CESifo WORKING PAPERS

7621
2019

April 2019

Market-based monetary policy uncertainty

Michael Bauer, Aeimit Lakdawala, Philippe Mueller

CESifo

Impressum:

CESifo Working Papers
ISSN 2364-1428 (electronic version)
Publisher and distributor: Munich Society for the Promotion of Economic Research - CESifo GmbH
The international platform of Ludwigs-Maximilians University's Center for Economic Studies and the ifo Institute
Poschingerstr. 5, 81679 Munich, Germany
Telephone +49 (0)89 2180-2740, Telefax +49 (0)89 2180-17845, email office@cesifo.de
Editor: Clemens Fuest
www.cesifo-group.org/wp

An electronic version of the paper may be downloaded
· from the SSRN website: www.SSRN.com
· from the RePEc website: www.RePEc.org
· from the CESifo website: www.CESifo-group.org/wp

CESifo *Working Paper No. 7621*
Category 7: Monetary Policy and International Finance

Market-based monetary policy uncertainty

Abstract

This paper investigates the role of monetary policy uncertainty for the transmission of FOMC actions to financial markets using a novel model-free measure of uncertainty based on derivative prices. We document a systematic pattern in monetary policy uncertainty over the course of the FOMC meeting cycle: On FOMC announcement days uncertainty tends to decline substantially, indicating the resolution of policy uncertainty. This decline is then reversed over the first two weeks of the intermeeting FOMC cycle. Both the level and the changes in uncertainty play an important role for the transmission of monetary policy to financial markets. First, changes in uncertainty have substantial effects on a variety of asset prices that are distinct from the effects of the conventional policy surprise measure. For example, the Fed's forward guidance announcements affected asset prices not only by adjusting the expected policy path but also by changing market-perceived uncertainty about this path. Second, at high levels of uncertainty a monetary policy surprise has only modest effects on assets, whereas with low uncertainty the impact is significantly more pronounced.

JEL-Codes: E430, E440, E470.

Keywords: monetary policy uncertainty, Federal Reserve, event study, monetary transmission, implied volatility.

Michael Bauer
Federal Reserve Bank of San Francisco
San Francisco / CA / USA
Michael.Bauer@sf.frb.org

*Aeimit Lakdawala**
Michigan State University
USA – East Lansing / MI 48824 / USA
aeimit@msu.edu

Philippe Mueller
Warwick Business School
Coventry / United Kingdom
Philippe.Mueller@wbs.ac.uk

*corresponding author

April 11, 2019
The authors thank seminar participants at the Federal Reserve Bank of San Francisco, Michigan State University, and Oakland University, and conference participants at the 2018 Midwest Macro Meetings for their helpful comments. We thank Brent Bundick for sharing the code and data for his monetary policy uncertainty measure. We also thank Shannon Sledz and Patrick Shultz for excellent research assistance. All remaining errors are ours.

1 Introduction

In early December 2008 the federal funds rate, the Federal Reserve's policy rate, stood at one percent, yet the uncertainty around its future evolution was substantial. Prices of options on fed funds futures implied that there was a roughly equal probability of 40% each that in March 2009 the fed funds rate would be either close to zero or 75 basis points.[1] The uncertainty was largely resolved on 16 December 2008 when the Federal Open Market Committee (FOMC) cut the target for the funds rate to a band of zero to 25 basis points and stated that it expected "low levels of the federal funds rate for some time." In response, option-implied probabilities for a reversal of the rate cut dropped to below 10%, meaning that the market assigned more than 90% probability to rates remaining at the zero lower bound through at least March 2009. An option-based measure of monetary policy uncertainty developed in this paper—the standard deviation of the market-based distribution of the future short rate—quantifies the extent to which FOMC announcements affect uncertainty about future monetary policy. For this particular meeting, the standard deviation for the one-year-ahead short rate dropped by 14 basis points, the largest drop in our sample.

There is a large literature, going back to Kuttner (2001) and Gürkaynak, Sack, and Swanson (2005), that uses an identification scheme based on high-frequency changes in asset prices to study the effects of changes in the expected path of the policy rate. However, the role of second moments and uncertainty in the transmission of monetary policy to financial markets has received much less attention. How do policy actions change the uncertainty around the expected policy rate path? What is the role of the level and changes of uncertainty around FOMC announcements for the financial market transmission? These are the questions this paper is focused on. We propose a high-frequency measure of uncertainty about future monetary policy which allows us to answer them, and we document several new stylized facts about the interrelation of policy actions, policy uncertainty and financial markets: (i) Federal Reserve policy actions tend to substantially reduce uncertainty about future short-term interest rates, (ii) uncertainty gradually increases over the course of the FOMC meeting cycle, with most of the ramp up concentrated in the first two weeks after the last meeting, and (iii) both levels and changes in policy uncertainty on days with FOMC announcements play an important role for the transmission of policy actions to financial markets.

Our measure of monetary policy uncertainty is based on prices of Eurodollar futures and options, and it estimates the conditional, risk-neutral standard deviation of the future short-term interest rate. Our measure is completely model-free, as it requires only the assumption

[1] These option-based (risk-neutral) probabilities were calculated by the Federal Reserve Bank of Cleveland and available on their website.

of absence of arbitrage, and can be calculated directly from observed option prices. Existing market-based measures of interest rate uncertainly—such as the MOVE index, the TIV index of Choi, Mueller, and Vedolin (2017) and the TYVIX index of the Chicago Mercantile Exchange—focus on long-term interest rates, and therefore include uncertainty about the term premium. By contrast, our measure isolates the uncertainty about the future path of *short-term* interest rates and thus directly captures monetary policy uncertainty.[2]

Equipped with this novel measure we first document that monetary policy uncertainty tends to decline substantially on days with FOMC announcements. Hence, on average, FOMC actions lower the perceived uncertainty about the future path of short term interest rates, i.e., they lead to a systematic *resolution of uncertainty*. This pattern is present in all sample periods we consider, and is robust to the exclusion of the most influential observations. We show that the largest changes in monetary policy uncertainty coincided with important news about the Fed's future policy plans in an intuitively interpretable way. For example, the Fed's forward guidance announcements during the recent zero-lower-bound episode dramatically lowered the dispersion of the market-perceived distribution for the future policy rate.

We propose a simple but highly effective trading strategy designed to benefit from this predictable decline in uncertainty around FOMC announcements. The strategy is to write straddles with at-the-money options on the day before scheduled FOMC announcements and to close the position after the FOMC meeting. This strategy generated large excess returns subject to only a moderate amount of risk, with annualized Sharpe ratios as high as 2.2 for near-term option contracts, about twice the Sharpe ratio for the pre-FOMC announcement drift of Lucca and Moench (2018). These results suggest that investors might be able to generate trading profits based on the empirical pattern we document in this paper.

Conventional monetary policy surprises, which reflect revisions to expected future policy rates, tend to be correlated with changes in the uncertainty about future policy rates. That is, when the FOMC announcement causes a hawkish surprise, uncertainty tends to fall less and in some cases may even increase. This correlation implies that one needs to control for the monetary policy surprise when investigating changes in monetary policy uncertainty. We find that the systematic decline in uncertainty in response to FOMC announcements is robust to controlling for the policy surprise. We also control for the policy surprise when we estimate the effects on asset prices using event-study regressions.

The cumulative decline in uncertainty on days with FOMC announcements is much larger than the modest downward drift over the course of our sample period. This raises the question

[2]Our measure reflects the market-implied distribution for the three-month LIBOR rate, and we carefully address the issue that during the financial crisis this rate deviated substantially from the Fed's policy rate using different sample periods where the spread between the two was stable.

of when the uncertainty is created. We show that neither major macro announcements nor speeches by FOMC members are the culprits. Instead, uncertainty tends to gradually drift upwards over the course of the FOMC cycle, and in particular over the first two weeks following the last FOMC meeting. This systematic and predictable pattern in market-based monetary policy uncertainty over the FOMC cycle, with a sudden decline after announcements and a gradual ramp-up thereafter, has not been previously documented. Our results provide a new perspective on the FOMC meeting cycle, policy information flow, and systematic changes in monetary policy uncertainty.

There is a large literature that studies the transmission of monetary policy to asset prices using policy surprises measured as the changes in the expected policy path. In contrast, we ask whether it is important to account for second moments—policy uncertainty—in estimating the financial market effects of FOMC policy actions. The answer is a resounding yes, with both levels and changes in uncertainty being relevant for the financial market transmission.

Changes in uncertainty around FOMC announcements have strong effects on asset prices. Increasing uncertainty raises long-term interest rates, over and above the effects of the conventional monetary policy surprise measure. Both nominal and real rates, and both yields and distant horizon forward rates, respond to changes in policy uncertainty. Furthermore, increases in monetary policy uncertainty have a significantly negative effect on the stock market, both in terms of a lower return on the S&P 500 index and in terms of an increase in the VIX. In the foreign exchange market, the US dollar appreciates when uncertainty increases.

The direction of these estimated effects is consistent with a risk-based explanation: In standard asset-pricing models, higher uncertainty raises the magnitude of risk premia, which would typically imply higher real and nominal yields and lower stock prices. In addition, this channel may also help explain existing estimates of strong positive effects of Fed policy surprises on real term premia (Hanson and Stein, 2015; Abrahams, Adrian, Crump, Moench, and Yu, 2016), since policy surprises are positively correlated with changes in policy uncertainty.

The estimated effects of changes in policy uncertainty on asset prices are generally larger significant during the post-crisis period. We also carry out an event study of the Fed's major announcements of unconventional monetary policies. The results suggest that these announcements often affected asset prices not only by adjusting the expected policy path but also by changing market-perceived uncertainty about this path. The uncertainty channel can be particularly powerful when the zero lower bound constrains the expected policy path and the main lever for forward guidance announcements is to affect second moments.

Furthermore, we document that the level of policy uncertainty matters significantly for the strength of the financial market effects of policy surprises. At high levels of uncertainty, a given policy surprise has only modest effects on asset prices. By contrast, when uncertainty is low and investors are more confident about the expected policy, then policy surprises have much more pronounced price effects.

Our paper is closely related to the literature studying the effects of monetary policy (and of FOMC announcements in particular) on asset prices, including, among many others, Bernanke and Kuttner (2005) and Gürkaynak, Sack, and Swanson (2005), and more recently, Hanson and Stein (2015) and Nakamura and Steinsson (2018). This literature focuses on changes in interest rates and expectations of future policy rates, that is, on first moments. Our evidence suggests that monetary policy actions are also transmitted through a separate channel that works through second moments, pertaining to the uncertainty about the future path of rates. Gürkaynak, Sack, and Swanson (2005) argue in favour of distinguishing between surprises in *current* short-term rates (their target surprise) and *expected future* short-term rates (their path surprise). We show that another relevant distinction is between changes in the *level* of the expected policy path and in the *uncertainty* around this future path. For gauging the effects of forward guidance this distinction becomes even more important: A central bank's forward guidance not only affects the expected policy path but also the market's uncertainty about the path. To capture both dimensions of forward guidance, it is necessary to measure policy uncertainty at a high enough frequency as we do in this paper.

A growing literature studies the measurement and macroeconomic effects of monetary policy uncertainty, prominent examples being Husted, Rogers, and Sun (2017) and Creal and Wu (2017). The uncertainty measures employed in this literature are generally based on surveys, textual analysis of newspapers, internet searches, or statistical/no-arbitrage models of interest rates, with the consequence that they generally cannot be used for high-frequency identification of the effects of monetary policy. Only a few recent studies carry out event studies of FOMC actions with a focus on the role of second moments, uncertainty and risk, and these are more closely related to our work.[3] Bundick, Herriford, and Smith (2017) study the effects of changes in monetary policy uncertainty on term premia in Treasury yields and document a positive relationship.[4] Bundick and Herriford (2017) show that monetary policy uncertainty has declined since the FOMC started releasing its Survey of Economic Projections. De Pooter, Favara, Modugno, and Wu (2018) condition on the level of policy uncertainty in event-study regressions for Treasury yields, and find evidence that yields respond less to policy surprises when the level of uncertainty was previously high. In contrast to these studies, our paper (i)

[3]In earlier work, Emmons, Lakdawala, and Neely (2006) used options on fed funds futures to study the market's evolving expectations about monetary policy decisions in the mid 2000s.

[4]Bundick, Herriford, and Smith (2017) also include the level of uncertainty in a recursively-identified VAR to estimate the macroeconomic effects of changes in monetary policy uncertainty.

proposes a new way to measure monetary policy uncertainty, (ii) reveals a systematic pattern for uncertainty over the FOMC cycle, and (iii) documents the important role of both level and changes in policy uncertainty for the transmission of FOMC actions to various financial asset prices.

In a recent paper, Kroencke, Schmeling, and Schrimpf (2018) document an “FOMC risk shift” as a separate dimension of FOMC announcement effects. They identify this risk-shift by changes in risk spreads and the VIX that are orthogonal to the conventional (first-moment) policy surprise, and show that this measure is correlated with stock returns. Their work raises the possibility of an “uncertainty channel” of policy announcements. We directly measure this uncertainty about future monetary policy and show that it has distinct effects on asset prices. Our paper is also related to the broader literature that studies the role of uncertainty and volatility for the term structure of interest rates, including Cieslak and Povala (2016), Choi, Mueller, and Vedolin (2017) and Mertens and Williams (2018). These papers all touch on issues relating to the role of monetary policy uncertainty for interest rates, but they do not use a high-frequency identification of the effects of monetary policy on financial markets.

Two recent papers also document profitable trading strategies around FOMC announcements: Lucca and Moench (2015) find a “pre-FOMC announcement drift”, i.e., large average excess stock returns during the 24 hours before an FOMC announcement while Mueller, Tahbaz-Salehi, and Vedolin (2017) find that on days with scheduled FOMC announcements the US dollar tends to depreciate, and that this effect is larger when the level of interest rate uncertainty (which they measure using the TIV) is elevated. By contrast, we document large excess returns of a trading strategy that benefits from the systematic resolution of uncertainty around FOMC announcements.

