Market-Based Monetary Policy Uncertainty*

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Abstract

Uncertainty about future policy rates plays a crucial role for the transmission of monetary policy to financial markets. We demonstrate this using event studies of FOMC announcements and a new model-free uncertainty measure based on derivatives. Over the "FOMC uncertainty cycle" announcements systematically resolve uncertainty, which then gradually ramps up again over the subsequent two weeks. Changes in uncertainty due to FOMC announcements have pronounced effects on asset prices, distinct from the effects of conventional policy surprises. Furthermore, the level of uncertainty determines the magnitude of the financial market reaction to surprises about the path of policy rates.

Keywords: monetary policy uncertainty, Federal Reserve, event study, monetary transmission, jumps, implied volatility, asset prices

JEL Classifications: E44,E52,E58

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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.*" Option markets thereafter assigned a probability of more than 90% to the policy rate remaining at the zero lower bound through at least March 2009, and the option-based standard deviation for the one-year-ahead short rate—according to the measure developed in this paper—dropped by 13 basis points, the second largest drop in our sample. Financial conditions eased substantially, with markedly lower interest rates and higher stock prices.

In this paper we study the role of uncertainty for the transmission of monetary policy. A large literature uses an identification scheme based on high-frequency changes to study the effects of shifts in the path of the expected policy rate on financial asset prices.[2] At the same time, the role of second moments and uncertainty in the transmission 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 policy uncertainty for the transmission of policy actions to financial markets? These are the questions we address in this paper. We propose a high-frequency measure of uncertainty about future monetary policy, and then use this measure in event studies to document several new stylized facts about the drivers of policy uncertainty and the effects of uncertainty on financial asset prices.

The paper makes three main contributions. First, we introduce a new measure of monetary

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

[2] This literature goes back to Cook and Hahn (1989). Prominent examples include Kuttner (2001), Bernanke and Kuttner (2005), Gürkaynak et al. (2005b), Hanson and Stein (2015) and Nakamura and Steinsson (2018).

policy uncertainty based on prices of derivatives written on future short-term interest rates. Specifically, we use Eurodollar futures and options to derive the conditional, risk-neutral standard deviation of changes in the short-term rate at different horizons. While we also consider the term structure of uncertainty, our baseline measure *mpu* captures monetary policy uncertainty at the one-year horizon. The *mpu* measure is straightforward to construct, model-free and requires only the assumption of absence of arbitrage. Moreover, it captures uncertainty about future short rates (and thus about monetary policy) more reliably and more directly than alternative measures of interest rate uncertainty proposed in the literature.[3]

Second, we document the underlying drivers of changes in monetary policy uncertainty. On average, FOMC announcements cause *mpu* to decline, i.e., they lead to a systematic *resolution of uncertainty*. After the announcement, *mpu* gradually ramps up over the course of the FOMC cycle, especially over the first two weeks. This systematic and predictable pattern, which we term the "FOMC uncertainty cycle," has to our knowledge not previously been documented.[4] We investigate other events as potential sources of uncertainty, such as macroeconomic announcements and speeches by FOMC participants, and find that none have an impact on short-rate uncertainty that comes close to that of FOMC announcements. Through the lens of a short-rate model with deterministic jumps, our evidence suggests that the tendency of *mpu* to decline at FOMC announcements is due to both the short-rate volatility caused by the FOMC and the compensation for bearing this risk, i.e., to FOMC jump risk premia. The patterns we document are robust to the choice of sample period, the exclusion of influential observations, and different horizons for uncertainty.

Besides this systematic pattern, changes in uncertainty exhibit substantial variation across FOMC meetings and this variation is tied to specific Fed policy actions. On the one hand,

[3]On the one hand, model-based measures generally rely on strong parametric assumptions such as (log-)normality. On the other hand, existing model-free measures, such as Cboe's SRVIX or SYVIX indices, capture uncertainty about longer-term interest rates such as swap rates or Treasury yields.

[4]Swanson (2006) found that since 1994 an options-based uncertainty measure declined around FOMC meeting days, attributing this to increased Fed transparency. We show that this resolution of uncertainty is the result of jumps in interest rates around FOMC meetings.

conventional monetary policy surprises, which reflect revisions to the expected policy path, are positively correlated with changes in uncertainty. For example, when the FOMC announcement contains a hawkish surprise, uncertainty tends to fall less than average and may even increase.[5] On the other hand, policy actions also have effects on uncertainty that are distinct from their effects on the expected policy path. In particular, uncertainty falls in response to forward guidance: FOMC meetings that are followed by the release of a Summary of Economic Projections (SEP) and a press conference lead to larger declines in uncertainty than other FOMC meetings over the same period (since 2012). Furthermore, the FOMC changed uncertainty about policy rates with forward guidance language in its policy statement. The most pronounced declines in uncertainty coincided with the introduction of phrases in the FOMC statement like "*...for some time*", "*...for an extended period*" and "*... at least through mid-2013*" that the FOMC used to signal the path of future policy rates. Large increases in uncertainty can also be traced back to significant announcements, usually drastic, unexpected policy actions, in some cases following an unscheduled meeting. Consistent with the view that changes in uncertainty occur in response to FOMC announcements, we find little correlation between *mpu* and the pre-FOMC announcement drift in the stock market that was documented by Lucca and Moench (2015). Because policy announcements appear to drive variation in *mpu*, the FOMC may have a separate policy lever that it can use to affect financial conditions, provided that uncertainty matters for the transmission to financial markets.

