

The Response of Stock Market Volatility to Futures-Based Measures of Monetary Policy Shocks

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Abstract: In this paper, we investigate the dynamic response of stock market volatility to changes in monetary policy. Using a vector autoregressive model, our findings reveal a significant and asymmetric response of stock returns and volatility to monetary policy shocks. Although the increase in the volatility risk premium, futures-trading volume, and leverage appear to contribute to a short-term increase in volatility, the longer-term dynamics of volatility are dominated by monetary policy's effect on fundamentals. The estimation results from a bivariate VAR-GARCH model suggest that the Fed does not respond to the stock market at a high frequency, but they also suggest that market participants' uncertainty regarding the monetary stance affects stock market volatility.

JEL classification: C32, C58, E52, E58, G10, G12

Key words: stock market volatility, federal funds futures, monetary policy, variance risk premium, vector autoregression, bivariate GARCH, leverage effect, volatility feedback effect

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1. Introduction

The effect of Federal Reserve (Fed) actions on the stock market has garnered substantial policy-making, practical and research interest. A change in the federal funds rate, the Fed's policy instrument, is closely associated with changes in various short-term interest rates. This, in turn, influences the discount rate used to value the cash flows from equities (i.e. dividends). Monetary policy also affects the stock market through its effect on financial leverage: each rate change by the Fed changes the cost for firms to finance their activities through issuing debt.¹ While the extant literature (Bernanke and Kuttner, 2005; Goto and Valkanov, 2002; Thorbecke, 1997 and Patelis, 1997; Tsai, 2014) widely documents a decrease in stock market returns following a monetary policy tightening, the effect of Fed actions on stock market volatility are less documented and understood. Nevertheless, the response of the stock market to Fed actions need not be limited to returns and can extend to stock price volatility through a number of channels.

On the one hand, as first documented in Black (1976) and Christie's (1982) seminal contributions, an asymmetric relationship exists between stock returns and volatility. Black (1976) and Christie (1982) attribute the increase in volatility to a higher leverage (debt-to-equity) ratio and researchers since refer to the asymmetric return-volatility relationship as the leverage effect. In view of the established decrease in stock prices following a monetary policy tightening, an increase in volatility can thus result from the leverage channel.

On the other hand, monetary policy can exert a direct influence on risk premiums and volatility. In fact, an alternative view of the asymmetric return-volatility relationship proposed by

¹ Researchers refer to the first channel as the "wealth channel" while the second channel is labeled the "balance sheet" channel. For a survey of the empirical and theoretical research on the relationship between the stock market and monetary policy, see Sellin (2001).

Campbell and Hentschel (1992) and subsequently referred to as the volatility feedback hypothesis, postulates that negative news spur an increase in future volatility. According to the volatility feedback hypothesis, time-varying risk premiums relate the increase in future volatility to a decrease in contemporaneous returns. More specifically, the negative news leads to an increase in the expected stock returns (i.e. risk premiums) as investors require additional compensation to account for the increased riskiness of holding stocks. If volatility is a priced risk factor, and given a positive correlation between future volatility and expected returns, the increase in future volatility feeds back into and lowers contemporaneous returns. In sum, negative news decreases returns contemporaneously and increases both future volatility and expected stock returns. An unexpected monetary policy tightening constitutes negative news to stocks whose future cash flows (dividends) are valued at a higher than expected discount rate. This implies that a monetary policy shock is expected to decrease returns contemporaneously and to increase future stock market volatility. Evidently, both the leverage and volatility feedback channels can operate simultaneously as argued in Wu (2001).

An unexpected monetary policy tightening, which represents new information to investors, can also increase volatility through its effect on trading activity. In light of the new information available in the market, investors may rebalance their portfolios more intensively between equities and bonds thus spurring an increase in trading volume. The increase in trading volume could, in turn, translate into higher volatility due to the well-known positive relation between volatility and trading volume (Karpoff, 1987; Andersen, 1996, among others). Such an increase in volatility would also be in line with Ross's (1989) analysis suggesting that information flow into the market positively correlates with volatility.

While previous research (Bomfim, 2003; Lee, 2006) uses Generalized Autoregressive Conditional Heteroskedasticity (GARCH) models to investigate the link between monetary policy surprises and the volatility of some assets, the existing literature did not assess the *dynamic* effect of monetary policy shocks on stock market volatility (volatility risk premium) nor investigate the channels through which monetary policy affects volatility. In an influential contribution, Schwert (1989) studies the relationship between macroeconomic and stock market volatility but does not explicitly tackle the effect of monetary policy on stock market volatility.

In this paper, we undertake an in-depth analysis, at the monthly level, of the effect of futures-based monetary policy shocks on stock market volatility and the volatility risk premium. We examine the dynamic effects of monetary policy shocks, identified from Federal funds futures data, by employing a vector autoregressive (VAR) model. The use of market-based measures of monetary policy shocks allows us to avoid the need to resort to identifying assumptions and circumvents dimensionality (degrees of freedom) problems in the estimated VAR. Our goal from this analysis is threefold. First, we assess the dynamic response of stock market volatility and the volatility risk premium to monetary policy shocks. Second, our analysis allows us to characterize asymmetries in the return-volatility relationship. Third, we study the channels through which monetary policy shocks affect stock market volatility by analyzing the joint response of several financial variables to market-based measures of monetary policy shocks. By inspecting the channels of monetary policy transmission to volatility, we also identify the importance of changes in the risk premium or leverage on stock market volatility and, therefore investigate in further detail the importance of the volatility feedback and leverage effect hypotheses.

Our baseline results show a contemporaneous decrease in excess returns of 1% and an increase in stock market volatility which peaks one month following the monetary policy shock at 0.4%. The results illustrate the asymmetric return-volatility relationship. We further explore the high-frequency effect of monetary policy expectations on stock market volatility by estimating a bivariate VAR-GARCH model relating federal funds futures to stock market volatility. Our results lend empirical support to the hypothesis that market participants' uncertainty about the future course of monetary policy is an important determinant of stock market volatility.

To the best of our knowledge, this study is the first to examine the dynamic response of stock market volatility (volatility risk premium) to monetary policy shocks and to examine the transmission of monetary policy to volatility. Such an exploration would be of central importance from a theoretical and practical perspective. Theoretically, volatility is a key component of many derivative pricing models and an understanding of the dynamic response of volatility to monetary policy shocks would allow for better derivative pricing. From a practical perspective, the advent of derivatives on market volatility and their increasing popularity with investors shows that volatility, while itself not being a tradable asset, can be profitably traded as underlying asset for a number of derivatives contracts.² In addition, a more complete understanding of the role of monetary policy in affecting the volatility risk premium would contribute to a better understanding of risk taking behavior in financial markets.

² Such as the Chicago Board of Options Exchange (CBOE)'s futures and options on the VIX index which began trading in 2004 and 2006, respectively. In addition, variance swaps currently have a liquid market. Carr and Wu (2006) discuss variance swap contracts and the return that accrues to investors from holding such contracts around FOMC announcement days.

The plan of the paper is as follows: Section 2 discusses the data and variables we employ, Section 3 presents the econometric methodology and results while Section 4 offers some concluding remarks.