Finally, some recent papers have documented that the VIX tends to fall on days with FOMC meetings (Fernandez-Perez, Frijns, and Tourani-Rad, 2017; Amengual and Xiu, 2018; Gu, Kurov, and Wolfe, 2018). We present a comparison that shows the decline in policy uncertainty to be significantly larger than the decline in the VIX. Furthermore, the VIX increases in the days leading up to the FOMC meeting (Hu, Pan, Wang, and Zhu, 2018), while policy uncertainty increases early on in the intermeeting FOMC period. Our results suggest that around FOMC announcements and over the FOMC cycle, changes in monetary policy uncertainty are likely to be the underlying driver of changes in overall market uncertainty, including the uncertainty about the stock market as measured by the VIX.

2 Measuring policy uncertainty using options

In this section we describe how we construct a model-free measure of the uncertainty about future short-term interest rates. Estimates of the market-based *expectations* of future short rates can be obtained from interest rates of different maturities, and rates on fed funds and Eurodollar futures are commonly used for this purpose. But to estimate the *uncertainty* around these expectations we need to turn to option markets. Prices of option contracts with the same expiration but different strikes provide information about the market-implied distribution of short rates.

Our uncertainty measure will be based on prices of options on Eurodollar futures, which are contracts with payoffs tied to the three-month LIBOR rate, the benchmark rate underlying trillions of dollars worth of derivative contracts.[5] We only use option expirations that coincide with those of the underlying futures contracts, so that in effect LIBOR is the options' underlying. The futures prices are from Bloomberg and the option prices are directly from the Chicago Mercantile Exchange. Our main reason to use Eurodollar futures and options data is the high liquidity of Eurodollar futures and options, their long maturity horizons, and the availability of extensive historical data. Derivative contracts also exist for the federal funds rate, but their market is much less liquid and data availability much more limited—both in terms of historical time span and length of horizons of the derivative contracts—limiting their usefulness for our purpose. Below we discuss the issue of the spread between LIBOR and the federal funds rate.

Our methodology provides a model-free estimate of the conditional variance, given prices of futures and options at time t, of LIBOR at time T:

$$Var_t(L_T) = Var_t(F_{T,T}) = E_t F_{T,T}^2 - (E_t F_{T,T})^2 = E_t F_{T,T}^2 - F_{t,T}^2, \tag{1}$$

where L_t is LIBOR, $F_{t,T}$ is the forward LIBOR rate, and $L_T = F_{T,T}$. The conditional means and variances in equation (1) are taken under the T-forward measure, which uses a time-T bond as the numeraire so that the price p_t of a future payoff x_T is $p_t = P_{t,T} E_t(x_T)$ with $P_{t,T}$ the price of a zero-coupon bond maturing at T. The use of the T-forward measure instead of the closely related risk-neutral measure is necessary to account for stochastic interest rates. The last equality in equation (1) follows from the fact that the forward rate is a martingale under the forward-T measure. Since $x^2 = 2\int_0^\infty \max(0, x-K)dK$ for any $x \geq 0$ we have

$$E_t F_{T,T}^2 = 2\int_0^\infty E_t \max(0, F_{T,T} - K)dK = \frac{2}{P_{t,T}} \int_0^\infty c(K)dK,$$

[5] For detailed information see https://www.cmegroup.com/trading/interest-rates/eurodollar.html.

where $c(K) = P_{t,T} E_t \max(0, F_{T,T} - K)$ is the time-t price of a call option with strike K, expiration T, and underlying $F_{t,T}$. Plugging this expression into equation (1) and using put-call-parity $c(K) - p(K) = P_{t,T}(F_{t,T} - K)$ we obtain[6]

$$\begin{aligned}
Var_t(L_T) &= \frac{2}{P_{t,T}} \int_0^\infty c(K)dK - F_{t,T}^2 \\
&= \frac{2}{P_{t,T}} \left(\int_0^{F_{t,T}} p(K) + P_{t,T}(F_{t,T} - K)dK + \int_{F_{t,T}}^\infty c(K)dK \right) - F_{t,T}^2 \\
&= \frac{2}{P_{t,T}} \left(\int_0^{F_{t,T}} p(K) + \int_{F_{t,T}}^\infty c(K)dK \right) \qquad (2) \\
&= 2 \int_0^\infty \left[\frac{c(K)}{P_{t,T}} - \max(0, F_{t,T} - K) \right] dK. \qquad (3)
\end{aligned}$$

Expression 2 shows that the risk-neutral variance can be written as a portfolio of out-of-the-money puts and calls, with parallels to the formula for the fair strike of a variance swap (e.g., equation (6) in Choi, Mueller, and Vedolin, 2017). Expression 3 is useful for the empirical implementation, to be explained below.

To gain intuition, it is useful to compare our model-free variance to common model-based estimates. The famous Black (1976) model assumes that F_t follows a geometric Brownian motion with instantaneous volatility σ. In this case the conditional distribution of L_T is log-normal and $Var_t(L_T) = F_t^2[e^{\sigma^2\tau} - 1] \approx F_t^2\sigma^2\tau$ with $\tau = T - t$. While the Black implied volatility σ estimates the (annualized) volatility of $\log(L_T)$ and therefore pertains to a *return*, the so-called "normalized volatility" $F_t\sigma$ estimates the (annualized) volatility of the *level* L_T, which is more relevant in the context of interest rates. An alternative, direct estimate of this level-volatility is the implied volatility from the classic Bachelier model, which assumes a normal instead of a log-normal distribution. This is commonly referred to as "normal (implied) volatility" or "basis point volatility." Our uncertainty measure also pertains to the level of future interest rates, but it does not require any such parametric assumptions. Note that we do not even need to assume that forward rates follow an Ito-process, so that our measure is robust to the presence of jumps. One might call our measure a "model-free basis point volatility."

The measure is straightforward to implement empirically.[7] For each trading date and

[6] This derivation is related to that in Martin (2017) of an expression for the risk-neutral variance of simple returns on a stock index in terms of option prices.

[7] We abstract from the fact that Eurodollar options are American options on futures contracts, and not, as our derivations assume, European options on forward contracts. Existing results suggest that accounting for early exercise would lead to only minor adjustments; see Bikbov and Chernov (2009) and Choi, Mueller, and Vedolin (2017). In addition, since we only use out-of-the-money options any adjustment for early exercise

futures contract (i.e., expiration date) we proceed as follows: First, we select out-of-the-money put and call contracts and collect their closing prices. Second, we calculate the risk-free interest rate and $P_{t,T}$ based on the zero-coupon yield curve of Gürkaynak, Sack, and Wright (2007).[8] Third, we obtain a smooth call-price function $c(K)$ by translating observed option prices into Black implied volatilities (IVs), fitting a cubic spline, and translating the fitted IVs back into call prices.[9] The availability of a smooth estimate of $c(K)$ allows for a finer grid of strike prices and an increase in the accuracy of the numerical integration. Note that we do not assume the validity of the Black model but just use it to fit a function in strike/IV space which is more reliable than fitting in strike/price space (Jiang and Tian, 2005). Fourth, we approximate the integral in expression (3) using the trapezoidal rule over a grid of 60 strikes and an interval of 3 percent above and below the current futures rate (subject to a lower bound of zero). The square root is then an estimate of the standard deviation of the LIBOR rate at the expiration of the contract. For each trading day, we obtain this volatility estimate for all available quarterly contract expirations.

The maturity of Eurodollar futures and options is not constant and instead follows a seasaw pattern due to the fixed expiration dates. Since our focus will be on (daily) changes in uncertainty, we require constant-maturity uncertainty measures, which we construct for maturities of 0.5, 1, 1.5, and 2 years by linearly interpolating the volatility measures from adjacent contracts. Figure 1 displays our uncertainty measures. Several features are worth mentioning: First, there is considerable variation over the course of our sample. At the one-year horizon, for example, the measure ranges from about a quarter percent to two percent. Second, all measures were substantially elevated during the financial crisis, but dropped notably during the 2010-2014 episode when the Fed's policy rate remained close to zero and forward guidance about its future evolution was in place. Third, the measures at different horizons are closely correlated. For example, the correlation between the series for the 6-month and one-year horizons is 0.95. For the remainder of this paper we use the monetary policy uncertainty measure for the one-year horizon and denote this by *mpu*.

Our ultimate interest is in the uncertainty about the future fed funds rate. However, since LIBOR trades at a spread over the federal funds rate, *mpu* measures not only uncertainty about the future policy rate but also uncertainty about this time-varying spread. The difference between LIBOR and the fed funds rate is best measured by the LIBOR-OIS spread, which is calculated based on rates of the same horizon and considered as an indicator of financial

would be minimal, since the early-exercise premium increases with the moneyness of options.

[8]The market convention is to discount using OIS rates (see footnote 10), but doing so would make little difference for our estimation of a smooth call-price function.

[9]For strikes outside the range of observed option prices we take the IV at the bounds of the range.

stress.[10] Before the 2008 financial crisis, LIBOR was closely tied to the federal funds rate, and this spread was low and stable. For example, over the period from January 2002 to June 2007 LIBOR-OIS had a mean of 11 basis points and a standard deviation of 3.5 basis points. The spread spiked over the course of the financial crisis, as worries about the health of the banking system translated into dramatically increased interbank borrowing rates. By the end of 2009 LIBOR-OIS returned again to relatively low and stable levels, with only occasional and much less pronounced spikes. This suggests that outside of the financial crisis, uncertainty about future LIBOR rates mainly reflects uncertainty about future monetary policy. In order to ensure the robustness of our results against changes in uncertainty about LIBOR-OIS and financial stress, we report all of our empirical results not only for our full sample period but also for a pre-crisis sample period ending in June 2007 (before LIBOR-OIS increased dramatically), and a post-crisis period beginning in July 2009 (after LIBOR-OIS returned to a regime of relative stability).

Several different measures of interest rate uncertainty, policy uncertainty, and monetary policy uncertainty have been proposed in recent years. Since our main interest is on the financial market effects of central bank policy actions, we require the measure to be available at high frequency, i.e., at least daily. This rules out measures based on survey expectations of future interest rates, as used for example by Volker (2017) and Istrefi and Mouabbi (2017), or the recently developed uncertainty measures based on newspaper articles and internet searches, such as Husted, Rogers, and Sun (2017). Similarly, estimates of policy uncertainty based on no-arbitrage yield curve models with stochastic volatility, such as Creal and Wu (2017), are generally available only at monthly frequency. While such models could in principle be estimated at a daily frequency, volatility is inferred (filtered) from the time series behavior of interest rates, which makes it problematic to use the resulting uncertainty estimates in high-frequency event studies.

Our measure is also better suited to analyze uncertainty about future policy rates than existing market-based measures. A widely used market-based measure of interest rate uncertainty is the MOVE index, which is based on short-dated options (with expirations up to 30 days) on medium- to long-term Treasury bonds. The issue with the MOVE is that it is based on relatively illiquid options written on the actual Treasury securities. A related but arguably more reliable measure is the TIV index, described in Choi, Mueller, and Vedolin (2017): They show how to replicate a variance swap in the fixed income market and use these results to

[10]The relevant LIBOR rate is for a three-month term while the fed funds rate is for overnight loans. Rates on "Overnight Indexed Swaps" (OIS) with a three-month tenor reflect the market's (risk-neutral) expectation for the fed funds rate over this period, and are therefore the appropriate rate to compare three-month LIBOR to.

construct their "Treasury Implied Volatility" index from options on Treasury futures.[11] TIV and TYVIX are calculated using liquid options on very liquid futures, like our measure. But they capture the near-term uncertainty about future long-term interest rates, whereas we want to measure the uncertainty about future short-term interest rates, to understand the uncertainty about monetary policy. While short-term rates are determined by the Federal Reserve, long-term rates are affected by a multitude of factors, including on the one hand expectations about future monetary policy, and on the other hand the term premium which reflects all other supply and demand forces in Treasury markets. To avoid confounding uncertainty about monetary policy with uncertainty about various other drivers of long-term bond prices, our measure needs to use prices of derivatives written on short-term interest rates, and Eurodollar options are the best choice for the reasons given above.[12] Finally, two recent papers also use Eurodollar options to derive measures of uncertainty. Bundick, Herriford, and Smith (2017) apply the VIX formula to the prices of these options, which provides estimates of the volatility of the return on a Eurodollar futures contract. This volatility is related to, but not identical to the volatility for the level of the future short rate. De Pooter, Favara, Modugno, and Wu (2018) use the Black model (i.e., a log-normal distribution) and at-the-money option prices to derive a model-based dispersion measure for future short rates. By contrast, our approach provides a direct, model-free estimate of the market-perceived volatility of future short rates for a constant future horizon.

Since our measure is based on observed market prices, it reflects not only investors' perceptions about the likelihood of different future outcomes but also the risk premia. The same is of course true for all market-based measures including the commonly used monetary policy surprise measures (Gürkaynak, Sack, and Swanson, 2005; Nakamura and Steinsson, 2018). More specifically, we measure "risk-adjusted" variance, which includes not only "real-world" variance but also a variance risk premium.[13] Estimation of real-world variance would require a dynamic model of short-term interest rates and the yield curve, as, for example, in Creal and Wu (2017). Our approach of relying on market-based measures, by contrast, avoids the need for such models and produces a measure of uncertainty at a daily frequency. In our context, one might even view it as an advantage that our measure includes variance risk premia, if interest lies not only with changes in the actual uncertainty associated with future short rates but also with changes in the associated risk compensation due to FOMC policy

[11] In 2013, the CBOE/CME launched the TYVIX index that is virtually identical to the TIV (see, Chicago Board of Option Exchange (2015)), followed by a launch of Treasury Volatility Index Futures (VXTY) in 2014.

[12] The TIV and the MOVE have only a modest correlation with our measure: the correlation with our one-year measure is 0.49 and 0.64, respectively.

[13] As discussed above, we measure variance under the T-forward measure, which is similar to the usual "risk-neutral" measure in that it incorporates risk-discounting.

announcements. Both are arguably relevant for the uncertainty dimension of monetary policy actions.

