-1.560 ***
	p-value	[0.000]	[0.004]	[0.031]	[0.000]
	F-stat	20.750	3.449	2.479	12.700
	R-squared	0.297	0.367	0.691	0.224
	Observations	689	689	694	693

Notes: The Table reports changes of risk measures around 17 announcements of unconventional monetary policy based on an event study regression.P-values based on the F-test for the null of coefficients on QE dummies equal to zero following Krishnamurthy and Vissing-Jorgensen (2011). *, **, and *** indicate coefficients significant at 10%, 5%, and 1% level respectively.

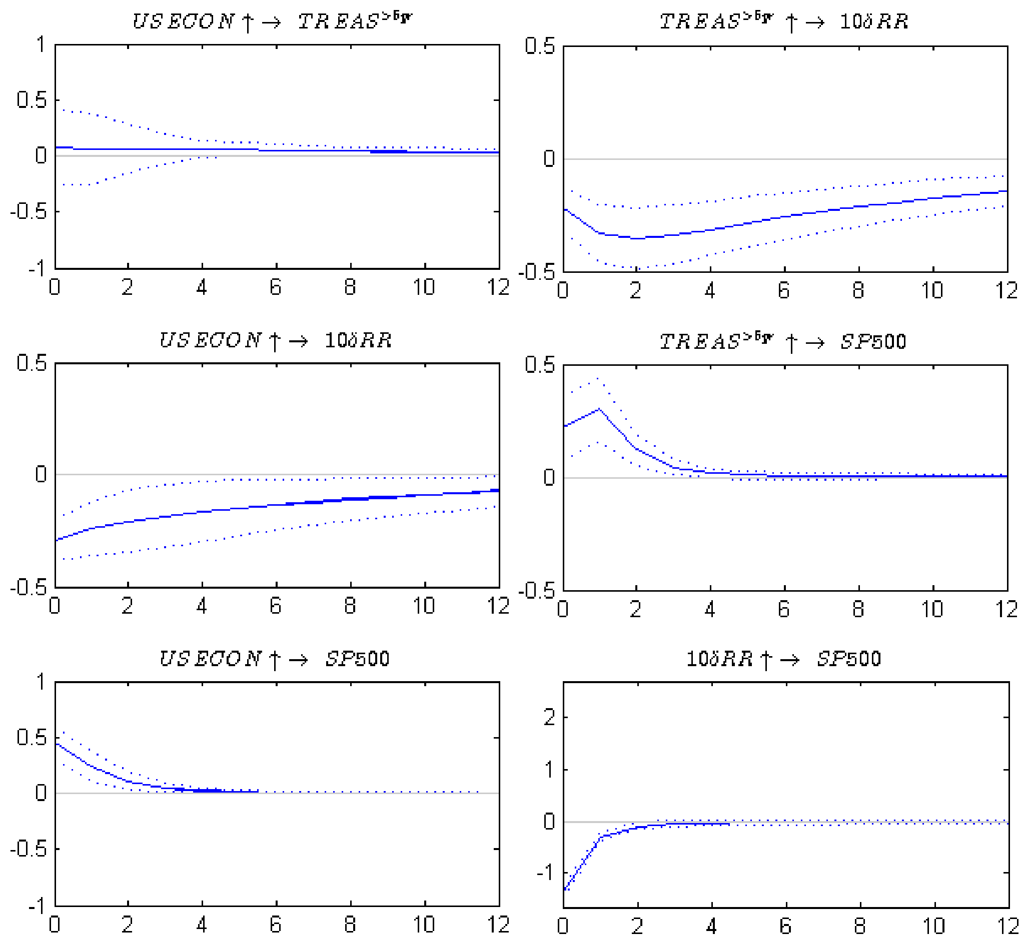
A. Robustness

Figure 10. Event Study of Variables in Logarithms



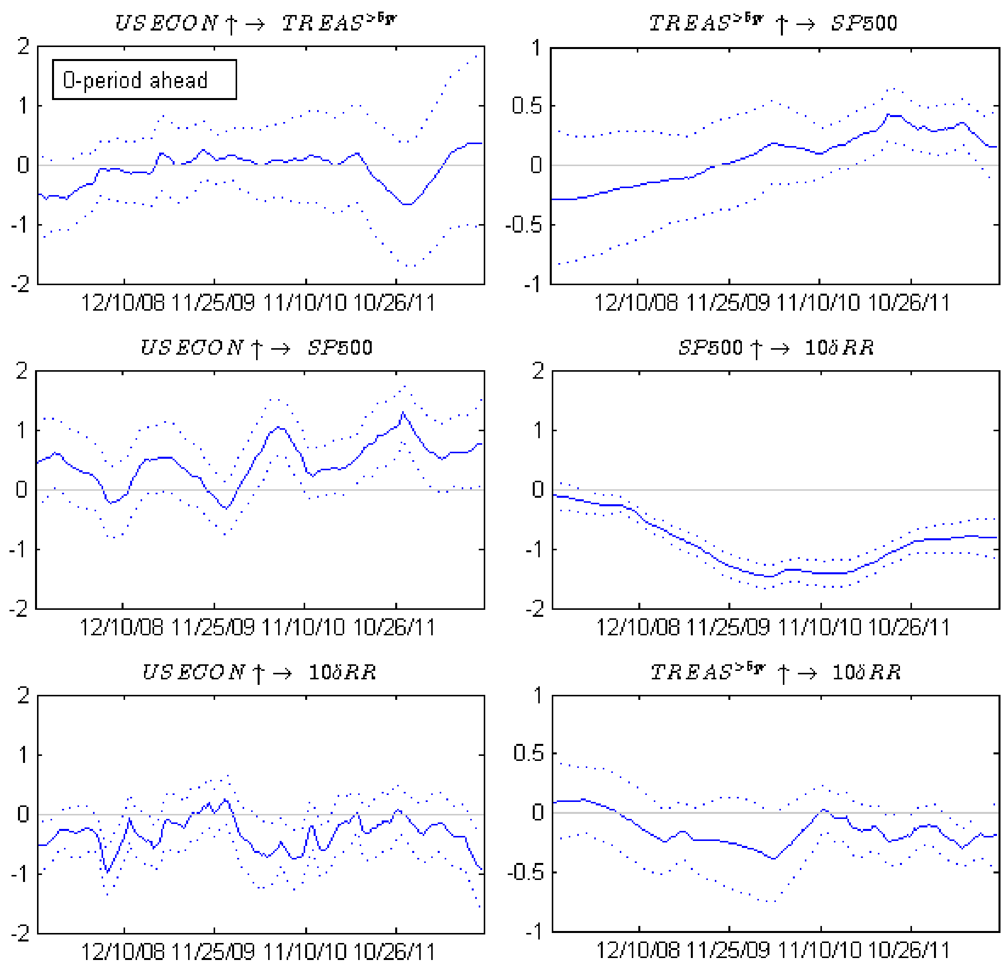
Notes: Average readings of logs of 10- and 25-delta risk reversals ($10\delta RR$ and $25\delta RR$), implied volatility (IV), and realized volatility (RV)22 days before and after the 17 announcement dates associated with Federal Reserve's unconventional monetary policy measures, as indicated in Table II.