2. Data and Variable Description

Our data comprise daily and monthly observations on excess returns on the S&P 500 index, federal funds futures as well as implied and realized volatilities. Our baseline sample spans the period January 1990 to December 2007. In order to investigate the effect of the financial crisis on our results, we extend the sample to December 2008 and report two sets of results based on the baseline and extended samples. The starting and ending dates of our baseline and extended samples are dictated by the availability of implied volatility and Federal funds target rate data.³

We discuss next our data and variables in further detail.

2.1 Daily data

2.1.1 Stock returns

Daily closing price data on the Standard and Poor's S&P500 index are obtained from Yahoo! Finance. Continuously compounded daily returns are computed as:

$$R_{n,t} = \ln(P_{n,t}) - \ln(P_{n-1,t}), \quad (1)$$

³ Admittedly, we cover only part of the financial crisis by extending the sample to December 2008. However, our sample period is dictated by data availability. On the one hand, data on S&P 500 implied volatility (the VIX index) is available only starting January 1990. On the other hand, the Federal funds target rate series was discontinued in December 2008 and replaced by upper and lower bound target rate series. This change occurred with the onset of subprime mortgage crisis and the ensuing decrease of the Fed funds rate towards the zero lower bound.

where $P_{n,t}$ denotes the closing index price on day n of month t .⁴

2.1.2 Federal funds futures

Federal funds futures, officially known as 30-day interest rate futures, are interest rate futures that settle on the average of the month's overnight funds rate. These futures contracts started trading on the Chicago Board of Trade (CBOT) in 1988 and contracts ranging from the current (spot) month to several months ahead exist. Gurkaynak, Sack and Swanson (2007) and Hamilton (2009) provide empirical evidence supporting the efficiency of the federal funds futures market.

We employ daily changes in federal funds futures rates to gauge changes in monetary policy expectations. Hamilton (2009) maintains that daily changes federal funds futures rates are indicative of market participants' expectations of the future level of the federal funds rate. This, in turn, implies that daily changes in federal funds futures contracts signal market participants' changing expectations about the future course of monetary policy and can be used as a direct gauge of monetary policy expectations. Following Hamilton (2009), we use daily changes in the implied rates, $\Delta FFF_{n,t}^1 = FFF_{n,t}^1 - FFF_{n-1,t}^1$, to measure changes in market participants' expectations of the future course of monetary policy.

2.2 Monthly data

2.2.1 Excess returns and realized volatility

Monthly excess returns on the S&P500 index are computed by subtracting the three month T-bill rate (considered as a proxy for the risk-free rate) from the monthly returns on the S&P500:

⁴ Monthly continuously compounded returns on the S&P 500 are computed from monthly closing price data in a similar manner to equation (1).

$$ER_t = R_t - TB_t. \quad (2)$$

Monthly realized stock market volatility is computed, in turn, from daily squared returns as in Bandi and Perron (2006):

$$VOL_t = \sqrt{\frac{252}{N} \sum_{n=1}^N R_{n,t}^2}, \quad (3)$$

where N denotes the number of trading days in month t .

2.2.2 Monthly monetary policy shocks

Given the evidence in favor of the efficiency of federal funds futures, several studies have also proposed extracting monthly monetary policy shocks from these contracts. Following Bernanke and Kuttner (2005), a monthly monetary policy shocks series is computed from futures prices. Let $FFF_{n,t}^1$ denote the one-month-ahead implied rate for day n of month t , and $FFTR_{n,t}$ denote the Federal funds *target* rate for day n in month t , the monthly monetary policy shock is given by:

$$MP_t = \frac{1}{N} \sum_{n=1}^N FFTR_{n,t} - FFF_{N,t-1}^1, \quad (4)$$

where $FFF_{N,t-1}^1$ denotes the one-month-ahead futures rate on the last (N^{th}) day of month $t-1$.

In the absence of a time-varying risk premium⁵, the one-month Federal funds futures rate at time t represents market participants' expectation of the average Federal funds rate, the Fed's main policy rate before the onset of the subprime mortgage crisis, in month $t+1$. The difference between the average target rate in month t and the one-month-ahead futures rate in month $t-1$

⁵ We test for the unbiasedness and efficiency of federal funds futures rates in predicting the federal funds rate. Regression results (available from the authors upon request) indicate that unbiasedness and efficiency cannot be rejected for the one-month-ahead contract used to compute monthly monetary policy shocks.

therefore represents the unexpected component of the target rate change (i.e. the monetary policy surprise).

2.2.3 Variance and volatility risk premiums

The Chicago Board Options Exchange (CBOE)'s option-implied volatility (VIX) index is widely viewed by policymakers and market participants as an investor "fear gauge" (Whaley, 2000; Blanchard 2009). The VIX index (*IVOL*), which is constructed from S&P 500 options with a constant thirty calendar days to expiry, also represents market participants' expectation of realized volatility over the next 22 trading days. Prior research suggests, however, that the VIX is a biased and inefficient predictor of future S&P 500 realized volatility (Chernov, 2007).

In light of option-implied volatility's bias, recent research defines the variance risk premium (*VRP*) as the difference between the risk-neutral and physical (i.e. statistical or objective) expectations of the return variance. Let Var_{t+1} denote the return variance on the S&P 500. Following Zhou (2010), the variance risk premium is defined as:

$$VRP_t = E_t^Q(Var_{t+1}) - E_t^P(Var_{t+1}), \quad (5)$$

where $E_t^Q(\cdot)$ and $E_t^P(\cdot)$ denote, respectively, the conditional expectation operators at time t under the physical and risk-neutral measures.

While prior research (Zhou, 2010; Bekaert and Hoerova, 2014) employs the squared VIX index as an empirical proxy for the risk-neutral S&P 500 return variance, the literature adopts a number of approaches for obtaining an estimate of the physical return variance measure. Recent research (Bollerslev, Tauchen and Zhou, 2009; Adrian and Shin, 2010) also defines the volatility risk premium as the difference between implied and realized volatilities. Following Bollerslev, Tauchen and Zhou (2009) and Adrian and Shin (2010), we define the volatility risk premium as

$VRP_t = IVOL_t - VOL_t$. As detailed subsequently, this allows us to obtain the response of the volatility risk premium to a monetary policy shock from the estimated VAR model in a straightforward manner.⁶

2.2.4 Financial variables

In addition to excess returns and volatility, we employ the following variables in the VAR model: the real interest rate (*RINT*) defined as the difference between the three month T-bill rate and the consumer price inflation, the change in the three month T-bill rate (*DTB*), the dividend yield on the S&P500 (*DY*), the change in the S&P 500 futures-trading volume (*VOLUME*) and financial leverage (*LEVERAGE*) as proxied for by the monthly growth rate in commercial and industrial loans made by all commercial banks. The time series dynamics of the endogenous variables employed in VAR estimation over the baseline period are displayed in Figure 1.

[Insert Figure 1 here]

Panels A and B of Table 1 additionally report the summary statistics of the variables employed in the empirical analysis for the baseline and extended sample periods, respectively.

[Insert Table 1 here]

The results in Table 1 indicate that the dividend yield exhibits very high persistence that is well documented in the literature. Table 1 also shows that the volatility risk premium is, on average, positive and despite the strong persistence in realized and implied volatilities, it exhibits only weak serial correlation.