The third contribution of our paper is to document that monetary policy uncertainty matters for the transmission of FOMC actions to financial markets: Changes in policy uncertainty have significant effects on asset prices that are distinct from the effects of shifts in expectations. An increase in uncertainty around FOMC announcements raises nominal as well as real long-term interest rates, has a negative effect on the stock market—lowering S&P 500 returns

[5] Vice versa, dovish surprises lower uncertainty more than average. The fact that policy rates were lowered substantially over the course of our sample does not explain the pattern of resolution of uncertainty around policy announcements—this finding is robust to controlling for the policy surprise.

and increasing the VIX—and causes the dollar to appreciate. An event study of the Fed's major announcements of unconventional monetary policies shows that balance sheet policies and forward guidance announcements often affected asset prices not only by lowering the expected policy path—the signaling channel emphasized by Bauer and Rudebusch (2014)—but also by lowering market-perceived uncertainty about this path. The uncertainty channel is particularly powerful when the zero lower bound constrains the policy rate and the main lever for forward guidance announcements is to affect second moments.

The direction of these estimated effects is consistent with a risk-based explanation: In standard asset-pricing models, higher uncertainty raises risk premia, leading to higher real and nominal yields and lower stock prices. We provide evidence supportive of this explanation in the positive response of estimated term premia to changes in policy uncertainty. In addition, this risk-based channel may also help explain existing estimates of strong positive effects of Fed policy surprises on real term premia (Hanson and Stein, 2015; Abrahams et al., 2016), since policy surprises are positively correlated with changes in policy uncertainty.

The level of uncertainty also matters for the transmission of policy actions to financial markets, as it determines the effectiveness of conventional 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. This empirical pattern is consistent with the prediction of a signal extraction model, where investors put higher (lower) weight on signals from the Fed when *mpu* is low (high), and dovetails existing finding that during period of high uncertainty, monetary policy shocks have smaller effects on the yield curve in VAR models (Tillmann, 2019) and on the macroeconomy (Aastveit et al., 2017).

Our findings have practical implications for the conduct of monetary policy. By affecting the market-perceived uncertainty around the policy rate, central banks have a separate tool to affect financial conditions. This is in addition to the traditional tool of adjusting market expectations for the expected level of the policy rate. Reductions in policy uncertainty can reduce the dispersion of investor beliefs around the outlook, lower risk premia, and further ease financial conditions. Monitoring market-based policy uncertainty with measures such as the one proposed in this paper could be helpful for monetary policymakers to fully understand the transmission of their actions to financial markets.

Our paper is related to multiple strands of the macroeconomics and finance literature. A growing number of papers study the measurement of monetary policy uncertainty. Text-based approaches using newspaper articles such as Husted et al. (2019) and model-based approaches using bond yield volatility such as Creal and Wu (2017) are promising but not suitable for our purpose of identifying the effects of policy announcements via event studies, as they are generally not available at sufficiently high frequency. Market-based measures, by contrast, are available at daily or higher frequencies. A few papers propose market-based measures of the uncertainty about future short rates, both of which also use Eurodollar options data.[6] Swanson (2006) and De Pooter et al. (2018) calculate a dispersion measure using the Black model, assuming log-normality of future interest rates.[7] Bundick et al. (2017) apply the well-known VIX formula to Eurodollar options, which yields a measure that in practice is similar to ours though it measures the volatility of returns (logs) instead of changes (levels). Our *mpu* measure is model-free, based on modern variance-swap theory, straightforward to calculate, and it captures exactly the conditional standard deviation of the future level of short-term interest rates.

A large literature uses high-frequency event studies to estimate the effects of monetary policy announcements on financial markets (Kuttner, 2001; Bernanke and Kuttner, 2005; Gürkaynak et al., 2005b; Hanson and Stein, 2015; 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

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

[7]Swanson (2006) shows that this measure is broadly similar to an alternative measure based on a more flexible step-function density function.

through a separate uncertainty channel pertaining to second moments of future short rates. Gürkaynak et al. (2005b) 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.

Some recent papers also consider the role of second moments in the transmission of monetary policy. Bundick et al. (2017) estimate a positive relationship between monetary policy uncertainty and Treasury term premia. Bundick and Herriford (2017) show that monetary policy uncertainty has declined since the FOMC started releasing its Survey of Economic Projections. De Pooter et al. (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 reveals and explains a systematic pattern for uncertainty over the FOMC cycle, shows that policy actions and in particular forward guidance substantially affect uncertainty, and comprehensively documents the important role of both the level of and the changes in policy uncertainty for the transmission of FOMC actions to various financial asset prices.[8]

In a recent paper, Kroencke et al. (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. They hypothesize an "uncertainty channel" of policy announcements for which we provide direct evidence. 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 et al. (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

[8]In older work, Ederington and Lee (1996) and Beber and Brandt (2006) documented declines in option-implied interest rate volatility around macroeconomic announcements. We show that the resolution of uncertainty on FOMC days is much more pronounced than on macro announcement days.

of monetary policy on financial markets. Lucca and Moench (2015) and Mueller et al. (2017) document profitable trading strategies around FOMC announcements, related to our results on an option-based strategy that benefits from the systematic declines in uncertainty around FOMC announcements. Finally, some recent papers have documented that the VIX tends to fall on days with FOMC meetings (Fernandez-Perez et al., 2017; Amengual and Xiu, 2018; Gu et al., 2018). Compared to the patterns in the VIX, *mpu* exhibits a more pronounced decline and subsequent rampup. Stock prices are affected by many other factors besides interest rates, and a clear identification of the FOMC uncertainty cycle requires direct measurement of policy-rate uncertainty as we do in this paper.

2 Measuring policy uncertainty with option prices

In this section we describe how we construct a model-free measure of the uncertainty about future short-term interest rates. Market-based *expectations* of future short rates can be obtained from interest rates across maturities, such as fed funds and Eurodollar futures rates. But estimation of the *uncertainty* around these expectations requires option prices, which provide information about the entire market-implied distribution of future short rates.