3 Uncertainty over the FOMC cycle

In the following section, we use our measure to investigate the role of policy uncertainty for the transmission of monetary policy to financial markets. We first study the behavior of monetary policy uncertainty on days with FOMC announcements and compare this to the behavior on other days. Our sample from January 1994 to December 2017 includes 203 FOMC announcements days, 11 of which are unscheduled.[14]

Our first main result is immediately apparent from Figure 2, which plots the daily changes in *mpu* on FOMC days. The figure clearly shows that *mpu* falls on the vast majority of these days. Specifically, uncertainty falls on about four out of five days (165 out of 203). Table 1 reports summary statistics and shows that the average decline on FOMC days was 1.7 basis points (bps), strongly statistically significant with a p-value below 0.001. This decline on FOMC days stands in contrast to the average change on all other days, which is essentially zero; the difference in means on FOMC days and other days is strongly significant. Moreover, the magnitude of the average decline on FOMC days is equal to about four fifths of the standard deviation of the daily changes in *mpu* on non-FOMC days (which is 2.1 bps) and more than half of the standard deviation on FOMC days (which is 2.9 bps), meaning that the decline in uncertainty is both statistically and economically significant.

Thus, the monetary policy announcements and actions of the FOMC on meeting days typically lead to a *resolution of uncertainty* about the future path of interest rates that is reflected in an average decline in *mpu*. A priori it is not obvious how FOMC announcements would be expected to affect uncertainty about the future policy path, given that they include various pieces of information such as the committee's economic outlook, decisions about conventional and unconventional monetary policies, and communication about the likely future path of policy rates, that is, forward guidance. One might reasonably expect FOMC policy actions to increase uncertainty, because they often create surprises and market volatility, as documented in the extensive literature on the effects of monetary policy surprises on financial markets (for example Gürkaynak, Sack, and Swanson, 2005; Bernanke and Kuttner, 2005; Bauer, 2015). On the other hand, there are at least two different reasons why monetary pol-

[14]We drop the FOMC meeting on 17 September 2001 from our sample, as is commonly done in the event study literature due to the unique nature of this first meeting after 9/11. While we include all other unscheduled FOMC meetings, we note that all our results remain essentially unchanged when we exclude these days from our sample.

icy announcements can reduce uncertainty. First, by providing information about the future course of monetary policy, the FOMC might be able to increase market participants' confidence in certain future scenarios, and to help coordinate them on a particular belief. This, after all, is a central function of central bank communication (Blinder, Ehrmann, Fratzscher, De Haan, and Jansen, 2008). Second, a more mechanical explanation is based on the fact that FOMC announcements are the most important events for fixed-income markets: After one has occurred, fewer of these important market-moving events remain over the horizon of our uncertainty measure. Our results capture both these channels of a reduction in policy uncertainty through FOMC announcements.

Our sample includes the financial crisis of 2007–2009, a unique episode with unprecedented levels of uncertainty and monetary policy interventions. We therefore also consider a subsample that ends in June 2007 before the onset of the crisis, as well as one that begins in July 2009 after the crisis abated (see also the discussion in Section 2). Table 1 reports summary statistics for these subsamples. For both the pre- and post-crisis samples results are very similar with significant declines in *mpu* on FOMC days and zero average change on other days. During the post-crisis sample, the average decline is 1.2 basis points, which is about 25% below the 1.6 basis average decline during the pre-crisis sample. This is mostly due to the fact that the overall level of uncertainty was substantially lower during the post-crisis episode as discussed in Section 2 and shown in Figure 1.

Over the last decade the FOMC made substantial changes to the way the outlook for the economy and interest rates is communicated to the public. Starting in October 2007 the FOMC began releasing economic forecasts of the individual committee members, the Survey of Economic Projections (SEP). However, it was not until April 2011 that the SEP was released on the same day as the FOMC statement; previously, the forecasts were released together with the Minutes three weeks after the meeting. Furthermore, in April 2011 Chairman Ben Bernanke started the tradition of holding regular press conferences at every other FOMC meeting. Finally, from January 2012 onwards the FOMC also started releasing committee members' projections for the appropriate future path of the policy rate, the so-called "dot plot," as part of the SEP. Through these new channels of communication, the Fed has provided more information about economic fundamentals and the rationale underlying the policy actions. Table 2 shows the summary statistics for FOMC meetings starting in January 2012, i.e., once these major changes in communication were in place. The first column reports statistics for all 48 meetings during this period, while the next two columns are for days with and without the release of the SEP, respectively. The average decline in uncertainty measured over this period was somewhat smaller than the decline measured over the entire post-crisis period, and much smaller compared to the overall decline measured for the full sample, unsurprisingly given that the level of uncertainty was generally low during this recent period of continued robust economic recovery. Importantly, during this episode declines in uncertainty are due mainly to FOMC meetings with an SEP release (with a dot plot and press conference), which exhibited an average decline about six times larger than on other FOMC meetings. Similarly, the standard deviation of the change in *mpu* is substantially larger on days with an SEP release and press conference. This finding is consistent with the interpretation that the FOMC provides substantially more information on these days, and that it might be able to increase market participants' confidence about the rate outlook. Consistent with this, Boguth, Gregoire, and Martineau (2018) find that more attention is being paid to these particular FOMC meetings.[15] Viewed through the lens of our *mpu* measure we find that since 2012 the new communication tools used by the FOMC have been successful in providing useful information and resolving part of the market's uncertainty.[16]

In order to get a better intuitive understanding of the effects of FOMC announcements on uncertainty, it is useful to consider the days with the largest changes in more detail. In Table 3 we list the days with the ten biggest declines and the five biggest increases in *mpu*. To provide some context we include some commentary on what happened on the day, often taken directly from the FOMC statement. In addition, the table reports a measure of the monetary policy surprise, the first principal component of changes in Eurodollar futures rates for contracts expiring over the next four quarters, which is similar to the methodology in Nakamura and Steinsson (2018) though they also include changes in fed funds futures.[17] A positive value of the surprise measure indicates that new information on the day of the FOMC announcement—likely in the FOMC statement or the press conference—caused market participants to revise their expectations about the policy path over the next year upwards, suggesting a hawkish policy surprise. This measure is scaled so that its effect on the 1 year ahead futures rate is equal to one.

For most of the days listed in Table 3 there is a clear and intuitive link between the language used in the FOMC statement and the change in *mpu*. The two FOMC announcements that triggered the largest declines in the *mpu* measure are both related to forward guidance. On

[15] Lucca and Moench (2018) updated their findings on the pre-FOMC announcement drift and found that since the Fed started holding press conferences after certain meetings, excess stock returns are earned only leading up to those meetings and not others.

[16] Bundick and Herriford (2017) also investigated the impact of SEP releases on monetary policy uncertainty, but focusing on the level instead of changes: They show that monetary policy uncertainty has declined since the FOMC started releasing its Survey of Economic Projections.

[17] We use daily changes in futures rates in order to be consistent with our daily measure of policy uncertainty, acknowledging that intraday changes in futures rates may yield higher precision in FOMC event studies (Gürkaynak, Sack, and Swanson, 2005).

16 December 2008 the zero lower bound is finally reached and the FOMC made it clear that "weak economic conditions are likely to warrant exceptionally low levels of the federal funds rate for some time." On 9 August 2011 the FOMC introduced calendar-based forward guidance, stating that it "currently anticipates that economic conditions–including low rates of resource utilization and a subdued outlook for inflation over the medium run–are likely to warrant exceptionally low levels for the federal funds rate at least through mid-2013." Financial markets reacted strongly to both forward guidance announcements and *mpu* declined substantially, by 13.8 and 13.5 basis points, respectively. At the same time, the measure of monetary policy surprise shows that on 16 December 2008 market participants were somewhat caught off guard by the aggressive cut and the accompanying unambiguous message about the future path of monetary policy, whereas the announcement of 9 August 2011 did not contain a major policy surprise but merely reduced uncertainty. The next two dates in Table 3 are again two examples where the drop in uncertainty is of a similar magnitude while the monetary policy surprise is completely different. On 6 July 1995 the FOMC was cutting the target rate for the first time in three years, clearly signaling a change in the stance of monetary policy. In doing so the FOMC surprised the market as indicated by the relatively large negative value in the measure of monetary policy surprise while at the same time removing uncertainty by using very clear language to indicate that a turning point in the stance of monetary policy has been reached. On the other hand, on 17 November 1998 the FOMC announced the third cut of the target fed funds rate in a row (that was largely anticipated judging by the monetary policy surprise measure), while signaling at the same time that there may not be further cuts going forward, thus reducing uncertainty significantly.

For all FOMC announcements listed in Table 3 the change in *mpu* and the monetary policy surprise have the same sign. While the large declines did not always coincide with large dovish surprises, and vice versa, there appears to be a positive correlation. Indeed, the scatter plot in Figure 3 reveals a pronounced positive correlation between changes in *mpu* and the monetary policy surprises on FOMC days. The correlation coefficient is 0.52, and Table 4 reports the corresponding regression results. A more hawkish policy surprise is associated with less of a decline or even an increase in policy uncertainty. In line with the scatter plot, the subsample results indicate that the relationship is strong in both the pre- and post-crisis sample and only slightly weaker during the crisis period. Notably, the positive relationship between first and second moments of future interest rates is not unique to monetary policy days. This positive relationship is mainly driven by the fact that uncertainty about future interest rates is positively related to the overall level of interest rates.[18] An increase in the

[18]In the full sample, including FOMC and non-FOMC days, the correlation between the level of *mpu* and the level of the (interpolated) futures rate is 0.74. For daily changes, the correlation is 0.49.

expected level of future short rates tends to also increase the uncertainty about future short rates. Therefore, controlling for the policy surprise is important when assessing the financial market transmission of changes in monetary policy uncertainty, and we will do so in Section 4. But our key result about the resolution of uncertainty on FOMC days is not affected by the positive relationship between the uncertainty and the policy surprise: Table 4 shows that the constants of the regression on the policy surprise are negative and significant, and are identical to the mean changes reported in Table 1. That is, the reason for the decline in uncertainty on FOMC days is not that the average FOMC surprise is dovish, which in turn leads to lower uncertainty. Instead, the decline in uncertainty is robust to controlling for the correlation between changes in uncertainty and changes in first moment expectations.

A natural question is whether investors can exploit the pattern we have documented. To answer it we calculate returns on short straddle positions around FOMC announcements. A straddle is an option strategy based on buying (long straddle) or selling (short straddle) both puts and calls with the same strike price, usually at-the-money. We consider a short straddle position which benefits when implied volatility declines. This trading strategy is constructed using Eurodollar contracts ED1 through ED6, corresponding to the current-quarter to five-quarters-ahead expirations. We focus on scheduled FOMC announcements, as investors cannot anticipate unscheduled FOMC meetings. The strategy is to sell (write) at-the-money puts and calls with the same strike price on the day before the FOMC meeting, and then close the position on the day of or the day after the FOMC meeting. We consider both one-day and two-day holding periods since our results below will show a further decline in uncertainty on the day after the FOMC meeting. Excess returns are calculated as the change in value divided by the proceeds at initiation of the position, minus the daily interest at the fed funds rate on the day before the meeting (the risk-free return).[19] We calculate annualized Sharpe ratios for a strategy that shorts straddles around FOMC announcements and is invested in cash on all other days of the year.[20]

The results documented in Table 5 suggest that such a strategy might in practice be quite profitable. The mean percentage returns are around 5-10 percent for near-term contracts (ED1-ED2), and about 2-4 percent for longer contracts (ED3-ED6). The Sharpe ratios are very large: For one-day excess returns the Sharpe ratios exceed 2.0 for near-term contracts and decline to about 1.4-1.7 for longer contracts. For two-day holding periods, excess returns are slightly more volatile, and Sharpe ratios range from about 1.0 to 1.8. By comparison,

[19]Straddle returns are highly correlated with changes in our uncertainty measures, with correlation coefficients of 0.59 to 0.74 on FOMC announcement days for long straddles.

[20]As in Lucca and Moench (2015) we calculate annualized Sharpe ratios as $\sqrt{8}$ times the per-meeting Sharpe ratio, because there are eight scheduled FOMC meetings per year.

the pre-FOMC announcement returns in Lucca and Moench (2015) have annualized Sharpe ratios around 1.1. We have found qualitatively similar results for the pre- and post-crisis sample periods, with slightly larger Sharpe ratios before than after the crisis, consistent with the summary statistics in Table 1 (we omit the results for the sake of brevity). A caveat is that we do not account for transaction costs in our calculation, as we have used closing prices instead of bid and ask prices. However, at-the-money option contracts for near-term expirations—those where short straddles are most profitable—tend to be the most liquid. For these contracts, bid-ask spreads are generally small, on the order of just a few basis points, suggesting that transaction costs are an order of magnitude smaller than the average returns in Table 5. Our findings suggest that investors might be able to profitably exploit the systematic declines in interest rate uncertainty and option-implied volatility around FOMC announcements.

Having documented the pattern of declining uncertainty on FOMC announcements, the natural next question is when uncertainty is actually created. The cumulative decline in *mpu* on FOMC days (3.4 percentage points per Table 1) is much larger than the decline in uncertainty over the course of our sample period (about one half percentage point, as evident in Figure 1). As a consequence, on non-FOMC days uncertainty increases in total by 2.8 percentage points (see Table 1). Can we pin-point certain events which specifically created the uncertainty? One hypothesis, based on the fact that macroeconomic data releases create substantial volatility in stock and bond markets (Fleming and Remolona, 1999; Andersen, Bollerslev, Diebold, and Vega, 2007), is that *mpu* increases on days with major macro data announcements. The data does not support this hypothesis: In Appendix A we show that uncertainty on average declines on days with major macro data announcements, such as the release of the employment report by the Bureau of Labor Statistics. Alternatively, one may ask whether it is possible to link changes in *mpu* to speeches by FOMC participants, which could potentially create market uncertainty given that the thrust of these speeches in terms of the policy outlook often differs substantially across participants. But there is no evidence in the data to support this view: We show in Appendix B that the average change in *mpu* on days with speeches by FOMC participants is in fact essentially zero. The creation of monetary policy uncertainty is not linked to these specific macro or policy events.