⁶ As discussed in Section 3.1, defining the volatility risk premium in this manner allows us to avert computing the response of a generated variable (which is subject to estimation uncertainty) to an *MP* shock. We thank an anonymous referee for suggesting this approach. We note that the volatility (variance) risk premium represents the expected returns from selling a volatility (variance) swap. For further details, see Bollerslev, Tauchen and Zhou (2009), Bekaert, Hoerova and Lo Duca (2013) and Berkaert and Hoerova (2014).

3. Econometric Methodology and Results

3.1 The VAR model

In this section, we present the VAR model employed and study the channels of transmission of monetary policy shocks to volatility. Campbell (1991) provides a decomposition that relates unexpected stock returns to changes in expectations of future dividend growth, interest rates and future stock returns. Patelis (1997) and Bernanke and Kuttner (2005) employ Campbell's (1991) decomposition to assess excess stock returns' response to a monetary policy. Let ER_t denote excess returns at time t . Then, following Campbell (1991) excess returns can be written as:

$$ER_{t+1} - E_t(ER_{t+1}) = (E_{t+1} - E_t) \left(\sum_{j=0}^{\infty} \rho^j \Delta D_{t+1+j} \right) - (E_{t+1} - E_t) \left(\sum_{j=0}^{\infty} \rho^j RINT_t \right) - (E_{t+1} - E_t) \left(\sum_{j=0}^{\infty} \rho^j ER_{t+1+j} \right), \quad (6)$$

where $E_t(\cdot)$ denotes the conditional expectation operator (given the information set at time t), D_t denotes the log dividend at time t , $RINT_t$ denotes the real interest rate at time t and ρ is a constant (generally set close to one) which equals the ratio of ex-dividends to the cum-dividends.

As convincingly argued in Patelis (1997) and Bernanke and Kuttner (2005), the decomposition in equation (6) illustrates the various channels through which monetary policy can affect returns. Contractionary monetary policy can exert an effect on stock market returns by decreasing expected future dividends, increasing expected excess returns or increasing the future expected real interest rates. As argued earlier, monetary policy's effect can extend to volatility through a multitude of channels: its effect on time-varying risk premiums (volatility feedback hypothesis), on financial leverage (leverage effect) or on discount rates and trading activity.

In order to simultaneously examine the response of stock market volatility, returns and the transmission of monetary policy to volatility, the variables included in equation (6) are

incorporated into our VAR. Following prior research (Bagliano and Favero, 1998, 1999; Bernanke and Kuttner, 2005; Faust, Swanson and Wright, 2004) we circumvent identification problems by incorporating market-based measures of monetary policy shocks obtained from Federal funds futures data as an exogenous variable in the VAR model. More specifically, we employ the following VARX(p,q) model to assess the effect of monetary policy shocks (MP),⁷ computed from equation (4), on financial variables:

$$Y_t = A_1 Y_{t-1} + \Phi_0 MP_t + \omega_t, \quad (7)$$

where $Y_t = [ER \ VOL \ VRP \ RINT \ DTB \ DY \ LEVERAGE \ VOLUME]$. In equation (7), Φ_0 summarizes the contemporaneous response of Y_t to an exogenous monetary policy shock while the effect of the monetary policy shock at time t on Y_{t+j} is measured by $A_1^j \Phi_0$.

In addition to excess returns, realized volatility, the volatility risk premium, the real interest rate, the change in the T-bill rate and the dividend yield, we include in the VAR a measure of financial leverage and the change in S&P 500 futures-trading volume. Bessembinder and Seguin (1993) provide empirical evidence of a positive correlation between unexpected futures-trading volume and volatility. Following Bessembinder and Seguin (1993), we consider the residuals from a AR(10) model of the change in log volume to be the unexpected component of S&P 500 futures volume.⁸

⁷ A lag order of three for Y_t is selected by AIC. Using a VARX(1,0) yields similar results.

⁸ As argued in Bessembinder and Seguin (1993) and given that extracting the unexpected component of the futures-trading volume is the primary goal, using an AR model with arbitrarily long lags would be sufficient. We note that our results are unchanged when we use a well specified ARMA model. Our impulse responses are also not affected when we detrend S&P 500 futures volume by subtracting from it its one or two-year moving average instead of log differencing.

The responses of the financial variables to a one standard deviation (9 basis points and 10 basis points increases in the baseline and extended samples, respectively) contractionary monetary policy (*MP*) shock, for a horizon of twelve months, are displayed in Figures 2 and 3 for the baseline and extended samples, respectively.

[Insert Figures 2 and 3 here]

The impulse responses in Figure 2 show that a one standard deviation contractionary shock leads to a contemporaneous decrease of one percentage point in excess returns. The well-established (Thorbecke, 1997; Bernanke and Kuttner, 2005, Tsai, 2014) initial decrease in excess returns is short-lived and lasts for around one month. When we extend the sample to December 2008 (Figure 3), we find that the contemporaneous negative response of excess returns to an *MP* shock is qualitatively maintained but decreases in magnitude.

While the response of returns is in line with results reported in prior studies, a number of interesting and novel observations emerge from the dynamic response of realized volatility to a monetary policy shock. In our baseline sample, an *MP* shock leads to an increase in realized volatility whose response peaks at around 0.4% one month after the shock. Figure 3 shows that realized volatility's response to a monetary tightening is at its highest contemporaneously at 0.7%. While the response of realized volatility reverts back to zero three months after the shock in the baseline sample (Figure 2), realized volatility's response remains persistently positive and only gradually dies out twelve months after the shock in the extended sample (Figure 3). Our findings from the baseline and extended samples confirm the widely documented (Black, 1976; Christie, 1982; Campbell and Hentschel, 1992) asymmetric response of volatility to negative return shocks and conform to economic intuition.

While both the leverage effect and volatility feedback hypotheses imply an asymmetric return-volatility response, we note that the causality implications of the two hypotheses are different. In fact, the leverage effect hypothesis stipulates that future volatility increases because of the contemporaneous decrease in stock prices (and the resulting increase in the debt-to-equity ratio) whereas the volatility feedback hypothesis postulates that the increase future volatility drives the decrease in contemporaneous stock returns. Therefore, as argued in Wu (2001) and Bekaert and Wu (2000), the causality implications of the two hypotheses are different. Causality runs from stock returns to volatility under the leverage effect hypothesis whereas the volatility feedback hypothesis implies that the increase in volatility causes stock returns to decrease contemporaneously. A closer inspection of the dynamic response of financial leverage and the variance risk premium to an *MP* shock, as discussed next, can assist in determining the importance of the leverage and risk aversion channels in the transmission of *MP* shocks to volatility.