2.1 Construction

Eurodollar futures are contracts with payoffs tied to the three-month U.S. dollar London Interbank Offered Rate, or LIBOR, the key benchmark short-term interest rate underlying trillions of dollars worth of derivative contracts. These futures contracts are the most liquid exchange-traded interest rate derivatives in the world. Denoting by $F_{t,T}$ the time-t value of a Eurodollar futures contract expiring at T, the value at expiration is $F_{T,T} = 100 - L_T$, where L_T is LIBOR in percent. Tied to each futures contract are option contracts, with payoff $max(F_{T,T} - K, 0)$ for call options and $max(K - F_{T,T}, 0)$ for put options, where K is the strike price. These Eurodollar options are effectively options on LIBOR. For a given trading date

t and an expiration date T we can use the prices of call options, $c_{t,T}(K)$, and put options, $p_{t,T}(K)$ to calculate the market-based conditional variance of future LIBOR, $Var_t(L_T)$, the basis for our market-based uncertainty measure.[9] Appendix A shows that:

$$Var_t(L_T) = \frac{2}{P_{t,T}} \left(\int_0^{F_{t,T}} p_{t,T}(K) + \int_{F_{t,T}}^{\infty} c_{t,T}(K) dK \right) = 2 \int_0^{\infty} \left[\frac{c_{t,T}(K)}{P_{t,T}} - \max(0, F_{t,T} - K) \right] dK,$$

where $P_{t,T}$ is the price of a zero-coupon bond maturing at T. The first expression shows that the conditional variance of future LIBOR can be written as a portfolio of out-of-the-money Eurodollar puts and calls, while the second expression is useful for the implementation.[10] Our measure of monetary policy uncertainty is $mpu_t^{(h)} = \sqrt{Var_t(L_{t+h})}$.

The measure is straightforward to implement empirically.[11] Our data includes daily prices of Eurodollar futures and options from CME Group, for the period from January 1990 to October 2019. We focus on quarterly contract expirations, with $ED1$ denoting the current-quarter contract, $ED2$ the contract for the following quarter, and so forth. For each trading date and expiration we first select out-of-the-money put and call prices with prices above the minimum tick size, and calculate the risk-free interest rate and $P_{t,T}$ based on the zero-coupon yield curve of Gürkaynak et al. (2007).[12] To accurately approximate the integral in (A.3) we obtain a smooth call-price function $\hat{c}(K)$ by translating observed option prices into Black

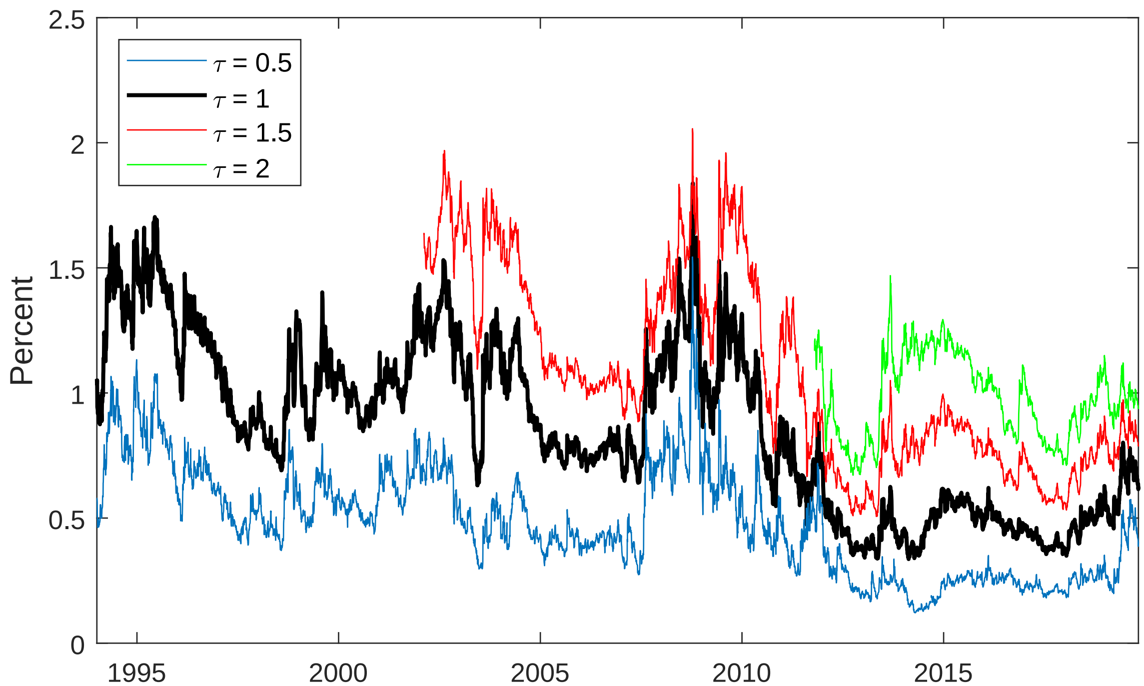
[9]The option-implied variance $Var_t(L_T)$ is taken under the so-called T-forward measure, under which a time-T bond is the numeraire. (To ease notation we omit a superscript such as $\mathbb{Q}_T$ with the variance operator.) This measure is similar to the familiar "risk-neutral" measure, in that both reflect probabilities implied by market prices; under deterministic interest rates both measures would be identical, but the T-forward measure is more convenient for option pricing in the case of stochastic interest rates.