However, it turns out that uncertainty varies in a systematic way over the course of the intermeeting FOMC period. This is evident in Figure 4 which plots the average change over the FOMC cycle relative to the day before the FOMC meeting, i.e., the average of $mpu_{t+j-1} - mpu_{t-1}$ across all FOMC days t, for each value of j ranging from -14 to $+14$ (since the average FOMC intermeeting cycle is about six weeks or 30 business days). In

Figure 4 we only include changes in uncertainty before and after scheduled FOMC meetings, while Appendix C shows that including unscheduled meetings gives similar results. Shaded areas show 95%-confidence intervals using White heteroscedasticity-robust standard errors. The significant one-day decline around scheduled FOMC meetings of about two basis points evident in the figure (for $j = 1$) closely corresponds to the average change across all FOMC meetings in the first column of Table 1. Figure 4 reveals that this decline tends to continue for a second day, meaning that the two-day change around FOMC days is slightly larger than the one-day change. But the most striking pattern is that after this initial drop, *mpu* steadily rises during the following days. The most pronounced increase occurs over the ten trading days after the day following the FOMC meeting, i.e., from $j = 2$ to about $j = 12$. At that point, the average change relative to the day before the meeting is close to zero and statistically insignificant.[21] That is, there is a predictable gradual ramp-up in monetary policy uncertainty over the first two weeks of an intermeeting FOMC cycle. This finding is robust to the choice of sample period as well as to the treatment of outliers, as we show in Appendix C. Notably, excluding the 50 days with the largest increases in *mpu* still leads to a very similar pattern of uncertainty between FOMC meetings, confirming that the gradual increase in uncertainty is a robust pattern that is not driven by a few specific days.

Finally, we compare the systematic pattern of *mpu* over the FOMC cycle to that for the VIX, which measures stock market uncertainty using short-dated S&P 500 options. A number of recent papers have documented that the VIX tends to fall on days with FOMC meetings (Fernandez-Perez, Frijns, and Tourani-Rad, 2017; Amengual and Xiu, 2018; Gu, Kurov, and Wolfe, 2018). Figure 5 shows changes in *mpu* (top panel) and the VIX (bottom panel) over the FOMC cycle, normalized in each case by the full-sample standard deviation of daily changes.[22] The top panel shows that *mpu* falls by about 0.8 standard deviations after FOMC announcements, consistent with the results in Table 1. The average one-day decline in the VIX, shown in the bottom panel, is only about 0.4 standard deviations. The much more pronounced decline in *mpu* supports the conclusion that changes in monetary policy uncertainty around FOMC announcements are likely the underlying driver of changes in overall market uncertainty, including the uncertainty about the stock market as measured by the VIX. Another crucial difference is that the VIX increases in the last couple of days leading up to the FOMC meeting, consistent with the results documented in Hu, Pan, Wang, and Zhu (2018), which is a very different pattern from the ramp-up in *mpu* over the first two weeks of the cycle. Overall, there is a much more pronounced pattern of decline and

[21] The confidence intervals show that around eight days after the FOMC meeting, the change in uncertainty relative to its pre-FOMC level *mpu* is statistically insignificant.

[22] Figure 5 is constructed similarly as Figure 4 and shows only changes for scheduled FOMC meetings.

subsequent ramp-up in *mpu* than in the VIX.

4 Monetary policy transmission to asset prices

Having established how uncertainty about the future path of short-term rates changes on FOMC announcement days and over the FOMC meeting cycle, we now investigate its role in the transmission of monetary policy to financial markets.

We estimate the financial market effects of FOMC actions using the event-study approach common in this literature (Gürkaynak, Sack, and Swanson, 2005; Nakamura and Steinsson, 2018). We employ three different regression specifications. First, we include the common baseline regression that estimates the response of asset prices to a market-based measure of the surprise component of FOMC announcements. Our monetary policy surprise (*mps*) is the first principal component of daily changes in Eurodollar futures rates for contracts expiring one to four quarters ahead.[23] Second, we add to the regression the daily change in uncertainty, Δmpu, to estimate its direct effect on asset prices while controlling for its correlation with *mps*. Third, we further add an interaction effect between *mps* and the level of *mpu* before the FOMC announcement, in order to study whether the prevailing level of uncertainty affects the financial market transmission of policy surprises.[24]

Table 6 reports regression estimates for changes in five- and ten-year Treasury yields from Gürkaynak, Sack, and Wright (2007). In this and the following tables we report results for the full, pre-crisis and post-crisis samples. For each yield the first specification confirms the well-established result that policy surprises have sizeable and significant effects on yields. The second regression specification shows a statistically significant and positive response to Δmpu in all three samples. An increase in monetary policy uncertainty results in an increase in long-term Treasury yields, even after accounting for the policy surprise. A one standard deviation increase in the *mpu* measure raises the five- and ten-year yields by around 2 basis points (bps) in the full sample and around 3 bps in the post-crisis sample.[25] The effects of uncertainty are larger in the post-crisis sample. During that episode, some FOMC announcements caused large changes in uncertainty, as documented in Section 3. For example, *mpu* dropped by 13.5 bps around the 9 August 2011 FOMC meeting, and our regression predicts a 18.5 bps decline

[23]See Section 3 for further discussion. We use a daily window for *mps* to be consistent with our *mpu* measure, which is available only at a daily frequency. We have found in additional, unreported results that using either a tighter 30-minute window or a wider two-day window leads to qualitatively similar conclusions.

[24]To economize on space in our tables, we do not report the coefficient on the lagged level of uncertainty, which we include in the third regression specification to accurately estimate the interaction effect. We further omit the estimated constant terms.

[25]The increase in R^2 for yields is around 0.05 in the full sample and 0.1 in the post-crisis sample.

in the ten-year Treasury yield, close to the actual decline of 20.5 bps.

The results in Table 6 are generally consistent with the findings of Bundick, Herriford, and Smith (2017), who estimate positive effects of changes in monetary policy uncertainty on term premia in Treasury yields. While there are several differences between our empirical frameworks—including not only the dependent variable but also the uncertainty measure and sample choice—one difference may be particularly consequential: We control for changes in the expected policy path, measured by *mps*, since changes in first and second moments of the policy path are substantially correlated (see Section 3).

Using our third specification we investigate if the response of bond yields to policy surprises depends on the level of monetary policy uncertainty on the day before the FOMC meeting (mpu_{t-1}). The interaction coefficients are negative and significant in the full and post-crisis samples but essentially zero for the pre-crisis samples. This means that during and after the crisis yields responded more strongly to monetary policy surprises when uncertainty was low. To aid in interpreting the magnitude of the coefficients, we use the 25^{th} and 75^{th} percentiles of mpu_{t-1} to classify periods into "low" and "high" uncertainty. The five-year (ten-year) yield increases by 96 (67) bps when uncertainty is low but only by 58 (37) bps when uncertainty is high. These results are consistent with De Pooter, Favara, Modugno, and Wu (2018) who also find that responses of Treasury yields to monetary policy surprises are larger (smaller) when the level of uncertainty is low (high),

Our results in Table 6 focused on nominal bond yields, whereas several recent papers have studied the response of real and nominal forward rates to monetary policy surprises (Hanson and Stein, 2015; Nakamura and Steinsson, 2018). In Table 7 we follow this route, using the specification of Hanson and Stein (2015, Table 1). The dependent variables are the two-day changes in the five- and ten-year instantaneous forwards rates, both nominal and real (real rates are based on the TIPS yield curve of Gürkaynak, Sack, and Wright, 2010). The monetary policy surprise is now measured as the change in the two-year Treasury yield, again for consistency with Hanson and Stein (2015). These regressions, shown in Table 7, imply bigger estimated effects on the forward rates, including substantial and significant effects on real forwards.[26] Results for the regressions with only the monetary policy surprise are in line with those of Hanson and Stein (2015): In addition to long-term nominal rates, long-term real rates also respond substantially and significantly to monetary policy surprises. The second columns add both the two day change in *mpu* and the interaction of *mps* with the level of uncertainty two days before the FOMC meeting (mpu_{t-1}) as additional regressors. Both the

[26]The full sample is now restricted to January 1999 to December 2017, based on the availability of the real forwards data. The pre-crisis sample runs from January 1999 to June 2007 while the post-crisis sample period, as before, is from July 2009 to December 2017.

five-year and ten-year real forward rates react significantly to changes in mpu. The effects are sizeable as well. A one standard deviation increase in mpu (over 7 bps for the two day change) raises the five-year real forward rate by 11 bps and the 10-year real forward rate by 6 bps. Moreover, the interaction coefficients for the real forwards are negative and significant in the pre- and post-crisis samples, suggesting that when uncertainty is high the effects of monetary policy surprises on real rates are lower. Finally, for the full and post-crisis samples there is a substantial increase in R^2 for both nominal and real forward rate regressions when we add Δmpu and the interaction. For example, in the post-crisis sample the R^2 for the real five-year forward goes from 0.46 to 0.65. Complementary to the nominal yield responses in Table 6, the estimates here highlight the robust effects of policy uncertainty on the bond market even with the Hanson and Stein (2015) specification of using broader measures of both the event-study window and the monetary policy surprise.

Table 8 presents regression results for the stock market and exchange rates. The first three columns show the response of the daily return in the S&P 500 index. The stock market response to the monetary policy surprise is a little smaller for the full sample relative to Bernanke and Kuttner (2005) and Gürkaynak, Sack, and Swanson (2005).[27] More importantly, the second column shows that when monetary policy uncertainty rises stock prices fall, and that this effect is significant and substantial. A one standard deviation increase in mpu reduces stock prices by an additional 0.5%, after accounting for the effect from the policy surprise. Similar to the bond yield results, this effect is stronger in the post-crisis sample. The third column shows that, except for the post-crisis sample, there is a strongly significant interaction effect and a much stronger response of stock prices to the policy surprise more generally. The prevailing level of uncertainty played a crucial role in determining the effects of changes in the policy path on the stock market. As with other asset prices, the response is much more muted when the level of uncertainty is high.

The next three columns show the effects on the implied volatility of the stock market as measured by the VIX index. The VIX tends to increase with a hawkish policy surprise. When we add Δmpu to the regression, we find statistically significant and substantial effects. A one standard deviation increase in uncertainty increases the VIX by 1 percentage point in the full sample and by 1.8 percentage points in the post-crisis sample. Recent work has documented an average fall in VIX on FOMC days, see for example Fernandez-Perez, Frijns, and Tourani-Rad (2017), Gu, Kurov, and Wolfe (2018), Hu, Pan, Wang, and Zhu (2018) and Amengual and Xiu

[27] This result is partly driven by our choice of the daily window to construct the monetary policy surprise. Using a higher frequency intra-day monetary policy surprise measure does give larger effects on stock prices, as noted in Lakdawala and Schaffer (2018). But using the higher frequency policy surprise does not affect how stock prices respond to uncertainty, which is the main focus here.

(2018). Our results of uncertainty resolution from Section 3 combined with these estimates suggest that changes in monetary policy uncertainty are a crucial factor that drive changes in the VIX on FOMC days. This is especially so for the post-crisis sample, where almost half of the variation in the VIX on FOMC days can be explained by changes in our *mpu* measure. Regarding the interaction effects, we find that in all sample periods the response of the VIX to policy surprises is significantly smaller when the level of uncertainty is high, and vice versa.

Finally, we find a similar pattern in the transmission of uncertainty to the foreign exchange market using a US dollar index, calculated with an equal-weighted foreign exchange portfolio that goes long the G9 currencies and short the US dollar.[28] The regression on *mps* shows that a contractionary policy surprise leads to an appreciation of the dollar, consistent with the notion that tighter Fed policy make dollar fixed income investments more attractive and increase demand for dollars. When we add Δmpu to the regression, the response of the exchange rate to changes in uncertainty is significant and substantial. For the full sample, a one standard deviation rise in uncertainty leads to an appreciation of the US Dollar index by 0.2%. In the third specification, the interaction effects are large and strongly significant in all three samples, and the R^2 is substantially higher. The estimates clearly show that the dollar response to the policy surprise depends crucially on the level of uncertainty before the FOMC meeting. For example, after a hawkish policy surprise, the dollar appreciates by 7.8% when uncertainty is low but only by 1.2% when uncertainty is high.

Our results so far indicate a strong response of asset prices to changes in monetary policy uncertainty during the post-crisis period. Of course, this episode was not a normal period for monetary policy, as the FOMC continued to announce unconventional policies including quantitative easing (QE) and forward guidance (FG). To understand the role of changes in monetary policy uncertainty for the financial market effects of unconventional monetary policies, we carry out an event study of the major FOMC announcements, following a large and growing literature including, among many others, Gagnon, Raskin, Remache, and Sack (2011), Krishnamurthy and Vissing-Jorgensen (2011) and Bauer and Rudebusch (2014). We choose key events for QE1, QE2, the maturity extension program (MEP), and QE3 among those identified in the existing literature, in particular Bauer and Neely (2014) and Kuttner (2018). For the FG events were follow Raskin (2013) and Swanson (2017).

The event-study estimates in Table 9 show that changes in policy uncertainty are a highly relevant second dimension of the Fed's recent unconventional policy announcements, including

[28]The return to the dollar index is constructed by forming an equal weighted portfolio of the Australian dollar, the Canadian dollar, the British pound, the euro, the Japanese yen, the New Zealand dollar, the Norwegian krone, the Swedish krona and the Swiss franc. The portfolio is rebalanced monthly but returns are calculated on a daily basis. The portfolio is equivalent to the dollar portfolio for example used in Lustig, Roussanov, and Verdelhan (2011).

both QE and FG. The announcements of QE1 in late 2008 and early 2009 had substantial effects on asset prices, as has been extensively documented in the literature. The large declines in *mps* suggest that an important reason for these effects was that the expected path of the future policy rate was revised downward due to implicit and explicit signaling effects in these announcements (Bauer and Rudebusch, 2014). But we also see that these announcements substantially lowered the uncertainty around the expected policy path. In fact, the *mpu* measure fell by about 3-6 standard deviations (which are estimated over the full sample and reported in the bottom row of the table), and the decline of about 14 bps on December 16, 2008 is the largest drop in our sample. These estimates suggest that signaling worked not only through first but also through second moments of the perceived distribution of future policy rates.[29] The announcements about QE2 on November 3, 2010 and the MEP on September 21, 2011, had smaller and more mixed effects on financial markets. Another major FOMC policy action was the FG announcement on August 9, 2011, when the FOMC indicated that it would likely keep the policy rate near zero "at least through mid-2013" and began a phase of calendar-based FG. In response there was a modestly negative policy surprise of about negative 5 bps, but a dramatic decline in policy uncertainty, indeed the second largest decline in *mpu* in our sample. Treasury yields plummeted, the stock market jumped, with a historically large decline in the VIX of 13 percentage/index points, and the dollar depreciated 1.5 percent against other major currencies. These large asset price responses, strongly significant based on the reported standard deviations, appear to have been caused by the Fed's explicit FG language through its effects on the perceived distribution of the future policy rate. In this instance, when the policy rate was already at the zero lower bound and expected to remain there for the near future, changes in the second moment of this distribution were at least as important as changes in the first moment caused by the announcement. Other FG announcements also generally reduced policy uncertainty and supported financial market conditions. By contrast, the "taper tantrum"—the episode in mid-2013 of increased speculation about the timing of the end of QE, caused by public remarks of Chairman Bernanke about the tapering of asset purchases—increased uncertainty and tightened financial conditions. Around the FOMC announcement and press conference on June 19, 2013 policy uncertainty increased together with expectations for the future policy rate, while Treasury yields jumped and stock prices declined. Finally we note the SEP releases coinciding with the FOMC announcements in March and September 2015, which are discussed in more detail in Swanson (2017). Both featured dovish interest rate projections relative to market expectations, and lowered both the expected path as well

[29] A caveat to this interpretation is that the decline in *mpu* reflects not only changes in uncertainty about the fed funds rate but also about the future LIBOR-OIS spread, which undoubtedly played a role during this heightened financial stress episode.

as the uncertainty around this path, according to our estimates. Long-term Treasury yields fell significantly in response, a final example of the impact of forward guidance—this time in the form of the SEP dot plot—on not only first but also second moments of the policy path.