Given that the volatility feedback hypothesis attributes the response of volatility to changes in risk premiums, we turn to a more extensive analysis of the effect of monetary policy changes on the volatility risk premium. A number of studies (Rosenberg and Engle, 2002; Bollerslev, Tauchen and Zhou, 2009; Bollerslev, Gibson and Zhou, 2011; Bekaert and Hoerova, 2014) provide empirical evidence of a positive correlation between market-wide risk aversion and the variance risk premium.⁹ Examining the response of the volatility risk premium to an *MP* shock would therefore shed light on the effect of a monetary policy tightening on investors'

⁹ Bollerslev, Gibson and Zhou (2011) provide empirical evidence that macroeconomic factors and yield spreads affect the variance risk premium. The significance of the yield spreads in affecting the variance risk premium implies that monetary policy changes can also significantly affect market-wide risk aversion.

perceptions of risk. The responses of the volatility risk premium to a contractionary monetary policy shock over the baseline and extended sample periods are displayed in Figures 2 and 3, respectively. Our baseline results show a contemporaneous increase in the *VRP* of 0.4% due to the *MP* shock. The response of the *VRP* is short-lived as the effect of an *MP* shock dissipates in one month. Due to the positive correlation between the volatility risk premium and market-wide risk aversion, our baseline sample results suggest that market-wide risk aversion increases following a contractionary monetary policy shock. While the impulse response analysis over the baseline period lends support to the volatility feedback hypothesis according to which changes in risk premiums drive volatility, our conclusions are somewhat moderated by the insignificance of the *VRP*'s response over the extended sample (Figure 3)

As argued earlier, a monetary policy shock can affect returns and volatility through its effect on discount rates, risk premiums, financial leverage or trading activity. Regardless of the exact channel through which Fed actions operate, we argue that a monetary policy tightening constitutes negative news to stocks. The negative news translates into an increase in realized volatility (and expected returns) and a decrease in excess returns. We turn next to assessing the importance of the other channels of transmission of an *MP* shock to realized volatility.

The leverage effect hypothesis posits that changes in volatility are driven by changes in leverage. The VAR model in equation (7) therefore comprises a measure of financial leverage and Figures 2 and 3 lend empirical support to the presumption that monetary policy shocks transmit to volatility through the leverage channel. As expected, the increase in interest rates following the monetary policy shock also increases leverage due to the increase in the cost of

issuing debt. The slow mean reverting increase in leverage, in turn, corresponds with an increase in stock market volatility.

The change in the T-bill rate exhibits a positive response to a futures-based monetary policy shock across both the baseline and extended samples. The response of the change in the T-bill rate reverts back to zero around six months following the shock. The dynamics of the real interest rate show an initial decrease (which is insignificant in the baseline sample).¹⁰ The real interest rate then turns and remains persistently positive for twelve months after the *MP* shock. The decrease in the real interest rate indicates that, following the monetary policy shock, inflation increases proportionately more than the nominal interest rate. Taken together, the responses of the interest rate variables are also suggestive of an important response of short-term interest rates, and by extension, of discount rates, to monetary policy shocks.

The unexpected S&P 500 futures-trading volume increases contemporaneously due to the monetary policy shock. The increase in trading volume is short-lived in both samples and lasts for one month following which trading volume becomes slightly negative. The response of unexpected futures trading volume reverts back to zero six (twelve) months after the *MP* shock in the baseline (extended) sample. The positive relationship between futures-trading activity and volatility is consistent with Bessembinder and Seguin (1993) and with the notion that the monetary policy shocks constitute new information arrival into the market that drives investors to rebalance their portfolios more intensively.

Finally, the dividend yield also strongly responds to a monetary policy shock. Due to the decrease in stock prices, the dividend yield shows a persistent increase in both the baseline and

¹⁰ The decrease in the real interest rate likely reflects the presence of a price puzzle in the VAR, a finding which is not uncommon in the monetary VAR literature.

extended samples. In sum, the impulse responses in Figures 2 and 3 uncover that the risk premium, discount (interest) rate, leverage, trading volume and dividend channels all contribute to the short-term increase in volatility.

In order to better assess the importance of each of the channels, Panels A and B of Table 2 provide the forecast error variance decompositions for a horizon of twelve months for the baseline and extended sample periods, respectively.

[Insert Table 2 here]

The variance decompositions for the baseline sample, reported in Panel A, show that a monetary policy shock accounts for 2.40%, 0.60% and 1.31% of the variance of excess returns, realized volatility and volatility risk premium, respectively. Whereas an *MP* shock accounts only for a small proportion of the variance of futures-trading volume (0.62%), its effect on the change in the T-bill rate (14%) and the dividend yield (4.66%) is more sizeable. The results for the extended sample, reported in Panel B of Table 2, show that a monetary policy innovation accounts for a larger proportion of the variance of the real interest rate, realized volatility, the dividend yield, leverage and futures-trading volume.

The variance decompositions in Table 2 lend support to the hypothesis that monetary policy's impact on excess returns appears to propagate through the dividend yield channel, while an *MP* shock's effect on volatility transmits through the risk premium and futures-trading volume channels. The contribution of the financial leverage channel appears to be more modest.¹¹ The variance decompositions also indicate that, aside from an own shock, the largest proportion of the variance of realized volatility is due to innovations in returns whereas

¹¹ Using high-frequency firm-level data, Tsai (2014) provides empirical evidence that financially constrained firms are more responsive to a monetary policy surprise. We view Tsai's (2014) results as indicative that the importance of the leverage channel might be better discerned at the individual equity level and using higher frequency data.

innovations to excess returns and the real interest rate contribute the most to the variance of the volatility risk premium. Our results also suggest that once the effect of an *MP* shock on interest rates, trading volume and risk premium dies out, the dynamics of excess and volatility are dominated by the persistent effect that monetary policy exerts on fundamentals (the dividend yield).

3.3 Federal funds futures and stock market volatility

In view of the response of stock market volatility to monetary policy uncovered in the prior section, we turn next to investigating the relationship among the stock market and monetary policy expectations, gauged using futures data, at the daily level. Specifically, we examine the volatility interaction among the stock and federal funds futures markets. To do so, we use daily continuously compounded returns on the S&P 500 (in percent) as well as the daily changes in the implied interest rates from federal funds futures (in basis points).

Hamilton (2009) maintains that daily changes in federal funds futures rates provide a direct measure of changes in market expectations of monetary policy actions. Using daily changes in futures rates would thus allow for investigating volatility relationships between monetary policy and the stock market. Hamilton (2009) also provides evidence that the daily changes in federal funds futures rates exhibit strong conditional heteroskedasticity. We conduct tests for ARCH effects for S&P 500 returns and the daily changes in federal funds futures rates and our results (not reported) indicate strong conditional heteroskedasticity in the series.

Given the conditional heteroskedasticity present in the daily changes in federal funds futures rates, we proceed to jointly modeling the stock and federal funds futures volatility using a

bivariate VAR-GARCH model. Unlike the VAR models considered previously, the model entertained in this section makes use of daily data and does not address the effect of a monetary policy shock on stock market volatility per se, but rather the volatility interaction between market-based measures of monetary policy expectations and the stock market. We treat stock market volatility as a latent process and employ the following constant correlation bivariate VAR-GARCH model proposed by Ling and McAleer (2003):

$$\begin{bmatrix} R_t \\ \Delta FFF_t^1 \end{bmatrix} = \begin{bmatrix} \mu_R \\ \mu_F \end{bmatrix} + \begin{bmatrix} \phi_{RR} & \phi_{RF} \\ \phi_{FR} & \phi_{FF} \end{bmatrix} \begin{bmatrix} R_{t-1} \\ \Delta FFF_{t-1}^1 \end{bmatrix} + \begin{bmatrix} \varepsilon_{R,t} \\ \varepsilon_{F,t} \end{bmatrix}, \quad (8)$$

$$\begin{bmatrix} \varepsilon_{R,t} \\ \varepsilon_{F,t} \end{bmatrix} = \begin{bmatrix} h_{R,t}^{1/2} & 0 \\ 0 & h_{F,t}^{1/2} \end{bmatrix} \begin{bmatrix} \eta_{R,t} \\ \eta_{F,t} \end{bmatrix}, \quad (9)$$