[10]These two expressions are similar to, respectively, the well-known formula for the fair strike of a variance swap (e.g., equation (6) in Choi et al., 2017), and the formula for model-free implied volatility of Britten-Jones and Neuberger (2000) and Jiang and Tian (2005). The difference in both cases is that we focus on the variance of the level, whereas those formulas apply to the variance of logs/returns. See also the swaption-based conditional variance for swap rates in Trolle and Schwartz (2014).

[11]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 et al. (2017). In addition, since we only use out-of-the-money options any adjustment for early exercise would be minimal, since there are no dividends and the early-exercise premium increases with the moneyness of options.

[12]Discounting with term LIBOR or OIS rates—the industry standard before and after the financial crisis, respectively—makes no practical difference for our results, but data on these rates are not easily available going back to the 1990s.

Figure 1: Option-based estimate of monetary policy uncertainty



Risk-neutral standard deviation of three-month LIBOR rate at horizon of h years, estimated from Eurodollar futures and options. Sample period: 1/3/1994 to 10/31/2019.

(1976) implied volatilities (IVs), linearly interpolating the IVs, and translating the fitted IVs back into call prices.[13] 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).

Figure 1 plots the level of *mpu* for constant horizons of series of 0.5, 1, 1.5, and 2 years—the maturity of Eurodollar contracts follows a sea-saw pattern due to the fixed expiration dates, and we use linear interpolation to construct constant maturities. For most of our analysis, we will focus on the one-year horizon, which is both sufficiently long to measure policy uncertainty beyond just the next one or two FOMC meetings, and is available for our whole sample period. In what follows we denote this one-year measure simply by *mpu*.

[13] We calculate the integral using the trapezoidal rule over a grid of 120 strikes in an interval of ± 3 around $F_{t,T}$. For strikes outside the range of observed option prices we use the IV at the bounds of the range.

Uncertainty exhibits considerable variation over the course of our sample, ranging from about 0.2 to two percent. Market-based uncertainty for LIBOR was elevated during the financial crisis. While the Fed lowered the policy rate to essentially zero in late 2008, *mpu* remained elevated until 2010, indicating high uncertainty about the timing of liftoff from the zero lower bound. Then with the introduction of extensive forward guidance by the Fed uncertainty dropped to very lower levels. Uncertainty rose again in 2014 before the Fed started raising the policy rate in late 2015. At the end of our sample, uncertainty remains somewhat below the levels observed before the crisis period. There is a moderate positive correlation between the level of interest rates and uncertainty, consistent with existing findings of a positive relationship between the level and volatility of short rates (Chan et al., 1992): Comparing the one-year interpolated Eurodollar futures rate (not shown) to one-year *mpu*, the correlation is 0.6 in levels and 0.4 in daily changes.

2.2 LIBOR vs. fed funds rate

The advantages of Eurodollar derivatives include their high liquidity, long maturity horizons, and extensive historical data, but a disadvantage is that the underlying rate is not the Fed's policy rate but LIBOR.[14] Since our ultimate interest is in the uncertainty about the future fed funds rate, we have to contend with the fact that LIBOR trades at a spread over the funds rate, due to the inherent risk of a three-month interbank loan vis-a-vis an overnight loan, and that *mpu* also captures uncertainty about this time-varying spread.

The difference between LIBOR and the funds rate is best measured by the LIBOR-OIS spread, which is calculated from rates with the same maturity and a widely used indicator of financial stress; for details see Appendix B. Before the 2008 financial crisis, LIBOR was closely tied to the funds rate and other short rates, and LIBOR-OIS was low and stable. Over the period from January 2002 to June 2007 its standard deviation was 4 basis points (bps), while

[14] We cannot use futures and options tied directly to the fed funds rate because these markets are quite illiquid, and the data availability of fed funds options is too limited, both in terms of historical time span and length of horizons of the derivative contracts.

mpu averaged about one percent, meaning that essentially all of the measured uncertainty pertains to the funds rate. During the financial crisis LIBOR-OIS spiked up as worries about the health of the banking system translated into dramatically increased interbank borrowing rates, and *mpu* was thus less useful as a measure of monetary policy uncertainty. By mid 2009, however, LIBOR-OIS returned to relatively low and stable levels, with only occasional and much less pronounced spikes. From July 2009 to the end of our sample, the variability of the spread was somewhat higher than in the pre-crisis period, but its standard deviation (9 bps) remained an order of magnitude smaller than the average level of market-based uncertainty (95 bps). Overall, outside of the period from July 2007 to June 2009 containing the financial crisis, the uncertainty about future LIBOR measured by *mpu* mainly reflects uncertainty about the future value of the funds rate, that is, about monetary policy. Thus, our sample will exclude the period from July 2007 to June 2009.

2.3 Comparison to other measures

Our model-free uncertainty measure has important advantages over more common volatility estimates. First, it is model-free. By contrast, the famous Black (1976) model assumes that $F_{t,T}$ follows a geometric Brownian motion with instantaneous volatility σ, thus $F_{T,T}$ is log-normal and $Var_t(L_T) = F_{t,T}^2[e^{\sigma^2 h} - 1] \approx F_{t,T}^2 \sigma^2 h$. The Black IV σ, which by itself estimates the (annualized) volatility of the log return $\log(F_{T,T}/F_{t,T})$, can be inferred from an observed option price. The model-based analog of $mpu_{t,h}$ is "normalized" or "basis point" (BP) volatility, $F_{t,T}\sigma$, which is typically calculated using Black IVs from at-the-money (ATM) call prices. We compare $mpu_{t,h}$ to Black BP vols, and find that correlations of daily changes are high but far from perfect, around 0.7 to 0.8, depending on the contract. Our measure is preferable over estimates based on the Black model—such as Black BP vol or the related dispersion measure of Swanson (2006) and De Pooter et al. (2018)—for the same reasons that have motivated the development of other model-free volatility measures such as the VIX, which measures stock market uncertainty using short-dated S&P 500 options: We do not have to rely on strong distributional assumptions, and our measure uses information from option contracts across a range of strikes instead of only from ATM contracts. 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."