Why does uncertainty play such a crucial role in the transmission of policy actions to financial markets? An explanation of the significant impact of changes in *mpu* on asset prices seems straightforward: In most asset pricing models, higher uncertainty raises the level of risk premia, as pointed out by Hanson and Stein (2015). This would lead to higher real and nominal interest rates, as well as to lower stock prices, exactly corresponding to the signs of the effects we estimate.[30] Our estimates of the asset price effects of changes in *mpu* are therefore consistent with a risk-based explanation from standard asset pricing models.[31] In addition, our findings may also contribute to an explanation of the effects of the conventional monetary policy surprise on asset prices. Hanson and Stein argue that the response of long-term real rates is due to the effects of monetary policy surprises on real term premia, but question that policy surprises could affect uncertainty in the way required to explain their findings, partly because "little evidence exists for it in the data" (p. 442). But we have shown (see Figure 3) that policy surprises are in fact positively correlated with changes in uncertainty. If monetary policy surprises indeed move real term premia as suggested by Hanson and Stein, our results suggest that systematic changes in monetary policy uncertainty in response to policy surprises are a likely reason for this relationship.

It is less straightforward to provide a risk-based explanation of our finding that the ex-ante level of uncertainty determines the effects of policy surprises on asset markets. However, there is some intuitive appeal to the notion that a given shift in the mean (a given policy surprise) has more pronounced effects on asset prices when beliefs are tightly concentrated around this mean, compared to a situation when beliefs are more disperse. In the former case the surprise is larger relative to the spread of the distribution, and this may well be a determinant of the magnitude of the financial market effects of the Fed's policy surprise.[32]

[30] The tendency of the dollar to appreciate in response to higher uncertainty can be explained with the upward shift in the Treasury yield curve. The response of the VIX could be due to a positive relationship of uncertainty across asset markets and/or to positive effects of higher uncertainty on variance risk premia.

[31] Consistent with this explanation, Bundick, Herriford, and Smith (2017) estimate positive effects of changes in policy uncertainty around FOMC announcement on changes in term premia in long-term interest rates.

[32] De Pooter, Favara, Modugno, and Wu (2018) point instead to a possible explanation based on the behavior of financial intermediaries.

5 Conclusion

The macro-finance literature has extensively studied the effects of changes in the first moment of the distribution of the future policy rate. In this paper we provide evidence that changes in the second moment of this distribution also have important consequences for financial markets, based on a novel model-free measure of uncertainty constructed from option prices. We document that on days with FOMC announcements, uncertainty about future short rates declines significantly, and over the two weeks following an FOMC meeting it gradually ramps up. We also find that monetary policy uncertainty plays an important role for the transmission of policy actions to financial markets, through two distinct channels: First, changes in uncertainty about the policy rate have substantial additional effects on a variety of asset prices, even after controlling for changes in the expected policy rate path. Second, the level of uncertainty leading up to a FOMC announcement is critical in determining how policy surprises are transmitted to financial markets. Specifically, policy surprises have much bigger effects on asset prices when monetary policy uncertainty is lower.

Our findings have implications for the conduct of monetary policy, including unconventional monetary policies such as forward guidance. They suggest that the FOMC may have an additional lever for affecting asset prices and financial conditions, namely by influencing the market's perceived uncertainty about the future path of the short rate. A reduction of this uncertainty via central bank communication can be an effective way to ease financial conditions. As a practical matter, interest rate projections, which we have shown to significantly reduce uncertainty, may be a particularly useful tool in communicating intentions for the future course of the policy rate to the public.

Our paper points to several fruitful directions for future research. Three questions in particular stand out. First, what is the optimal level of monetary policy uncertainty? Low uncertainty may be desirable because it can increase the effectiveness of a given policy measure. On the other hand, policy surprises create more volatility when uncertainty is low. This potential trade-off deserves further investigation. Second, what type of central bank communications and policy actions are most effective in lowering uncertainty? The use of novel tools of textual analysis and natural language processing appears particularly promising to address this question. Finally, what are the macroeconomic effects of changes in monetary policy uncertainty? Some recent studies have taken important first steps in this direction, including Husted, Rogers, and Sun (2017) and Bundick, Herriford, and Smith (2017). But much work remains to be done to make full use of high-frequency, market-based uncertainty measures to identify the causal effects of changes in monetary policy uncertainty on macroeconomic variables.

References

Abrahams, M., T. Adrian, R. K. Crump, E. Moench, and R. Yu (2016): "Decomposing real and nominal yield curves," *Journal of Monetary Economics*, 84, 182–200.

Amengual, D., and D. Xiu (2018): "Resolution of Policy Uncertainty and Sudden Declines in Volatility," *Journal of Econometrics*, 203, 297–315.

Andersen, T. G., T. Bollerslev, F. X. Diebold, and C. Vega (2007): "Real-time price discovery in global stock, bond and foreign exchange markets," *Journal of international Economics*, 73(2), 251–277.

Bauer, M. D. (2015): "Nominal Interest Rates and the News," *Journal of Money, Credit and Banking*, 47(2-3), 295–332.

Bauer, M. D., and C. J. Neely (2014): "International Channels of the Fed's Unconventional Monetary Policy," *Journal of International Money and Finance*, 44, 24–46.

Bauer, M. D., and G. D. Rudebusch (2014): "The Signaling Channel for Federal Reserve Bond Purchases," *International Journal of Central Banking*, 10(3), 233–289.

Bernanke, B. S., and K. N. Kuttner (2005): "What explains the stock market's reaction to Federal Reserve policy?," *The Journal of Finance*, 60(3), 1221–1257.

Bikbov, R., and M. Chernov (2009): "Unspanned stochastic volatility in affine models: evidence from eurodollar futures and options," *Management Science*, 55(8), 1292–1305.

Black, F. (1976): "The Pricing of Commodity Contracts," *Journal of Financial Economics*, 3, 167–179.

Blinder, A. S., M. Ehrmann, M. Fratzscher, J. De Haan, and D.-J. Jansen (2008): "Central bank communication and monetary policy: A survey of theory and evidence," *Journal of Economic Literature*, 46(4), 910–45.

Boguth, O., V. Gregoire, and C. Martineau (2018): "Shaping expectations and coordinating attention: The unintended consequences of FOMC press conferences," *Journal of Financial and Quantitative Analysis*, forthcoming.

Bundick, B., and T. Herriford (2017): "How Do FOMC Projections Affect Policy Uncertainty?," *Economic Review*, 102(2), 5–23.

Bundick, B., T. Herriford, and A. L. Smith (2017): "Forward Guidance, Monetary Policy Uncertainty, and the Term Premium," Working Paper, Federal Reserve Bank of City.

Chicago Board of Option Exchange (2015): "Guide to the CBOE / CBOT 10 Year Treasury Note Volatility Index (TYVIX Index)," TYVIX White Paper Part I.

Choi, H., P. Mueller, and A. Vedolin (2017): "Bond Variance Risk Premiums," *Review of Finance*, 21, 987–1022.

Cieslak, A., and P. Povala (2016): "Information in the Term Structure of Yield Curve Volatility," *Journal of Finance*, 71, 1393–1434.

Creal, D. D., and J. C. Wu (2017): "Monetary policy uncertainty and economic fluctuations," *International Economic Review*, 58(4), 1317–1354.

De Pooter, M., G. Favara, M. Modugno, and J. Wu (2018): "Monetary Policy Surprises and Monetary Policy Uncertainty," FEDS Notes May 18, Board of Governors of the Federal Reserve System.

Emmons, W. R., A. K. Lakdawala, and C. J. Neely (2006): "What are the odds? Option-based forecasts of FOMC target changes," *Federal Reserve Bank of St. Louis Review*, 88(6), 543–561.

Fernandez-Perez, A., B. Frijns, and A. Tourani-Rad (2017): "When no news is good news–The decrease in investor fear after the FOMC announcement," *Journal of Empirical Finance*, 41, 187–199.

Fleming, M. J., and E. M. Remolona (1999): "Price Formation and Liquidity in the U.S. Treasury Market: The Response to Public Information," *Journal of Finance*, 54(5), 1901–1915.

Gagnon, J., M. Raskin, J. Remache, and B. Sack (2011): "The Financial Market Effects of the Federal Reserve's Large-Scale Asset Purchases," *International Journal of Central Banking*, 7(1), 3–43.

Gu, C., A. Kurov, and M. H. Wolfe (2018): "Relief Rallies after FOMC Announcements as a Resolution of Uncertainty," *Journal of Empirical Finance*, 49, 1–18.

Gürkaynak, R., B. Sack, and J. Wright (2007): "The U.S. Treasury Yield Curve: 1961 to the Present," *Journal of Monetary Economics*, 54, 2291–2304.

——— (2010): "The TIPS Yield Curve and Inflation Compensation," *American Economic Journal: Macroeconomics*, 2, 70–92.

Gürkaynak, R. S., B. Sack, and E. Swanson (2005): "Do Actions Speak Louder Than Words? The Response of Asset Prices to Monetary Policy Actions and Statements," *International Journal of Central Banking*, 1(1).

Gürkaynak, R. S., B. Sack, and J. H. Wright (2007): "The U.S. Treasury yield curve: 1961 to the present," *Journal of Monetary Economics*, 54(8), 2291–2304.

Hanson, S. G., and J. C. Stein (2015): "Monetary Policy and Long-Term Real Rates," *Journal of Financial Economics*, 115, 429–448.

Hu, G. X., J. Pan, J. Wang, and H. Zhu (2018): "Premium for Heightened Uncertainty: Solving the FOMC Puzzle," Available at SSRN: https://ssrn.com/abstract=3290649.

Husted, L., J. Rogers, and B. Sun (2017): "Measuring Monetary Policy Uncertainty: The Federal Reserve, January 1985 – January 2016," International finance discussion paper, Federal Reserve Board of Governors.

Istrefi, K., and S. Mouabbi (2017): "Subjective interest rate uncertainty and the macroeconomy: A cross-country analysis," *Journal of International Money and Finance*.

Jiang, G., and Y. Tian (2005): "Model-Free Implied Volatility and Its Information Content," *Review of Financial Studies*, 18, 1305–1342.

Krishnamurthy, A., and A. Vissing-Jorgensen (2011): "The Effects of Quantitative Easing on Interest Rates: Channels and Implications for Policy," *Brookings Papers on Economic Activity*, pp. 215–265.

Kroencke, T. A., M. Schmeling, and A. Schrimpf (2018): "The FOMC risk shift," *Available at SSRN 3072912*.

Kuttner, K. N. (2001): "Monetary policy surprises and interest rates: Evidence from the Fed funds futures market," *Journal of Monetary Economics*, 47(3), 523–544.

Kuttner, K. N. (2018): "Outside the box: unconventional monetary policy in the Great Recession and beyond," *Journal of Economic Perspectives*, 32(4), 121–46.

Lakdawala, A., and M. Schaffer (2018): "Federal Reserve Private Information and the Stock Market," *Working Paper*.

Lucca, D., and E. Moench (2018): "The Pre-FOMC Announcement Drift: More Recent Evidence," Available at http://libertystreeteconomics.newyorkfed.org/2018/11/the-pre-fomc-announcement-drift-more-recent-evidence.html.

Lucca, D. O., and E. Moench (2015): "The Pre-FOMC Announcement Drift," *Journal of Finance*, 70, 329–371.

Lustig, H., N. Roussanov, and A. Verdelhan (2011): "Common Risk Factors in Currency Markets," *Review of Financial Studies*, 24(11), 3731–3777.

Martin, I. (2017): "What is the Expected Return on the Market?," *The Quarterly Journal of Economics*, 132(1), 367–433.

Mertens, T. M., and J. C. Williams (2018): "What to Expect from the Lower Bound on Interest Rates: Evidence from Derivatives Prices," Federal Reserve Bank of San Francisco Working Paper 2018-03.

Miranda-Agrippino, S. (2016): "Unsurprising Shocks: Information, Premia, and the Monetary Transmission," Working Paper 626, Bank for England.

Mueller, P., A. Tahbaz-Salehi, and A. Vedolin (2017): "Exchange Rates and Monetary Policy Uncertainty," *Journal of Finance*, 72, 1213–1252.

Nakamura, E., and J. Steinsson (2018): "High-Frequency Identification of Monetary Non-Neutrality: The Information Effect," *Quarterly Journal of Economics*, 133, 1283–1330.

Raskin, M. (2013): "The Effects of the Federal Reserve's Date-Based Forward Guidance," FEDS Working Paper 2013-37, Board of Governors of the Federal Reserve System.

Swanson, E. T. (2017): "Measuring the effects of Federal Reserve forward guidance and asset purchases on financial markets," Working Paper 23311, National Bureau of Economic Research.

Volker, D. (2017): "Monetary Policy Uncertainty and Interest Rates," Working Paper, Federal Reserve Bank of New York.

Appendix

A Macro news and policy uncertainty

Here we investigate the question whether the releases of macroeconomic data lead to increases in uncertainty. We focus our attention on macro news releases that get the most attention in the media and the financial markets. Following Bauer (2015) we consider three main categories:

- Days on which the Bureau of Labor Statistics releases its employment report,
- days with a release of either the Consumer Price Index (CPI) or the Producer Price Index (PPI), and
- days with new retail sales numbers.