$$\begin{bmatrix} h_{R,t} \\ h_{F,t} \end{bmatrix} = \begin{bmatrix} \omega_R \\ \omega_F \end{bmatrix} + \begin{bmatrix} \alpha_{RR} & \alpha_{RF} \\ \alpha_{FR} & \alpha_{FF} \end{bmatrix} \begin{bmatrix} \varepsilon_{R,t-1}^2 \\ \varepsilon_{F,t-1}^2 \end{bmatrix} + \begin{bmatrix} \beta_{RR} & \beta_{RF} \\ \beta_{FR} & \beta_{FF} \end{bmatrix} \begin{bmatrix} h_{R,t-1} \\ h_{F,t-1} \end{bmatrix}, \quad (10)$$

where $\begin{bmatrix} \eta_{R,t} & \eta_{F,t} \end{bmatrix}$ is an independently and identically distributed random vector with zero mean and covariance matrix Γ_0 (with diagonal elements equal to one), R_t are daily continuously compounded returns on the S&P 500 index, ΔFFF_t^1 are daily changes in the implied interest rates from the one-month-ahead federal funds futures contracts, and $h_{R,t}$ and $h_{F,t}$ denote the conditional volatilities of stock returns and federal funds futures, respectively.¹² Ling and McAleer's (2003) VAR-GARCH model allows for volatility interdependence across different markets as it models one return's volatility as dependent on its own lag, the lagged volatilities of the other variables in the system as well as the lagged squared residuals of all the variables

¹² We abstract from denoting the variables with the subscript n (to refer to daily data) and use the subscript t instead for notational simplicity. The lag length of the mean equation's VAR is determined using the AIC. The constant correlation coefficient between the standardized shocks is denoted by ρ .

included in the system. In the above bivariate VAR-GARCH model, α_{RF} and α_{FR} measure the effect of cross-squared residuals on volatility whereas β_{RF} and β_{FR} measure the cross-market volatility effect. For instance, determining whether federal funds futures volatility affects stock market volatility would entail assessing the significance of the parameters α_{RF} and β_{RF} .

The results from estimating the bivariate VAR-GARCH model in equations (8), (9) and (10) are reported in Table 3 for the baseline and extended samples.

[Insert Table 3 here]

In line with Hamilton (2009), the results indicate strong GARCH effects in the daily changes in federal funds futures as evinced by the large and significant β_{FF} coefficient on lagged federal funds futures volatility. While the cross-volatility effect coefficients, β_{RF} and β_{FR} , are not significant, the squared federal funds futures residuals positively affect stock return volatility as evinced by the coefficient α_{RF} .¹³ We view the results as suggestive that while the Fed does not respond to stock market developments at a high frequency, stock market volatility is affected by changes in market expectations of future monetary actions.

3.4 Policymaking and efficiency implications

The empirical evidence presented in this paper suggest a statistically and economically important reaction of stock market volatility and (to a lesser extent for the extended sample) market-wide

¹³ Following Ling and McAleer (2003), we examine the covariance-stationarity of our VAR-GARCH model by obtaining the roots of the characteristic equation. Both roots lie outside the unit circle and hence the model is covariance stationary. We thank an anonymous referee for suggesting that we examine covariance-stationarity and for proposing the use of a VAR-GARCH model.

risk aversion to monetary policy shocks. We discuss next the policy and market efficiency implications of our results.

The (weak-form) efficient markets hypothesis postulates that financial variables respond only to new information arrival. The contemporaneous decrease in excess returns and increases in realized volatility, volatility risk premium, futures-trading volume and the dividend yield due to a monetary surprise are consistent with market efficiency. From a policymaking perspective, the important responses of the financial variables to an *MP* shock exemplify the important effects that Fed actions can have on financial markets. More precisely, our baseline sample results indicate that a surprise change in the Fed target rate spurs an increase in volatility and in market-wide risk aversion (volatility risk premium). This implies, in turn, that a monetary policy tightening might be effective in reducing excessive risk-taking in financial markets.

Since December 2008, the Fed began explicitly announcing that it intends to keep the Fed funds target rate within a specified range for an extended period of time.¹⁴ This practice, dubbed forward guidance, is the latest effort to increase the transparency of the monetary policymaking process and aimed, to some extent, at calming financial markets which experienced remarkable volatility in the midst of the financial crisis.¹⁵ Prior research (Lange, Sack and Whitesell, 2003; Swanson, 2006; Kwapil and Scharler, 2013) notes that increased Fed transparency translated into improved (futures-based) expectations of Fed actions. The implementation of forward guidance

¹⁴ See, for example, <http://www.federalreserve.gov/newsevents/press/monetary/20090128a.htm> and http://www.federalreserve.gov/faqs/money_19277.htm for further details on the implementation of forward guidance.

¹⁵ Beginning in the 1990s, the Fed adopted a number of steps to progressively increase the transparency of the monetary policy making process. Since 1992, the Fed began to change the Fed funds target rate only during scheduled FOMC meetings (thus avoiding intermeeting target rate changes). In February 1994, the Fed started explicitly announcing changes to the Federal funds target rate undertaken at FOMC meetings. In 1999-2000, the Fed started releasing statements on the economic outlook, policy tilt and subsequently the “balance of risks”. Swanson (2006) provides an excellent overview of the different stages of increased Fed transparency.

by the Fed should have allowed financial market participants to perfect their forecast of conventional monetary policy actions during the financial crisis. The resulting smaller surprise component in target rate changes might have translated into a decrease in the effect of monetary policy on realized volatility (stock returns) and contributed, in conjunction with the unconventional monetary policy actions adopted by the Fed during the financial crisis, to calming financial markets.

Our VAR-GARCH results additionally suggest that conventional monetary policy actions appear not to respond to stock market volatility at a high-frequency. This, however, does not preclude the possibility that unconventional monetary policy actions did have a direct effect on stock market volatility and other financial variables or that the unconventional monetary policy actions were intended to reduce the elevated stock market volatility witnessed during the financial crisis.

4. Conclusion

This paper studies the dynamic response of stock market volatility to monetary policy. Using a VAR model that incorporates a futures-based measure of monetary policy shocks, our findings uncover a significant response of stock market volatility to monetary policy shocks. While several channels (volatility risk premium, leverage, volume and interest rates) contribute to the short-term increase in volatility, the longer-term dynamic response of volatility appears to be dominated by the persistent effect of monetary policy on stock market fundamentals (dividends). Our results also show an asymmetric return-volatility response to a monetary policy shock. In view of the important dynamic response of stock market volatility to monetary policy, we

investigate the volatility interaction between Federal funds futures contract and the stock market using a bivariate VAR-GARCH model. Our results suggest that the Fed does not respond to stock market developments at a high-frequency but that market participants' uncertainty about the future course of monetary policy is an important determinant of stock market volatility.

Our findings entail important practical and policy making implications. From a policy perspective, our results demonstrate that Fed actions have a significant effect on stock market volatility and, to a lesser extent, the volatility risk premium. This, in turn, implies that the Fed might be able to influence market volatility through better communication or forward guidance. From a trading perspective, our results show that investors might be able to trade profitably, by entering into suitable variance or volatility swap positions, due to the increase in volatility that follows a monetary policy shock. In light of the findings in this study, an interesting avenue for future research would be to examine the effect of increased Fed transparency and unconventional monetary policy actions on stock market volatility during the financial crisis. It would be particularly interesting to determine if, and the extent to which, the Fed's forward guidance and unconventional policies contributed to reducing asset price volatility.