Second, our measure directly measures uncertainty about the *level* of future short rates. In related work, Bundick et al. (2017) also construct a model-free uncertainty measure from Eurodollar options. They apply the well-known VIX formula to Eurodollar option prices, which delivers an estimate of the conditional variance of the log-return on Eurodollar futures. In practice, their estimate turns out to be quite similar to our conditional variance of future LIBOR, simply because the futures prices are close to 100 and the volatility of absolute and relative changes are therefore close.[15] We view our methodology as preferable as it directly estimates basis point volatility.

Third, we measure uncertainty about future *short-term* rates, as opposed to alternative market-based measures of interest rate uncertainty. Implied volatility from swaption prices are only available for swap rate tenors of one year or longer, and therefore measure uncertainty about a medium-term rate that is only loosely connected to the Fed's policy rate.[16] The most common market-based measures of interest rate uncertainty focus on even longer maturities: the MOVE index is based on short-dated options on medium- to long-term Treasury bonds; the "Treasury Implied Volatility" (TIV) index, a related and more reliable measure that is described in Choi et al. (2017), uses more liquid options on medium- and long-term Treasury futures; and the Chicago Board of Trade's SRVIX index measures the volatility in one-year swaptions for the ten-year swap rate tenor. While long-term swap and Treasury rates are of

[15] The correlations of daily changes of their and our measure range from 0.9 to 0.99, depending on the horizon maturity. We thank Brent Bundick for providing us with the code and data.

[16] Furthermore, swaptions are over-the-counter (OTC) derivatives and there is no unique, reliable data source with a sufficiently long history of prices available. Trolle and Schwartz (2014) use a method similar to ours to calculate model-free conditional variance of swap rates. Their data starts in December 2001. ATM swaption IVs can be obtained for a longer history, but these have the abovementioned shortcomings. We obtained ATM swaption IVs from Bloomberg for the period from May 2005 to December 2017, and for daily changes the correlation with one-year *mpu* is below 0.7.

course affected by monetary policy, they are also driven by various other factors underlying demand and supply in the bond market. It is a well-known fact in financial economics at least since Fama and Bliss (1987) that the term premium—the difference between a long-term rate and expected future average short-term rates—accounts for a considerable portion of the variation in long-term interest rates. The MOVE, TIV and SRVIX indices are not suitable for our our analysis, because they confound uncertainty about the term premium with our object of interest, the uncertainty about future short-term rates.[17]

While *mpu* measures uncertainty about short rates and is thus not affected by uncertainty about the term premium, it may well be affected by risk premia in a different way: Because we measure $Var_t(L_T)$ based on market prices our estimates reflect not only the variance anticipated by investors but also a variance risk premium.[18] Recent evidence suggests that variance risk premia in fixed income markets vary over time (Choi et al., 2017), hence changes in *mpu* may be driven by changes in both perceived uncertainty and the risk compensation for this uncertainty. In this paper, we follow a large existing macro-finance literature using market-based measures in event studies of monetary policy (prominent examples include Gürkaynak et al., 2005b; Nakamura and Steinsson, 2018). Separating variance from variance risk premia would instead require a dynamic model for volatility, as in Bekaert et al. (2013) and Creal and Wu (2017), with substantial estimation and specification uncertainty that would make it difficult to use the resulting estimates in a high-frequency event study. Our model-free approach guarantees that we accurately capture—on a day-to-day basis—how investors perceive and value the uncertainty about future short rates.

A fundamentally different way to gauge the public's uncertainty about the future course of monetary policy is to measure this uncertainty from an analysis of news articles.[19] This

[17]These series have low correlation with our measure: Over our sample period (excluding the financial crisis) the correlation of daily changes in the TIV with daily changes in *mpu* is only 0.19. Over the period where the SRVIX has been available, since June 2012, the correlation with *mpu* is 0.36, again in daily changes.

[18]As discussed above, $Var_t(L_T)$ captures variance not under the "real-world" probability measure, but under the T-forward measure, which is similar to the usual "risk-neutral" measure in that it incorporates risk-discounting.

[19]Yet another approach is the use of survey information, as in Volker (2017) and Istrefi and Mouabbi (2017).

type of news-based measurement of uncertainty was made prominent by Baker et al. (2016) and has recently been applied to monetary policy by Husted et al. (2019). Market-based and news-based approaches each have their respective advantages and should be viewed as complementary. Importantly, news-based measures reflect the sentiment in the broad population instead of just financial market participants. Furthermore, these measures are not affected by changes in the risk premia in asset prices, at least not directly. Market-based measures, by contrast, have a very clear economic interpretation in terms of a (square root of a) conditional variance of a future interest rate. And our market-based uncertainty measure is available at a sufficiently high frequency, which is crucial for our purpose of estimating the financial market effects of central bank policy actions.