Figure 11. VAR Order with $RISK_t^{10\delta RR}$ before $SP500_t$



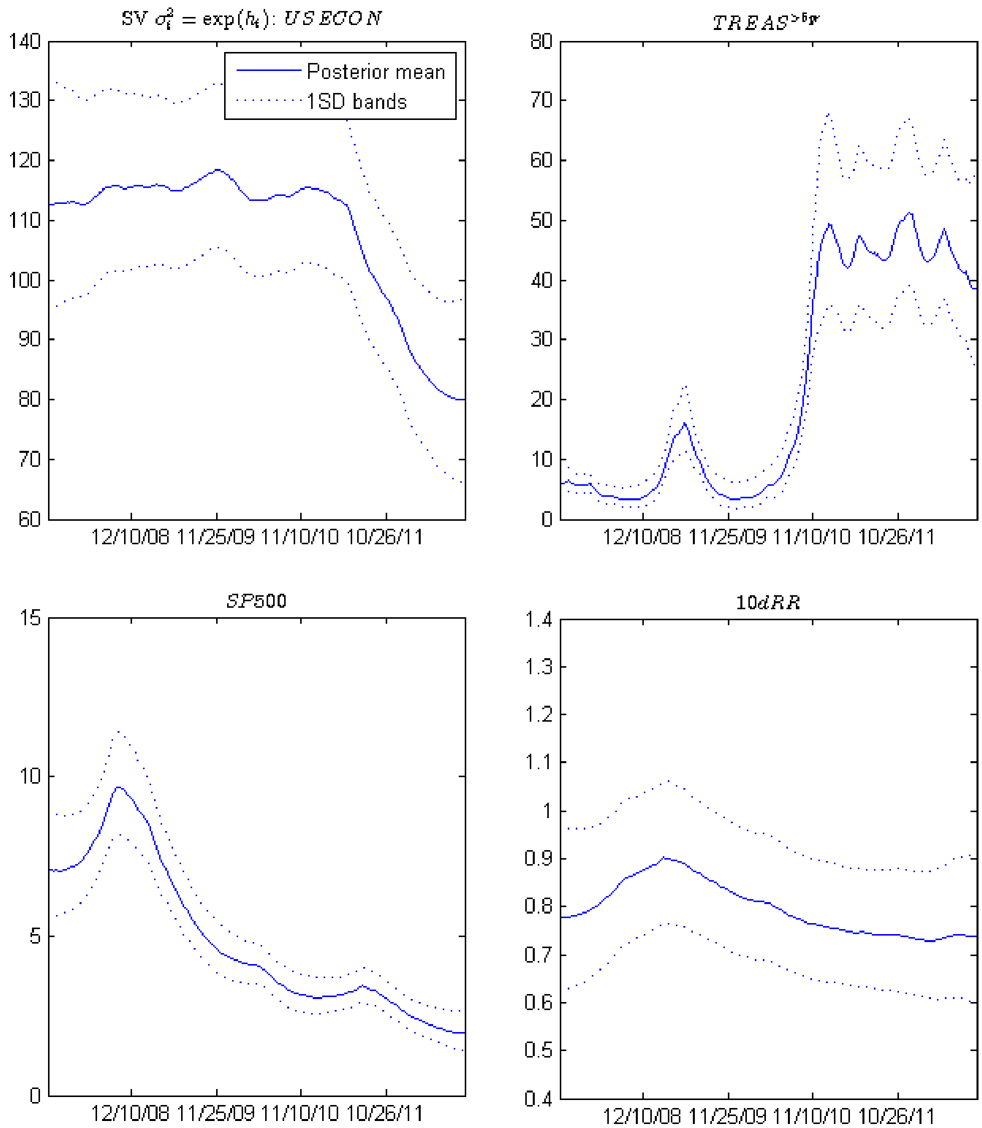
Notes: Impulse responses and 90% Monte-Carlo (MC) confidence bands of the the following VAR system: $\mathbf{y}_t = [USECON_t, TREAS_t^{>5yr}, RISK_t^{10\delta RR}, SP500_t]'$; where $USECON_t$ and $TREAS_t^{>5-years}$ enter the system in first differences, $RISK_t^{10\delta RR}$ in levels, and $SP500_t$ in log differences. The number of autoregressive lags is set to one with lag length chosen based on the Akaike Information Criterion. Confidence bands computed based on 10,000 MC samples after discarding first 1,000 as burn-in. We estimate the four-variable VAR model using weekly data from 9 January 2008 to 26 September 2012.

Figure 12. Time-Varying Impact of Federal Reserve Purchases on Risk Perceptions: Week-0



Notes: Time-series of 0-period ahead time-varying parameter Bayesian (TVP) VAR impulse responses with 68% credible interval bands. The Figure shows TVP-VAR impulse responses of the following system: $\mathbf{y}_t = [\ USECON_t,\ TREAS_t^{>5yr},\ SP500_t,\ RISK_t^{10\delta RR}]'$; where $USECON_t$ and $TREAS_t^{>5-years}$ enter the system in first differences, $SP500_t$ in log differences, and $RISK_t^{10\delta RR}$ in levels. The number of autoregressive lags is set to one following the fixed parameter VAR procedure. We estimate the four-variable TVP-VAR model using weekly data from 9 January 2008 to 26 September 2012.

Figure 13. Estimated Time-Varying Volatility of Structural Shocks to VAR System Variables



Notes: Posterior estimates of the mean of stochastic volatility of structural shocks with 68% credible interval bands. Estimates based on the following TVP-VAR system: $\mathbf{y}_t = [\,USECON_t,\, TREAS_t^{>5yr},\, SP500_t,\, RISK_t^{10\delta RR}]'$; where $USECON_t$ and $TREAS_t^{>5-years}$ enter the system in first differences, $SP500_t$ in log differences, and $RISK_t^{10\delta RR}$ in levels. The number of autoregressive lags is set to one following the fixed parameter VAR procedure. We estimate the four-variable TVP-VAR model using weekly data from 9 January 2008 to 26 September 2012.