Table A.1 shows the summary statistics for the change in monetary policy uncertainty on these news days, in comparison to the FOMC days. On average, uncertainty *falls* on these macro news days, but with an average fall that is an order of magnitude smaller relative to FOMC days.[33] The standard deviation on days with an employment report days is substantially higher than on FOMC days, with the largest increase in uncertainty occurring after the June 2009 report which initially showed a decline of 345,000 jobs. The standard deviation on CPI/PPI days and retail Sales days is lower relative to FOMC days. This evidence suggests that macro news releases tend to resolve uncertainty, as opposed to the hypothesis that they create additional uncertainty about future interest rates. Macro news cannot explain the rise in uncertainty outside of FOMC days.

B Fed speeches and policy uncertainty

Another possibility is that speeches given by Fed policy makers could be creating uncertainty about future short rates. To explore this, in Table B.1 below we show the summary statistics for changes in *mpu* on days when these speeches were made. The first column considers a speech given by all FOMC members, including governors and presidents. The last three columns focus on the last three Fed chair speech days. As is clear from the table, the mean change in *mpu* on days with speeches is negligible and statistically insignificant. This rules out the possibility that the uncertainty that is resolved with FOMC announcements is being created on speech days.

[33] In addition to the average change in uncertainty on news days, we also considered whether the surprise component of the news release is correlated with changes in policy uncertainty. We did not find any systematic relationship between the macro surprises and the change in policy uncertainty.

Table A.1: Summary statistics for policy/macro data announcement days

	FOMC	Employment	CPI/PPI	Retail sales
No. of observations	203	283	571	287
Mean	-0.017	-0.004	-0.003	-0.002
Median	-0.011	-0.007	-0.002	-0.001
Standard deviation	0.029	0.037	0.022	0.020
Minimum	-0.138	-0.107	-0.138	-0.074
Maximum	0.115	0.342	0.128	0.083
Cumulative change	-3.361	-1.028	-1.535	-0.474
Null hypothesis				
$\mu = 0$	0.000	0.101	0.004	0.171

Summary statistics for the change in policy uncertainty on major macro news release days in addition to FOMC announcement days. Bottom panel reports p-values for t-tests about the mean μ using White heteroscedasticity-robust standard errors The sample is January 1994 to December 2017.

Table B.1: Summary statistics for days with speeches by FOMC members

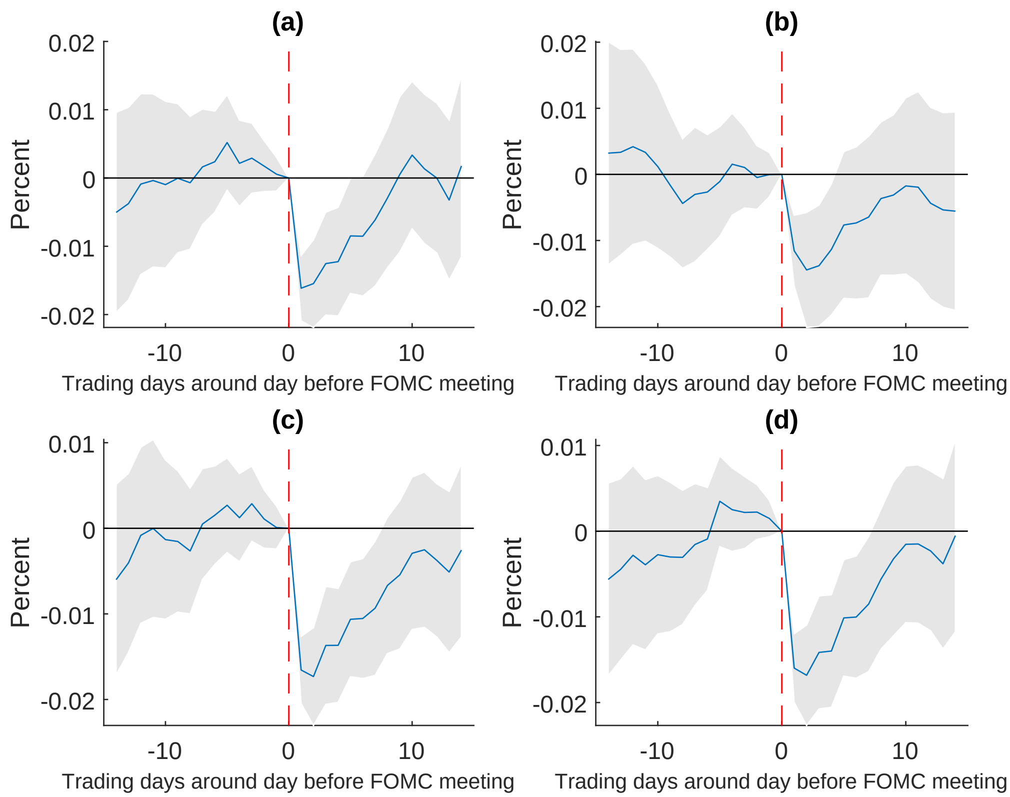
	All speeches	Greenspan	Bernanke	Yellen
No. of observations	2129	119	156	57
Mean	0.000	-0.002	0.002	-0.002
Median	0.000	-0.002	0.001	0.000
Standard deviation	0.021	0.015	0.029	0.013
Minimum	-0.200	-0.060	-0.200	-0.055
Maximum	0.342	0.032	0.154	0.027
Cumulative change	1.034	-0.211	0.240	-0.122
Null hypothesis:				
$\mu = 0$	0.295	0.188	0.514	0.222

Summary statistics for the change in monetary policy uncertainty on Fed speech days. The first column considers a speech given by any member of the FOMC. The last three columns focus on the last three Fed chair speech days. Bottom panel reports p-values for t-tests about the mean μ using White heteroscedasticity-robust standard errors. The sample period is from January 1994 to December 2017.

C Robustness of pattern over FOMC meeting cycle

In this section we document that the pattern of the resolution of uncertainty on FOMC days and the subsequent rise in the inter-meeting period is a result that is robust across a variety of dimensions. We present four robustness checks in figure C.1. Panel (a) shows the pattern for the pre-crisis sample of January 1994 to June 2007, while panel (b) shows it for the post-crisis sample of July 2009 to December 2017. Both of these figures show the same result of a clear and significant resolution of uncertainty on the day of the FOMC announcement, followed by a gradual ramp-up in the following two weeks. As we discussed in the main text, the fall in *mpu* on FOMC meeting days is lower in the post-crisis sample owing to the overall lower level of uncertainty in that sample. Panel (c) shows the pattern excluding unscheduled meetings from our sample, with no discernible effects on the results. Finally, we have checked to make sure that outliers are not driving this pattern. To be even more cautious, we tabulate the dates with the 50 biggest increases in *mpu*. Excluding these 50 dates also does not materially change the results, which are also presented in panel (d). Thus it appears that the documented rise in *mpu* is not being driven by any specific days but instead appears to be a gradual increase in uncertainty in between FOMC meetings.

Figure C.1: Changes in monetary policy uncertainty over the FOMC meeting cycle



The figure shows the average change in monetary policy uncertainty on trading days around the FOMC announcement, relative to the day before the FOMC announcement day (shown with dashed red line). Panel (a) restricts the sample to pre-crisis dates of January 1994 to June 2007. Panel (b) restricts the sample to post-crisis dates of July 2009 to December 2017. Panel (c) uses the full sample including unscheduled FOMC announcements. Panel (d) drops the 50 largest increases in *mpu*. The shaded gray shaded region shows 95% confidence intervals constructed using White heteroscedasticity-robust standard errors.

Table 1: Summary statistics for changes in monetary policy uncertainty

	1/1994 to 12/2017		1/1994 to 6/2007		7/2009 to 12/2017	
	FOMC	Non-FOMC	FOMC	Non-FOMC	FOMC	Non-FOMC
No. of observations	203	5787	112	3250	68	2060
Mean	-0.017	0.000	-0.016	0.001	-0.012	0.000
Median	-0.011	0.000	-0.010	0.000	-0.007	0.000
Standard deviation	0.029	0.021	0.026	0.019	0.023	0.017
Minimum	-0.138	-0.200	-0.119	-0.107	-0.134	-0.093
Maximum	0.115	0.342	0.054	0.198	0.026	0.102
Cumulative change	-3.361	2.840	-1.808	1.715	-0.786	0.121
Null hypothesis:						
$\mu^{FOMC} = 0$	0.000		0.000		0.000	
$\mu^{Non-FOMC} = 0$	0.070		0.117		0.874	
$\mu^{FOMC} = \mu^{Non-FOMC}$	0.000		0.000		0.000	

Summary statistics for changes in *mpu*, the market-based standard deviation for the short-term interest rate one year into the future, measured in percentage points. Bottom panel reports p-values for t-tests about the mean μ using White heteroscedasticity-robust standard errors.

Table 2: Summary statistics for changes in monetary policy uncertainty since 2012

	All FOMC	FOMC with SEP	FOMC without SEP
No. of observations	48	25	23
Mean	-0.007	-0.012	-0.002
Median	-0.006	-0.010	-0.003
Standard deviation	0.013	0.015	0.009
Minimum	-0.038	-0.038	-0.013
Maximum	0.020	0.020	0.019
Cumulative change	-0.391	-0.318	-0.073
Null Hypothesis			
$\mu = 0$	0.000	0.000	0.328
$\mu^{SEP} = \mu^{Non-SEP}$		0.000	

Summary statistics for the change in *mpu* on FOMC meeting days from January 2012 to December 2017. The first column is based on all meetings, while the next two columns split the meetings based on whether the Survey of Economic Projections (SEP) was released. Bottom panel reports p-values for t-tests about the mean μ using White heteroscedasticity-robust standard errors.

Table 3: FOMC announcements and the largest changes in monetary policy uncertainty

			Top 10 declines in monetary policy uncertainty
Meeting date	Δmpu	mps	Description
16 Dec 2008	-0.138	-0.322	ZLB is reached and clear forward guidance: "...weak economic conditions are likely to warrant exceptionally low levels of the federal funds rate for some time."
09 Aug 2011	-0.134	-0.046	Clear forward guidance and indication that rates will be kept low for at least another two years: "...warrant exceptionally low levels for the federal funds rate at least through mid-2013."
06 Jul 1995	-0.119	-0.235	First cut in 3 years signaling a change in the stance of monetary policy: "...inflationary pressures have receded enough to accommodate a modest adjustment in monetary conditions."
17 Nov 1998	-0.099	-0.030	Third cut in a row and signal that there may not be further cuts: " financial conditions can reasonably be expected to be consistent with fostering sustained economic expansion"
25 Nov 2008	-0.098	-0.172	Last meeting before reaching ZLB. Announcement of TALF "designed to increase credit availability and support economic activity by facilitating renewed issuance of consumer and small business ABS at more normal interest rate spreads."
17 May 1994	-0.091	-0.210	Fed funds target rate increased by 50bps to "...substantially remove the degree of monetary accommodation which prevailed throughout 1993."
18 Mar 2009	-0.081	-0.275	Announcement of QE1 expansion to buy "...an additional $750 billion of agency mortgage-backed securities" and to "purchase up to $300 billion of longer-term Treasury securities"
29 Oct 2008	-0.075	-0.106	Fed funds target rate cut by 50bps. Confirmation that the FOMC "...will act as needed to promote sustainable economic growth and price stability."
30 Jun 2004	-0.070	-0.118	Fed funds target rate increased by 25bps for the first time after it has remained at a low for over 12 months. Policy stance remains "accomodative" while the Fed maintains price stability.
06 May 2003	-0.070	-0.089	Signal of weaker economic conditions and potentially lower rates in the future:"...,the balance of risks to achieving its goals is weighted toward weakness over the foreseeable future."
			Top 5 increases in monetary policy uncertainty
Meeting Date	Δmpu	mps	Description
08 Oct 2008	0.115	0.072	Concerted actions by central banks around the world: "...the Bank of Canada, the Bank of England, the European Central Bank, the Federal Reserve, Sveriges Riksbank, and the Swiss National Bank are today announcing reductions in policy interest rates."
28 Jan 2004	0.054	0.136	FOMC meeting 6 months after the last cut and 6 months before the next raise. Balanced outlook: "...the upside and downside risks to the attainment of sustainable growth for the next few quarters are roughly equal."
18 Apr 1994	0.045	0.240	Unscheduled conference call: " will increase slightly the degree of pressure on reserve positions. This action is expected to be associated with a small increase in short-term money market interest rates."
04 Feb 1994	0.030	0.158	First rate hike in years in line with the FOMC decision "...to move toward a less accommodative stance in monetary policy"
27 Jan 2010	0.026	0.046	The FOMC " is gradually slowing the pace of" asset purchases as previously announced.

The 10 largest declines and five largest increases in monetary policy uncertainty, *mpu*, along with the monetary policy surprise, *mps*, and a brief narrative taken from the FOMC statement. For details see the main text.

Table 4: Regressions of change in uncertainty on policy surprise

	Jan-94 to Dec-17	Jan-94 to Jun-07	Jul-09 to Dec-17
mps	0.178	0.166	0.339
	[4.72]	[4.31]	[5.61]
Constant	-0.017	-0.016	-0.012
	[-9.71]	[-7.96]	[-5.65]
Observations	203	112	68
R-squared	0.271	0.312	0.443

Results for regressions of the daily change in uncertainty (Δmpu) on the policy surprise measure (mps) on days with FOMC announcements. In squared brackets are t-statistics based on White heteroscedasticity-robust standard errors.

Table 5: Excess returns on short straddles around FOMC announcements

	One-day returns			Two-day returns			
Contract	Mean	SD	SR	Mean	SD	SR	Obs.
ED1	9.3	11.7	2.26	10.5	16.5	1.81	186
ED2	5.0	6.2	2.27	4.7	10.0	1.34	192
ED3	3.2	4.6	2.00	3.6	6.3	1.64	192
ED4	2.5	4.1	1.76	2.6	6.7	1.10	192
ED5	2.3	3.8	1.72	2.2	5.5	1.13	191
ED6	1.6	3.2	1.44	2.0	5.8	0.96	189

Means and standard deviations (SD) in percent, and annualized Sharpe ratios (SR), for excess returns on short straddle positions around scheduled FOMC announcements. The strategy is to sell (write) a put and a call contract with the same strike (the one closest to the futures rate, that is, at-the-money) on the day before the FOMC meeting, and to buy-to-close the same contracts on either the day of or the day after the FOMC meeting (one-day vs. two-day returns). The excess returns are calculated as the change in value divided by the proceeds at initiation of the position, minus the risk-free overnight rate (we use the fed funds rate). The Sharpe ratios are annualized by multiplying by $\sqrt{8}$ because there are eight FOMC meetings per year, as in Lucca and Moench (2015). ED1 is the Eurodollar contract expiring at the end of the current quarter, ED2 expires at the end of the next quarter, and so forth.