3 The drivers of monetary policy uncertainty

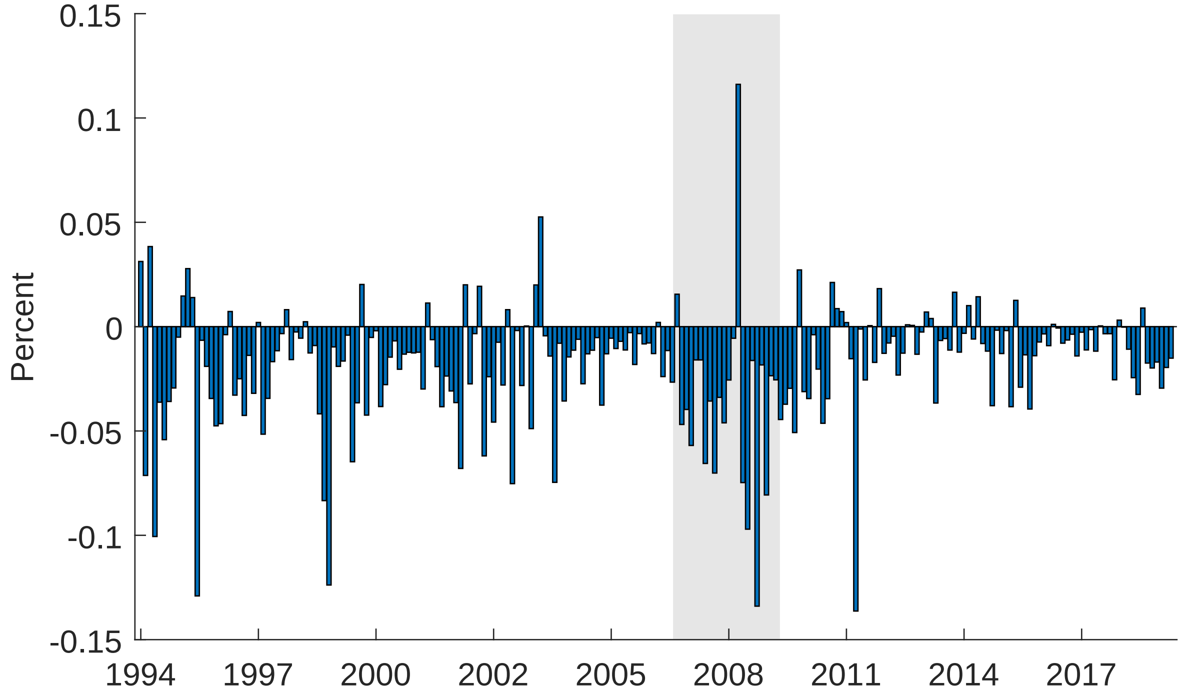
In this section we use an event study methodology to study the drivers of monetary policy uncertainty. We document a significant resolution of uncertainty as a result of FOMC meetings and a gradual ramp-up over the first two weeks of the intermeeting period, a pattern that we term the "FOMC uncertainty cycle." Beyond this systematic pattern, specific FOMC announcements cause pronounced changes in uncertainty, with the strongest effects due to forward guidance announcements.

3.1 Resolution of uncertainty on FOMC days

According to our new high-frequency measure, monetary policy uncertainty declines around most FOMC announcements. Figure 2 plots the daily changes in the one-year *mpu* measure for all 220 FOMC announcements occurring in the full sample period from 3 January 1994 to 31 October 2019. The uncertainty measure falls on over 80% of FOMC days (181 out of 220).

However, survey dispersion is not necessarily closely related to subjective uncertainty, and it is not available at a sufficiently high frequency.

Figure 2: Changes in policy uncertainty on FOMC announcement days



Daily changes in monetary policy uncertainty on days with FOMC announcements. The sample includes all 220 FOMC announcements from January 1994 to October 2019. The shaded region shows the period from July 2007 to June 2009 containing the Global Financial Crisis.

Many of the declines exceed five basis points.[20] Thus, the monetary policy announcements and actions of the FOMC typically lead to a substantial *resolution of uncertainty* about the future path of interest rates.

The summary statistics in Table 1 further describe the distribution of changes in mpu around FOMC announcements. For this and all following quantitative analysis we exclude the period from July 2007 to June 2009 containing the Global Financial Crisis (as discussed in Section 2.2), as well as unscheduled announcements, which leaves us with 191 meetings.[21] The first column of Table 1 shows that the average decline on FOMC days is 1.7 basis points (bps) and very strongly statistically significant. In terms of magnitude, the average decline on FOMC days is large relative to the variability in the time series: the standard deviation of daily changes in mpu is 2.6 bps. That is, the resolution of uncertainty on FOMC days is

[20] The average level of mpu is 87 basis points.
[21] All our results remain essentially unchanged when we include the unscheduled FOMC announcements.

Table 1: Summary statistics for changes in monetary policy uncertainty

	Jan-1994 to Oct-2019		Jan-2012 to Dec-2018		
	FOMC	Non-FOMC	All FOMC	With SEP	W/o SEP
Observations	191	5811	56	29	27
Mean	-0.017	0.000	-0.008	-0.013	-0.002
t-stat (mean)	-9.04	1.60	-4.67	-5.19	-1.40
Median	-0.012	0.000	-0.007	-0.011	-0.003
Standard deviation	0.026	0.020	0.013	0.014	0.009
Skewness	-1.60	1.32	-0.58	-0.36	0.69
Kurtosis	8.29	15.03	3.64	2.72	2.91
Minimum	-0.136	-0.110	-0.039	-0.039	-0.014
Maximum	0.053	0.223	0.018	0.016	0.018
Cumulative change	-3.18	2.40	-0.44	-0.38	-0.06

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. *t*-tests for mean use White heteroscedasticity-robust standard errors. The first two columns report results for our baseline sample period sample period from January 1994 to October 2019, excluding the period from July 2007 to June 2009 containing the Global Financial Crisis. The last three columns focus on the more recent period from January 2012 to December 2018, when every alternate FOMC meeting was followed by the release of the Summary of Economic Projections (SEP) and a press conference by the Chair.

both statistically and economically significant. The median decline in *mpu* is smaller than the mean decline, and there is pronounced left-skewness and excess kurtosis, reflecting the fact that some FOMC meetings lead to particularly large declines in *mpu* as evident in Figure 2. The decline in uncertainty around FOMC meetings stands in contrast to the average change on non-FOMC days, reported in the second column, which is essentially zero.