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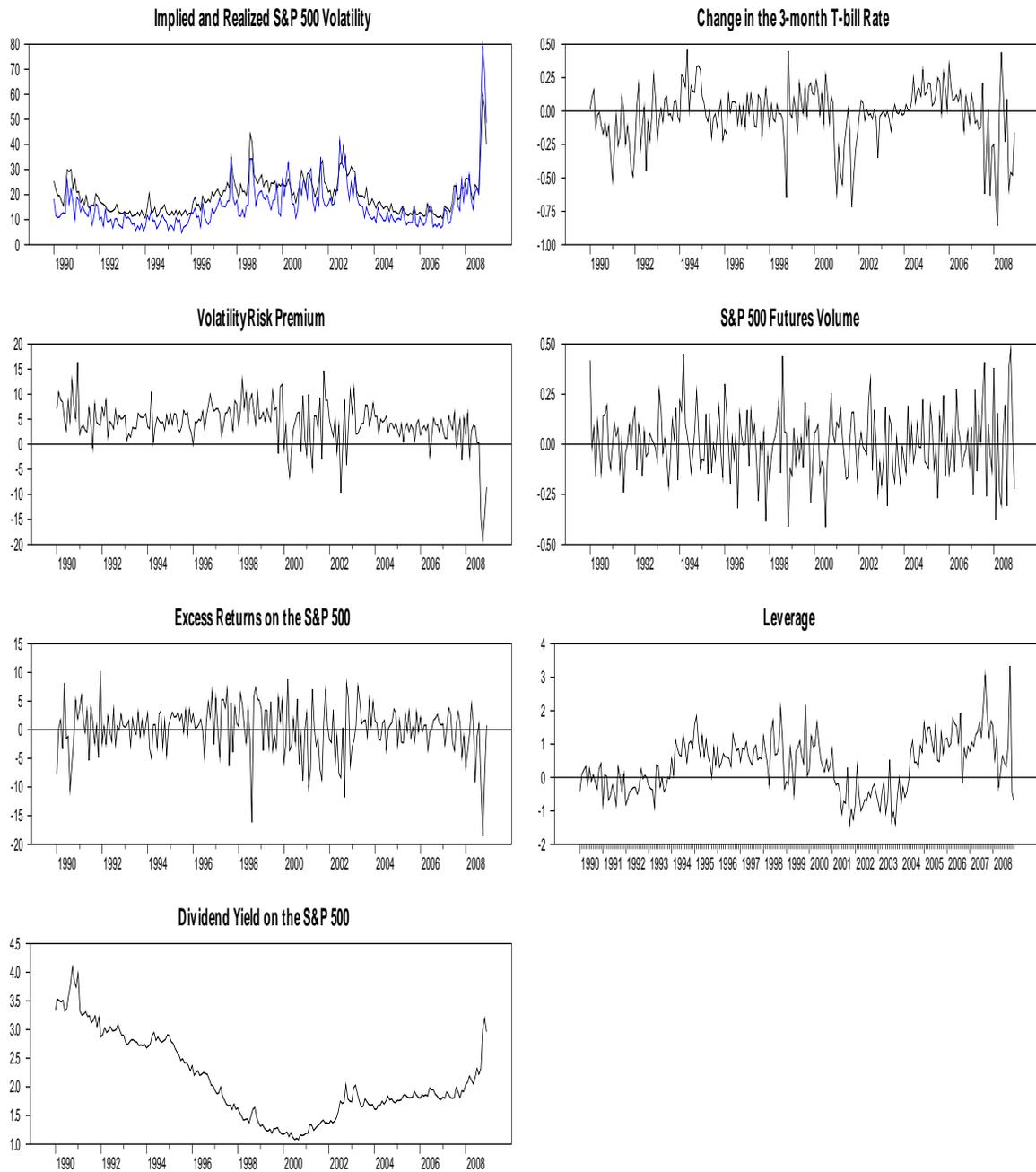


Figure 1: Time series dynamics of the endogenous variables used in the VAR estimation. The sample period is January 1990 to December 2008.