Table 6: Transmission of uncertainty to Treasury yields

	Full sample: Jan-1994 to Dec-2017 (203 obs.)					
	5 year yield			10 year yield		
mps	0.74	0.62	1.34	0.55	0.40	0.97
	[10.05]	[8.41]	[4.34]	[5.99]	[4.81]	[2.36]
Δmpu		0.69	0.82		0.85	0.98
		[2.97]	[3.54]		[3.76]	[4.40]
mps x mpu_{t-1}			-0.61			-0.48
			[-2.56]			[-1.54]
R^2	0.52	0.56	0.59	0.34	0.40	0.43
	Pre-crisis sample: Jan-1994 to Jun-2007 (112 obs.)					
	5 year yield			10 year yield		
mps	0.61	0.53	0.54	0.45	0.35	0.21
	[12.43]	[8.87]	[3.14]	[7.93]	[5.62]	[0.83]
Δmpu		0.48	0.49		0.56	0.55
		[2.42]	[2.27]		[2.47]	[2.35]
mps x mpu_{t-1}			-0.01			0.12
			[-0.06]			[0.57]
R^2	0.64	0.67	0.67	0.46	0.51	0.51
	Post-crisis sample: Jul-2009 to Dec-2017 (68 obs.)					
	5 year yield			10 year yield		
mps	1.06	0.66	1.81	0.70	0.23	1.25
	[6.65]	[4.04]	[4.78]	[3.64]	[1.20]	[2.96]
Δmpu		1.17	1.41		1.37	1.61
		[3.49]	[3.82]		[3.81]	[4.82]
mps x mpu_{t-1}			-1.64			-1.43
			[-2.82]			[-2.32]
R^2	0.41	0.48	0.60	0.19	0.29	0.42

Regressions of daily changes in the five-year and ten-year Treasury yields, on the monetary policy surprise (*mps*), the change in uncertainty (Δmpu), and the policy surprise interacted with the ex-ante level of uncertainty (mpu_{t-1}) on FOMC announcement days. In the third specification we also include mpu_{t-1} but don't report its coefficient to economize on space (as for all estimated constants). The t-statistics, based on White heteroscedasticity-robust standard errors, are reported in parentheses.

Table 7: Transmission of uncertainty to Treasury forward rates

	Full sample: Jan-1999 to Dec-2017 (161 obs.)							
	Nominal				Real			
	5 year		10 year		5 year		10 year	
mps	1.07	1.14	0.51	0.35	1.05	1.44	0.50	0.81
	[6.99]	[2.44]	[3.81]	[0.93]	[5.92]	[2.89]	[5.78]	[2.48]
Δmpu		1.77		1.18		1.59		0.78
		[6.11]		[3.34]		[5.05]		[3.37]
mps x mpu_{t-1}		-0.43		-0.10		-0.70		-0.46
		[-1.08]		[-0.32]		[-1.52]		[-1.46]
R^2	0.34	0.54	0.10	0.22	0.33	0.51	0.17	0.27
	Pre-crisis sample: Jan-1999 to Jun-2007 (70 obs.)							
	Nominal				Real			
	5 year		10 year		5 year		10 year	
mps	0.75	0.82	0.46	0.65	0.76	2.11	0.46	1.16
	[7.56]	[2.40]	[4.78]	[1.86]	[6.40]	[8.72]	[5.46]	[3.97]
Δmpu		1.65		1.37		0.26		0.47
		[3.10]		[2.64]		[0.78]		[1.40]
mps x mpu_{t-1}		-0.34		-0.41		-1.31		-0.70
		[-1.03]		[-1.25]		[-5.35]		[-2.46]
R^2	0.37	0.53	0.17	0.30	0.54	0.61	0.29	0.37
	Post-crisis sample: Jul-2009 to Dec-2017 (68 obs.)							
	Nominal				Real			
	5 year		10 year		5 year		10 year	
mps	1.80	2.22	0.59	0.37	1.62	2.29	0.82	1.91
	[6.19]	[3.81]	[1.89]	[0.55]	[7.28]	[6.04]	[3.50]	[3.58]
Δmpu		1.54		0.61		1.83		0.80
		[3.12]		[0.93]		[5.65]		[1.59]
mps x mpu_{t-1}		-1.78		-0.03		-2.45		-2.45
		[-1.82]		[-0.03]		[-4.19]		[-2.95]
R^2	0.40	0.49	0.06	0.08	0.46	0.65	0.17	0.27

The table shows regressions of two-day changes in Treasury forward rates on (i) the monetary policy surprise *mps*, measures as the two-day change in the two-year Treasury yield, (ii) the two-day change in monetary policy uncertainty (Δmpu), and (iii) *mps* interacted with the level of policy uncertainty on the day before the FOMC meeting (mpu_{t-1}) on FOMC announcement days. In the third specification we also include mpu_{t-1} but don't report its coefficient to economize on space (as for all estimated constants). The choice of two-day changes and the policy surprise measure follows Hanson and Stein (2015). t-statistics based on White heteroscedasticity-robust standard errors are reported in parentheses.

Table 8: Transmission of uncertainty to stock and foreign exchange market

	Full Sample: Jan-1994 to Dec-2017 (203 observations)								
	S&P 500			VIX			Dollar Index		
mps	-2.08	0.92	-13.95	0.82	-5.47	12.84	-3.18	-1.85	-14.35
	[-1.16]	[0.46]	[-3.05]	[0.34]	[-2.24]	[1.81]	[-4.57]	[-3.06]	[-4.17]
Δmpu		-16.86	-18.36		35.44	38.57		-7.49	-8.86
		[-3.21]	[-3.57]		[3.80]	[4.11]		[-4.51]	[-6.13]
mps x mpu_{t-1}			12.57			-15.49			10.57
			[3.35]			[-2.54]			[3.93]
R^2	0.01	0.10	0.13	0.00	0.19	0.23	0.18	0.27	0.39
	Pre-crisis sample: Jan-1994 to Jun-2007 (112 observations)								
	S&P 500			VIX			Dollar Index		
mps	-4.03	-3.66	-17.27	3.14	1.34	17.44	-0.90	-0.21	-6.15
	[-3.11]	[-1.66]	[-3.34]	[2.37]	[0.69]	[2.54]	[-1.69]	[-0.34]	[-2.00]
Δmpu		-2.22	-6.54		10.90	16.14		-4.19	-6.03
		[-0.30]	[-0.89]		[1.50]	[2.05]		[-2.09]	[-2.87]
mps x mpu_{t-1}			11.13			-13.16			4.87
			[2.72]			[-2.38]			[2.08]
R^2	0.10	0.10	0.14	0.06	0.10	0.17	0.04	0.08	0.15
	Post-crisis Sample: Jul-2009 to Dec-2017 (68 observations)								
	S&P 500			VIX			Dollar Index		
mps	-4.60	4.98	-2.21	9.64	-16.76	5.07	-9.62	-7.62	-19.64
	[-1.33]	[1.29]	[-0.27]	[1.39]	[-2.29]	[0.44]	[-5.71]	[-3.75]	[-5.22]
Δmpu		-28.27	-29.41		77.97	81.00		-5.92	-7.29
		[-3.53]	[-4.04]		[3.58]	[4.13]		[-2.22]	[-3.58]
mps x mpu_{t-1}			10.55			-32.34			18.03
			[0.93]			[-2.03]			[4.31]
R^2	0.04	0.25	0.27	0.04	0.47	0.51	0.42	0.45	0.55

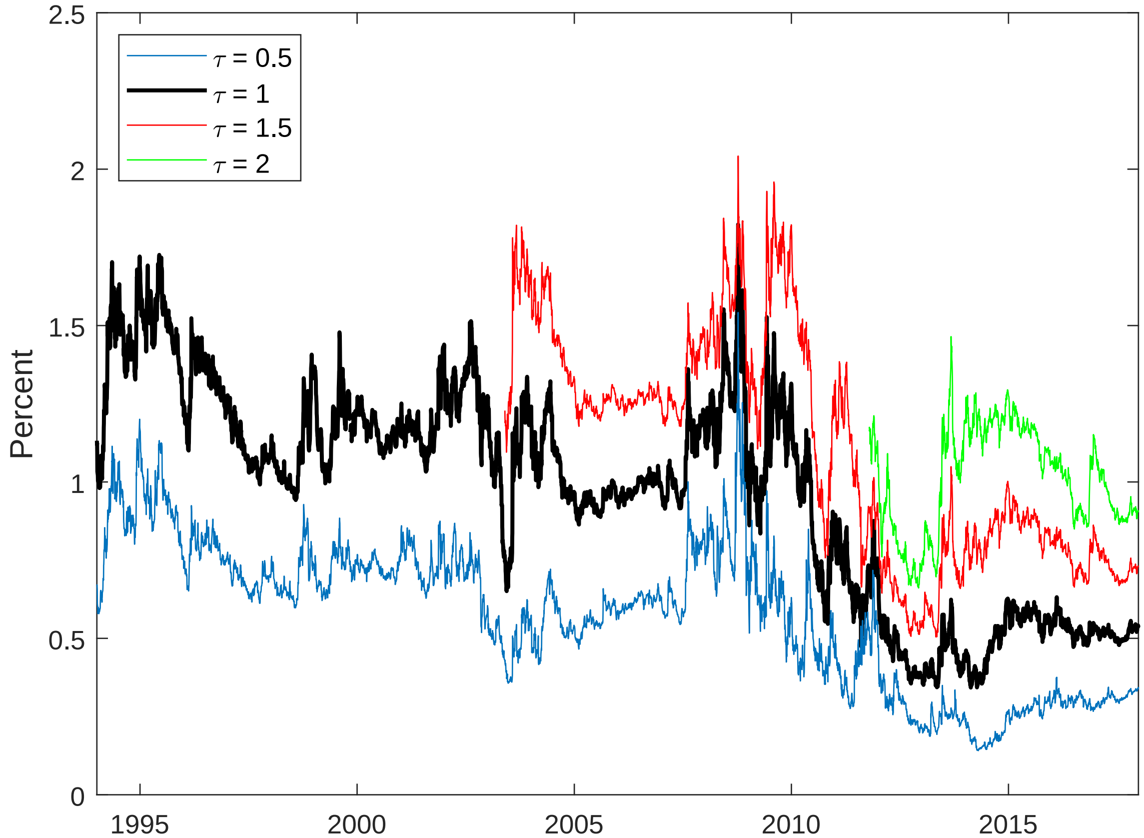
Regressions of daily returns in the S&P500 index, changes in the VIX index and returns to the dollar index (constructed by forming an equal weighted portfolio of nine major currencies, see text), on the monetary policy surprise (*mps*), the change in uncertainty (Δmpu), and the policy surprise interacted with the ex-ante level of uncertainty (mpu_{t-1}) on FOMC announcement days. In the third specification we also include mpu_{t-1} but don't report its coefficient to economize on space (as for all estimated constants). The t-statistics, based on White heteroscedasticity-robust standard errors, are reported in parentheses.

Table 9: Event study of quantitative easing and forward guidance

Date	Event	Δmpu	*mps*	5y yld	10y yld	S&P 500	VIX	Dollar
11/25/2008	QE1	-0.098	-0.172	-0.225	-0.214	0.653	-3.800	0.666
12/16/2008	QE1/FG	-0.138	-0.322	-0.163	-0.175	5.008	-4.390	2.349
3/18/2009	QE1/FG	-0.081	-0.275	-0.471	-0.519	2.064	-0.740	2.822
11/3/2010	QE2	-0.033	-0.004	-0.040	0.041	0.367	-2.010	0.564
8/9/2011	FG	-0.134	-0.046	-0.191	-0.205	4.632	-12.940	1.542
9/21/2011	MEP	0.002	0.060	0.018	-0.084	-2.983	4.460	-1.636
1/25/2012	FG	-0.018	-0.003	-0.094	-0.080	0.864	-0.600	0.460
9/13/2012	QE3/FG	-0.023	0.003	-0.037	-0.029	1.618	-1.750	0.535
12/12/2012	FG	0.001	0.011	0.023	0.057	0.045	0.380	0.211
6/19/2013	Taper Tantrum	0.008	0.037	0.170	0.137	-1.395	0.030	-0.933
12/17/2014	FG	-0.009	0.026	0.083	0.078	2.015	-4.130	-0.971
3/18/2015	FG	-0.038	-0.080	-0.153	-0.119	1.209	-1.690	1.901
9/17/2015	FG	-0.038	-0.084	-0.116	-0.090	-0.256	-0.210	0.529
Std. dev. (full sample)		0.021	0.015	0.061	0.060	1.154	1.565	0.494