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. Most significant are the introduction of press conferences held by the Chair and the release of the economic forecasts of the committee participants, the "Summary of Economic Projections" (SEP).[22] Through these communication channels the FOMC provides more information about economic fundamen-

[22]In October 2007, the FOMC began releasing the SEP together with the Minutes three weeks after the FOMC meeting and since April 2011 the SEP is released on the same day as the FOMC statement. In April 2011 Chairman Ben Bernanke also started the tradition of holding regular press conferences at every other FOMC meeting. From January 2012 onwards the FOMC also started releasing committee members' projections for the appropriate future path of the policy rate as part of the SEP, the so-called "dot plot." Since January 2019, every meeting is followed by a press conference.

tals and the rationale underlying the policy actions. The last three columns of Table 1 show summary statistics for changes in *mpu* since January 2012, i.e., for a period when all these major changes in communication are in place. Over this recent period, the average decline in uncertainty around FOMC meetings is only about half as large as over the full sample, but this average masks pronounced differences between meetings with and without an SEP release and press conference: Policy uncertainty declines mainly on SEP days, while on "non-SEP" days the average decline is small and not significantly different from zero (and the standard deviation is smaller as well). Thus, it appears that the release of information about the policy and economic outlook through the SEP and press conference contributes in important ways to the resolution of policy uncertainty.[23]

When exactly does uncertainty get resolved? A natural interpretation of our results is that resolution of uncertainty happens with the release of the FOMC announcement, usually at 2:15pm EST. However, several papers have documented pre-announcement effects for FOMC meetings in different financial asset prices. Most prominently, Lucca and Moench (2015) document a pre-announcement stock market drift that generates substantial excess returns. In addition, Hu et al. (2019) show that the VIX declines around FOMC meetings, and that these declines to some extent occur before the actual FOMC announcement. This raises the question whether *mpu* declines *before* the actual FOMC announcement. Since our *mpu* measure is daily, we cannot perform intraday analysis to conclusively answer this question. However, our evidence on the whole is most consistent with the view that changes in uncertainty occur in response to the actual announcement. First, Appendix C.1 shows that changes in *mpu* are only weakly correlated with the pre-FOMC drift of Lucca and Moench (2015). Additionally, unreported results show that orthogonalizing *mpu* with respect to the pre-FOMC drift has essentially no effect on our main results. Thus it appears that pre-announcement patterns

[23] Consistent with this interpretation, Boguth et al. (2018) find that more attention is being paid to these particular FOMC meetings. Bundick and Herriford (2017) also investigate 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 the "Summary of Economic Projections."

have little relation with changes in *mpu*. Furthermore, the results in Section 3.4 below show that changes in *mpu* are closely tied to the policy actions of the FOMC, further supporting the case that FOMC announcements and not a pre-announcement drift drives changes in policy uncertainty.

Many other types of news affect financial markets and could potentially drive changes in monetary policy uncertainty. Macroeconomic data releases are known to create substantial volatility in stock and bond markets (Fleming and Remolona, 1999; Andersen et al., 2007). In Appendix C.2 we show that *mpu* tends to decline only modestly on days with the most important macro announcements, such as the employment report. No macro release leads to a similarly large resolution of uncertainty as FOMC announcements. Other important news for financial markets include speeches by FOMC participants. One might expect these to increase uncertainty due to the wide range of views expressed about the outlook for monetary policy, but Appendix C.3 shows that they have no discernible effect on *mpu* at all. In terms of their impact on policy uncertainty, FOMC news are substantially more important than macro news or other monetary policy news.

3.2 A simple model of FOMC jumps

To help interpret our results we specify a simple model of interest rates in which FOMC announcements are treated as jumps at deterministic times, as in Piazzesi (2001). This assumption is justified because the FOMC meeting schedule is known in advance and the announcements often lead to substantial changes in asset prices (Gürkaynak et al., 2005b; Bauer, 2015). Our model is essentially the classic Bachelier model, in which asset price changes are normally distributed, augmented with deterministic jumps. The Eurodollar futures price, which moves one-for-one with LIBOR, follows

$$dF_t = \sigma dW_t + dJ_t, \quad J_t = \sum_{j=1}^{N_t} Z_j, \tag{1}$$

where F_t is the futures price (omitting the second subscript for the expiration), $W_t \sim N(0,t)$ is a standard Brownian motion and J_t is a jump process with deterministic jump times on FOMC days τ_j. The jumps Z_j are normally distributed with mean zero and variance σ_j^2, and N_t is the (known) number of jumps up to time t.[24] All distributions are specified under a market-based probability measure.[25] Thus, σ_j^2 is the market-based (or risk-neutral) FOMC jump variance. According to this model the conditional market-based variance is

$$mpu_{t,T}^2 = Var_t(F_T) = (T-t)\sigma^2 + \sum_{j:t<\tau_j\leq T} \sigma_j^2$$

where the sum is over all jumps occurring after time t up to and including T. This variance captures the (scaled) diffusion variance as well as the sum of all the jump variances up to the contract's expiration date. If t is a day with an FOMC meeting (that is, $t = \tau_j$, for FOMC meeting j), the model implies that

$$epe_{t,T} = Var_{t-\delta}(F_T) - Var_t(F_T) = \delta\sigma^2 + \sigma_j^2 > 0, \tag{2}$$

where $\delta = 1/250$ is one trading day measured in years. This negative change of the market-based variance for a fixed expiration T is an "*ex post* estimate (*epe*)" of the FOMC jump variance σ_j^2, provided that the diffusion term $\delta\sigma^2$ is sufficiently small.[26] Furthermore, fixed-expiration changes in mpu are

$$\Delta mpu_{t,T} = mpu_{t,T} - mpu_{t-\delta,T} = \sqrt{(T-t)\sigma^2 + \textstyle\sum_i \sigma_i^2} - \sqrt{(T-t+\delta)\sigma^2 + \sigma_j^2 + \textstyle\sum_i \sigma_i^2} < 0, \tag{3}$$

[24]The solution to the stochastic differential equation in (1) is $F_t = F_0 + \sigma W_t + \sum_{j=1}^{N_t} Z_j$.