Responses to MP

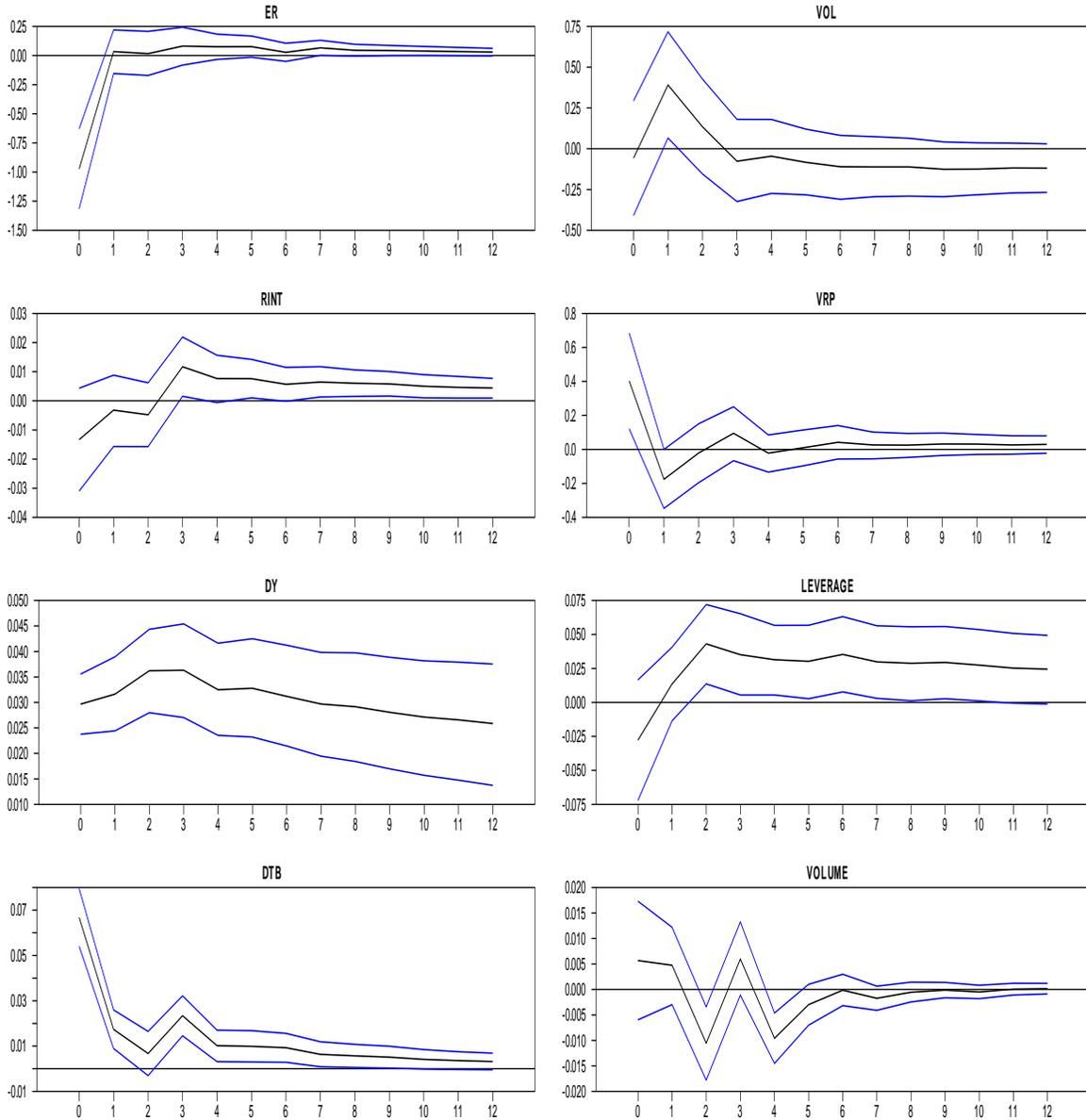


Figure 2: Responses to a monetary policy shock over the baseline sample (1990:01-2007:12). Response of excess returns on the S&P 500 (ER), stock market volatility (VOL), variance risk premium (VRP), the real interest rate (RINT), the dividend yield (DY), the change in the T-bill rate (DTB), financial leverage (LEVERAGE) and unexpected futures-trading volume (VOLUME) to a one standard deviation monetary policy shock (MP) as computed from the VAR model in equation (7). Blue lines are 95% confidence bands constructed using Monte Carlo simulation.

Responses to MP

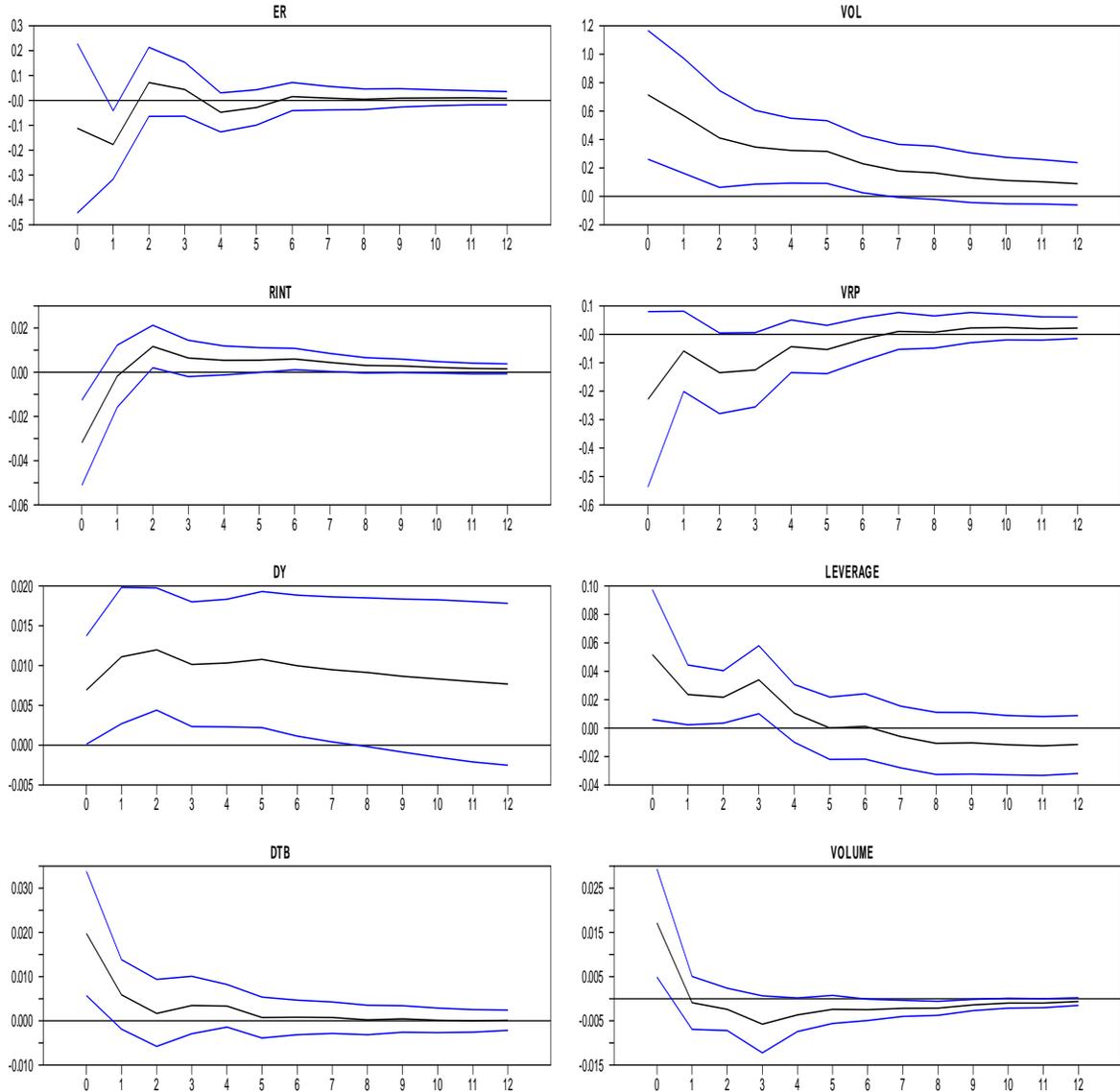


Figure 3: Responses to a monetary policy shock for the extended sample (1990:01-2008:12). Response of excess returns on the S&P 500 (ER), stock market volatility (VOL), variance risk premium (VRP), the real interest rate (RINT), the dividend yield (DY), the change in the T-bill rate (DTB), financial leverage (LEVERAGE) and unexpected futures-trading volume (VOLUME) to a one standard deviation monetary policy shock (MP) as computed from the VAR model in equation (7). Blue lines are 95% confidence bands constructed using Monte Carlo simulation.

Table 1
Descriptive Statistics

| <i>A: 1990:01-2007:12</i> | | | |
|--|-------------|------------------|------------------------|
| <i>Variable</i> | <i>Mean</i> | <i>Std. Dev.</i> | <i>Autocorrelation</i> |
| Excess Returns on S&P 500 (<i>ER</i>) | 0.31 | 3.96 | -0.03 |
| Realized Volatility of S&P 500 (<i>VOL</i>) | 14.35 | 6.66 | 0.68 |
| Volatility Risk Premium (<i>VRP</i>) | 4.59 | 3.50 | 0.11 |
| Monetary Policy Shocks (<i>MP</i>) | -0.03 | 0.09 | 0.16 |
| Real Interest Rate (<i>RINT</i>) | 0.10 | 0.24 | 0.38 |
| Change in 3-month T-bill Rate (<i>DTB</i>) | -0.02 | 0.19 | 0.44 |
| Dividend Yield on S&P 500 (<i>DY</i>) | 2.09 | 0.71 | 0.99 |
| Change in S&P 500 futures trading volume (<i>VOLUME</i>) | 0.00 | 0.15 | -0.04 |
| Commercial and Industrial Loan Growth (<i>LEVERAGE</i>) | 0.37 | 0.79 | 0.70 |
| <i>B: 1990:01-2008:12</i> | | | |
| Excess Returns on S&P 500 (<i>ER</i>) | 0.08 | 4.23 | 0.06 |
| Realized Volatility of S&P 500 (<i>VOL</i>) | 15.44 | 9.33 | 0.77 |
| Volatility Risk Premium (<i>VRP</i>) | 4.17 | 4.29 | 0.37 |
| Monetary Policy Shocks (<i>MP</i>) | 0.00 | 0.10 | 0.20 |
| Real Interest Rate (<i>RINT</i>) | 0.10 | 0.28 | 0.47 |
| Change in 3-month T-bill Rate (<i>DTB</i>) | -0.03 | 0.21 | 0.46 |
| Dividend Yield on S&P 500 (<i>DY</i>) | 2.11 | 0.70 | 0.98 |
| Change in S&P 500 futures trading volume (<i>VOLUME</i>) | 0.00 | 0.16 | -0.07 |
| Commercial and Industrial Loan Growth (<i>LEVERAGE</i>) | 0.30 | 0.81 | 0.64 |