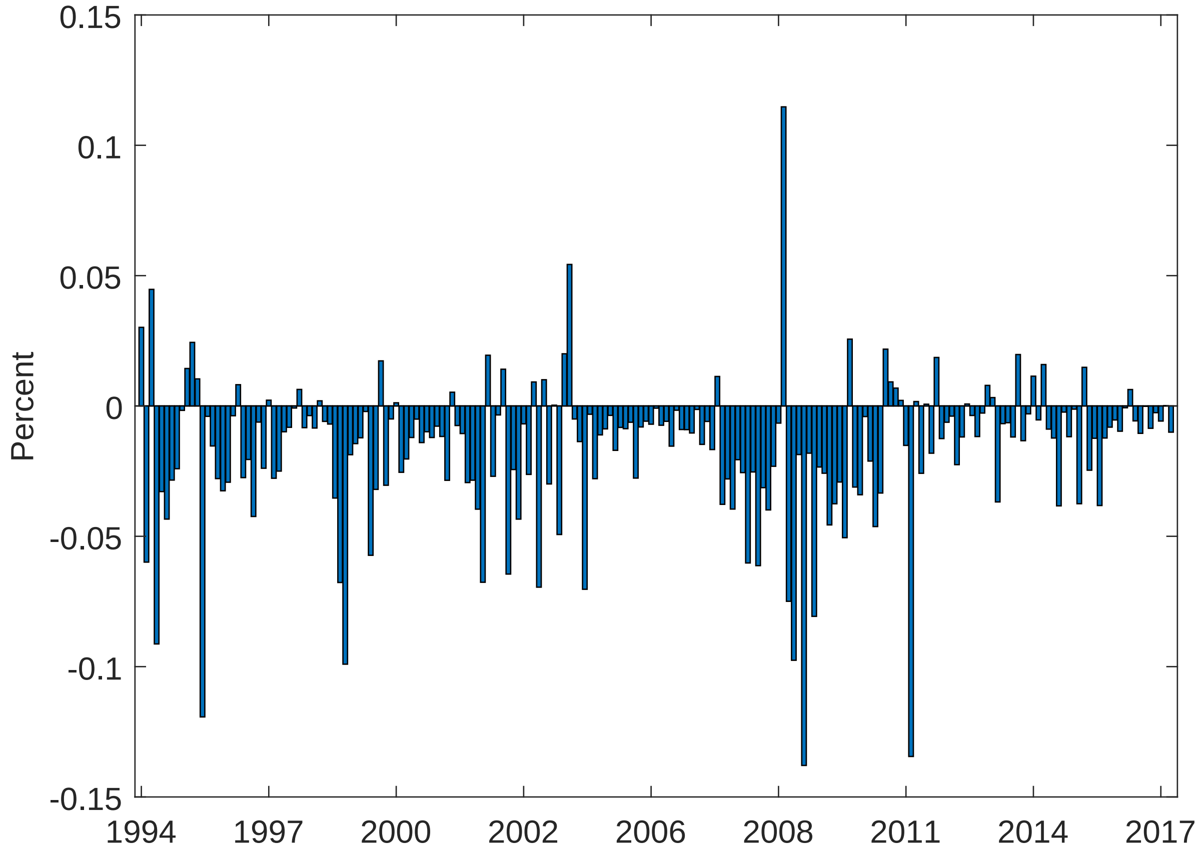
Changes in asset prices on selected days with major FOMC announcements about unconventional monetary policy, including the three large-scale asset purchase programs, or quantitative easing (QE), the maturity extension program (MEP), and forward guidance (FG). Δmpu are daily changes in our measure of monetary policy uncertainty, *mps* is the monetary policy surprise based on changes in Eurodollar futures rates.

Figure 1: Option-based estimate of monetary policy uncertainty



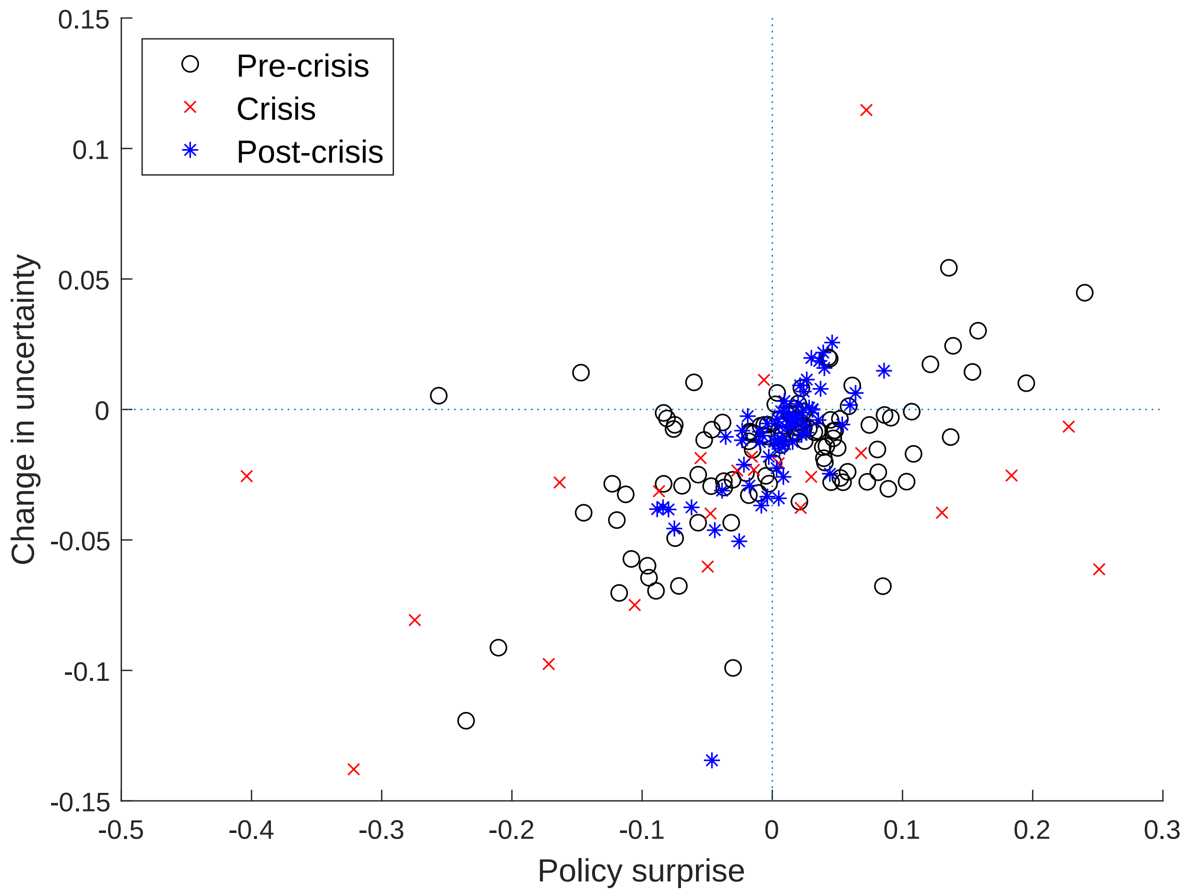
Risk-neutral standard deviation of three-month LIBOR rate at horizon of τ years, estimated from Eurodollar futures and options. Sample period: 1/3/1994 to 1/29/2018.

Figure 2: Changes in policy uncertainty on FOMC announcement days



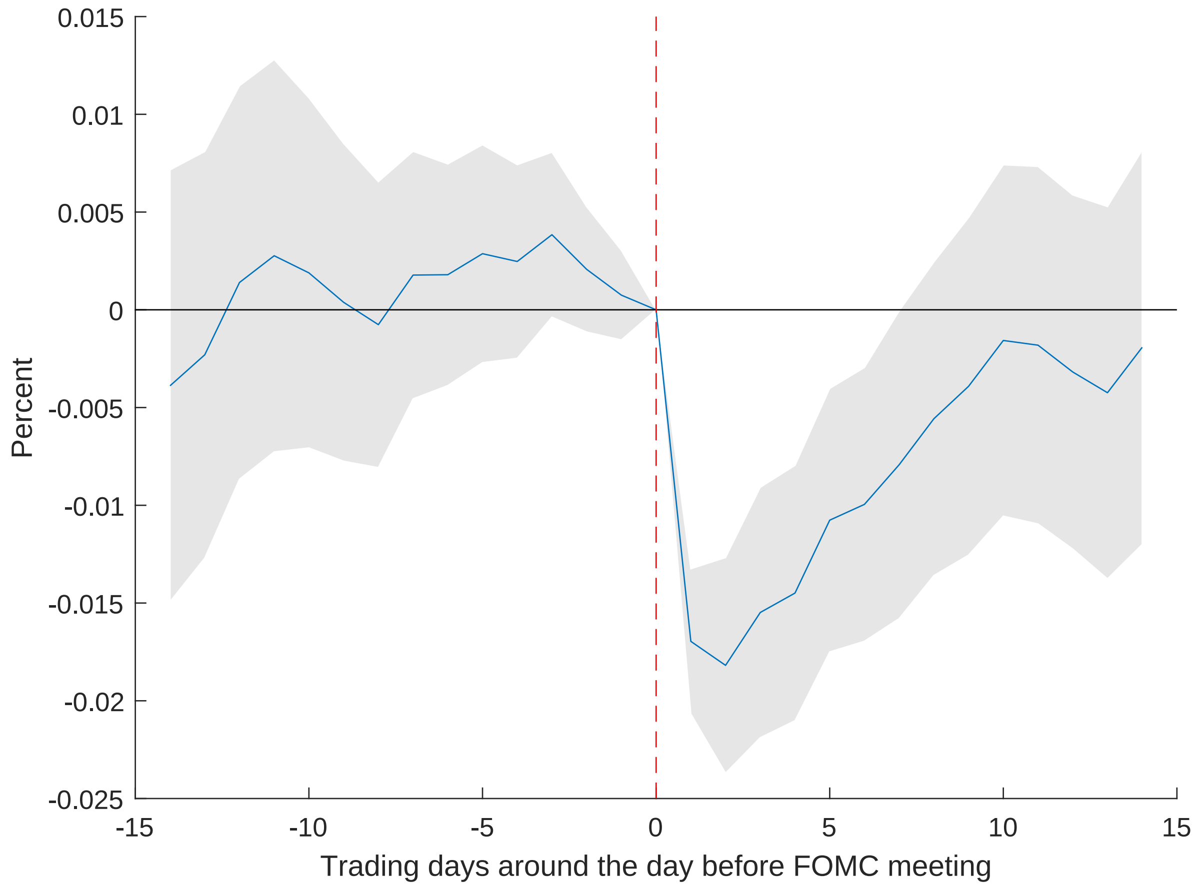
Daily change in monetary policy uncertainty on days with FOMC announcements. The sample includes 203 FOMC announcements from January 1994 to December 2017.

Figure 3: Monetary policy surprise and change in monetary policy uncertainty



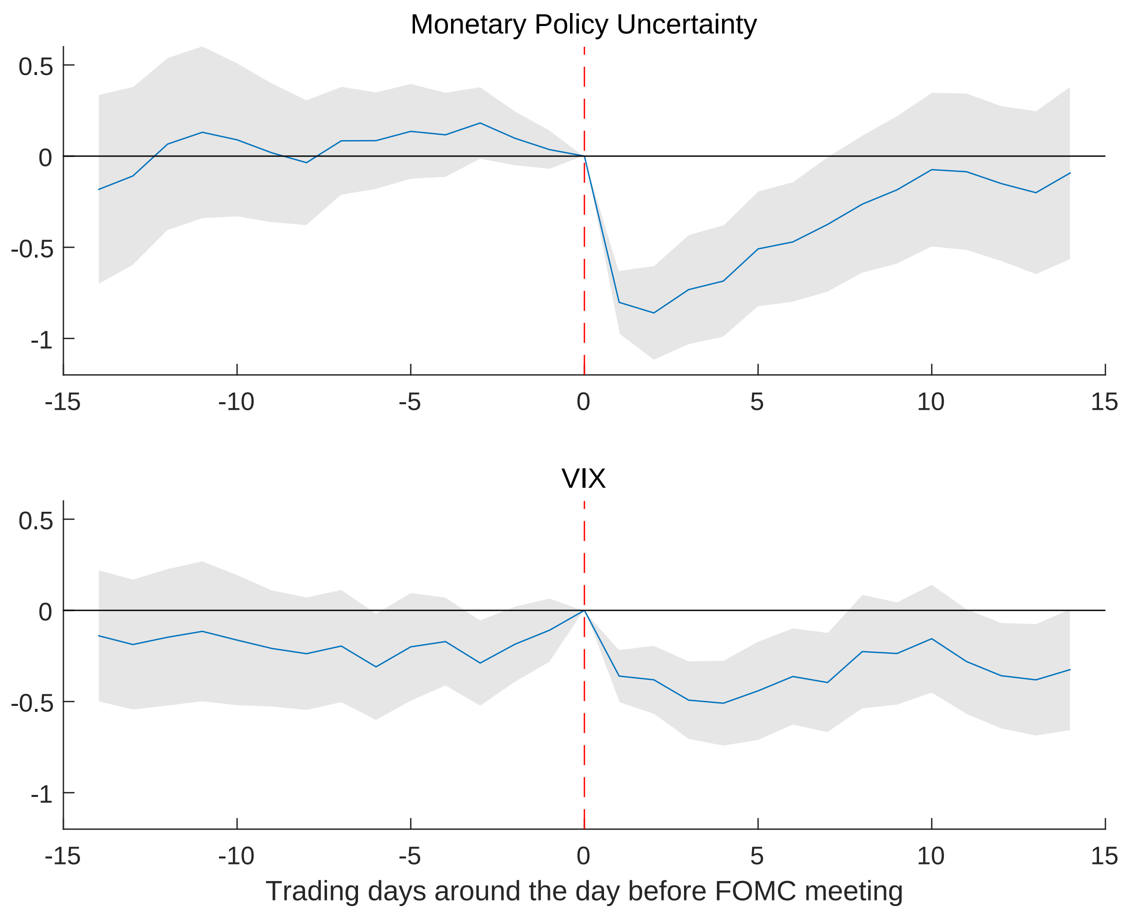
Scatter plot of the change in uncertainty against the policy surprise on FOMC announcment days. The pre-crisis sample is Jan 1994 to Jun 2007, the crisis period is taken to be from July 2007 to June 2009, and our post-crisis sample is from July 2009 to December 2017.

Figure 4: Changes in monetary policy uncertainty over the FOMC meeting cycle



The figure shows the average change in monetary policy uncertainty on trading days around the FOMC announcement, relative to the day before the FOMC announcement day (shown with dashed red line). The shaded gray region shows 95% confidence intervals constructed using White heteroscedasticity-robust standard errors. The sample includes 192 scheduled FOMC announcements from January 1994 to December 2017.

Figure 5: Changes in monetary policy uncertainty and VIX over the FOMC meeting cycle



The figure shows the average change in monetary policy uncertainty (top panel) and VIX (bottom panel) on trading days around the FOMC announcement, relative to the day before the FOMC announcement day (shown with dashed red line). Both series are normalized to show changes relative to the standard deviation of the daily change of the corresponding series on all days. The shaded gray region shows 95% confidence intervals constructed using White heteroscedasticity-robust standard errors. The sample includes 192 scheduled FOMC announcements from January 1994 to December 2017.