Notes: The table provides the sample mean, standard deviation and first-order autocorrelation for the variables used in the VAR estimation for the baseline (January 1990 to December 2007) and extended (January 1990 to December 2008) samples. All variables are in percent.

Table 2

Forecast Error Variance Decompositions

| <i>A: 1990:01-2007:12</i> | | | | | | | | |
|---------------------------|--------------------|----------|----------|----------|----------|----------|----------|----------|
| By Innovation in | Variable Explained | | | | | | | |
| | ER | VOL | VRP | RINT | DY | DTB | LEVERAGE | VOLUME |
| ER | 64.01*** | 18.70 | 5.09 | 1.29*** | 29.78*** | 9.64*** | 2.92*** | 9.58*** |
| VOL | 3.79 | 31.51*** | 2.39 | 6.54*** | 1.70*** | 4.48*** | 1.51 | 4.05*** |
| VRP | 5.67 | 13.87 | 68.07*** | 1.34*** | 2.33*** | 2.40*** | 12.04*** | 7.92*** |
| RINT | 1.87 | 9.42 | 5.74 | 72.17*** | 17.98*** | 3.45*** | 3.57*** | 2.65*** |
| DY | 12.92*** | 6.84 | 4.98 | 5.16*** | 40.57*** | 1.89*** | 3.83*** | 3.91*** |
| DTB | 1.44 | 3.19 | 3.97 | 5.52*** | 0.42 | 60.66*** | 21.66*** | 3.43*** |
| LEVERAGE | 0.25 | 3.73 | 2.29 | 2.31*** | 0.19 | 2.95*** | 48.27*** | 0.72*** |
| VOLUME | 7.62 | 12.11 | 6.12 | 2.93*** | 2.33*** | 0.51*** | 2.77*** | 67.07*** |
| MP | 2.40 | 0.60 | 1.31 | 2.68*** | 4.66*** | 14.00*** | 3.39*** | 0.62*** |

| <i>B: 1990:01-2008:12</i> | | | | | | | | |
|---------------------------|----------|----------|----------|----------|----------|----------|----------|----------|
| | ER | VOL | VRP | RINT | DY | DTB | LEVERAGE | VOLUME |
| ER | 63.31*** | 20.91** | 5.42 | 1.47*** | 25.61*** | 12.32*** | 3.53*** | 9.00*** |
| VOL | 3.88 | 30.92*** | 2.95 | 6.27*** | 2.29*** | 2.69*** | 1.30 | 4.04*** |
| VRP | 6.51 | 14.23 | 68.73*** | 1.08*** | 4.90*** | 1.11*** | 10.08*** | 8.20*** |
| RINT | 1.80 | 6.77 | 5.00 | 71.03*** | 15.76*** | 2.30*** | 2.54*** | 2.48*** |
| DY | 13.34*** | 5.64 | 3.94 | 5.44*** | 39.31*** | 0.93*** | 3.06*** | 3.66*** |
| DTB | 1.41 | 6.00 | 5.30 | 4.44*** | 0.81** | 66.39*** | 18.13*** | 4.38*** |
| LEVERAGE | 0.53 | 2.87 | 1.86 | 1.78*** | 0.19 | 1.11*** | 52.09*** | 0.48*** |
| VOLUME | 7.77 | 10.74 | 5.48 | 2.37*** | 3.27*** | 0.18 | 1.99** | 66.01*** |
| MP | 1.40 | 1.87 | 1.27 | 6.08*** | 7.82*** | 12.93*** | 7.23*** | 1.71*** |

Notes: The forecast error variance decomposition gives the percentage of the variance of the independent variables explained by a shock to one the VAR's variables over a twelve month horizon. * denotes statistical significance at the 10% level, ** at the 5% level and *** at the 1% level.

Table 3

Bivariate GARCH of stock market and Federal funds futures volatility

| <i>VAR-GARCH Estimation Results</i> | | | | |
|---|------------------|--------------------|------------------|--------------------|
| <i>Mean Equation</i> | 1990:01-2007:12 | | 1990:01-2008:12 | |
| | <i>Estimates</i> | <i>Std. Errors</i> | <i>Estimates</i> | <i>Std. Errors</i> |
| μ_R | 0.0419*** | 0.0101 | 0.0325** | 0.0139 |
| μ_F | 0.0419 | 0.0318 | -0.1344 | 0.1132 |
| ϕ_{RR} | -0.0303* | 0.0182 | 0.0025 | 0.0249 |
| ϕ_{RF} | -0.0038 | 0.0036 | -0.0015 | 0.0032 |
| ϕ_{FR} | -0.0683 | 0.0553 | -0.0019 | 0.0826 |
| ϕ_{FF} | 0.0821*** | 0.0276 | 0.0755*** | 0.0190 |
| <i>Variance Equation</i> | | | | |
| ω_R | 0.0051 | 0.0037 | 0.0136 | 0.0114 |
| ω_F | 0.1067 | 0.0682 | 0.5996 | 0.6178 |
| <i>ARCH Coefficients</i> | | | | |
| α_{RR} | 0.0400*** | 0.0138 | 0.0537*** | 0.0144 |
| α_{RF} | 0.0021* | 0.0012 | 0.0043*** | 0.0016 |
| α_{FR} | 0.0841 | 0.0639 | 0.1084 | 0.1702 |
| α_{FF} | 0.0303** | 0.0144 | 0.0315 | 0.0198 |
| <i>GARCH coefficients</i> | | | | |
| β_{RR} | 0.9559*** | 0.0157 | 0.9382*** | 0.0156 |
| β_{RF} | 0.0008 | 0.0449 | 0.0014 | 0.0582 |
| β_{FR} | 1.7317 | 3.6525 | 0.7873 | 1.4114 |
| β_{FF} | 0.9587*** | 0.0138 | 0.9583*** | 0.0238 |
| Constant Correlation Coefficient (ρ) | -0.0121 | 0.0261 | -0.0511* | 0.0278 |
| Tse (2000) LM Test | 0.6626 | 0.41 | 0.0128 | 0.90 |

Notes: The table provides the results from estimating the bivariate VAR-GARCH model in equations (8), (9) and (10). Bollerslev and Wooldridge (1992) robust standard errors are reported next to the estimated coefficients. * denotes significance at the 10% level, ** at the 5% level and *** at the 1% level. The last row reports Tse's (2000) Lagrange Multiplier (LM) test for the null of constant correlation and its p -value (right column).