[25]The probability measure could be either the forward-T measure discussed in Section 2.1 or the usual risk-neutral measure. The distinction is unimportant for our purpose here, as is the distinction between futures and forward prices.

[26]The term "*ex post* estimate" originates from Dubinsky et al. (2018) who consider deterministic jumps in stock prices around earnings announcements. They also suggest an *ex ante* estimate of jump variances, but this estimate is difficult to implement in our setting, since it requires that two successive futures contracts span the same FOMC meetings and we focus on contracts with quarterly expirations; contracts with monthly expirations are distinctly less liquid and have less historical data.

where the σ_i^2's are the variances for the remaining FOMC jumps after t until T. Note that our baseline measure of *mpu* shown in Figure 1 and 2 is a constant-horizon measure calculated by interpolating multiple contracts while the above measure is a constant-expiration measure that can be calculated from an individual contract.

The model suggests that *mpu* systematically declines around FOMC meetings because after the meeting there is one less market-moving event causing uncertainty. This "dropping-out" effect is a plausible explanation for the systematic resolution of uncertainty documented above. It can also explain why SEP meetings led to substantially larger resolution of uncertainty than non-SEP meetings: Over the relevant period from January 2012 to December 2018, the FOMC has only changed the policy rate at meetings with an SEP release. Thus, anticipated jump variances for SEP meetings are presumably larger, and more uncertainty is resolved after each of these meetings, than for FOMC meetings without an SEP release.

Table 2 reports additional evidence for the individual contracts ED1 to ED6, corresponding directly to the expressions in equations (2) and (3) for fixed expirations. The top panel shows summary statistics for $epe_{t,T}$. The means of $epe_{t,T}$ are positive and highly significant, and in volatility terms (i.e., by taking the square root) they range from 9 to 21 bps. The medians are lower due to the presence of fat right tails, and in volatility terms they range from 6 to 16 bps. The bottom panel of Table 2 shows summary statistics for $\Delta mpu_{t,T}$. Consistent with our previous results for the one-year *mpu* measure, the means are significantly negative with an average decline of about 1.7 to 2 bps. These magnitudes are smaller than the estimated jump volatilities, because they measure something quite different, namely the changes in the market-based standard deviation for the future short rate. The jump model is helpful in interpreting these quantities. Overall, the sizeable positive jump variances and declines in *mpu* are consistent with the presence of substantial FOMC jumps. Appendix C.4 provides additional evidence for FOMC jumps by comparing FOMC days to other days.

Taken literally, the model implies that (i) market-based variance and *mpu* should always decline around FOMC meetings, (ii) variation in the declines over time are only due to dif-

Table 2: Summary statistics for FOMC jumps across contracts

	ED1	ED2	ED3	ED4	ED5	ED6
Ex-post estimate of jump varianes						
Mean	0.009	0.017	0.027	0.034	0.038	0.043
t-stat	8.900	9.660	8.794	8.340	7.755	8.030
Median	0.004	0.009	0.015	0.017	0.020	0.026
Standard deviation	0.013	0.025	0.042	0.056	0.068	0.073
Fraction negative	0.087	0.115	0.178	0.141	0.188	0.186
Daily change in monetary policy uncertainty						
Mean	-0.019	-0.018	-0.019	-0.019	-0.018	-0.017
t-stat	-11.866	-12.515	-10.989	-10.236	-9.094	-8.878
Median	-0.014	-0.013	-0.016	-0.013	-0.013	-0.013
Standard deviation	0.021	0.020	0.024	0.026	0.027	0.026
Observations	173	191	191	191	191	188

Summary statistics for changes in variance/uncertainty around FOMC meetings. The top panel summarizes the ex-post estimate $epe_{t,T} = Var_{t-\delta}F_T - Var_tF_T$. The bottom panel summarizes $\Delta mpu_{t,T} = \sqrt{Var_tF_T} - \sqrt{Var_{t-\delta}F_T}$. There are 191 scheduled FOMC meetings in our sample period from January 1994 to October 2019, excluding the period from July 2007 to June 2009 containing the Global Financial Crisis (for the ED1 and ED6 contracts some observations are missing due to option data availability). t-statistics are calculated using White heteroskedasticity-robust standard errors.

ferences in the jump variances σ_j^2, and (iii) all contracts should exhibit identical declines. However, mpu sometimes increases around FOMC announcements—Table 2 shows that this happens for about 10-20% of the FOMC meetings, depending on the contract. Relatedly, one might argue that the variation in $epe_{t,T}$ is larger than can plausibly be explained by differences in anticipated jump variances σ_j^2. Finally, different Eurodollar contracts do not deliver identical jump variance estimates. The means in Table 2 differ notably across contracts, and the first principal component explains only 87% of the total variance of $epe_{t,T}$. The empirical deviations from the model's implications seem larger than what could be attributed to market noise or measurement error. But a simple extension of the model can reconcile these observations: While the jump variances were so far assumed to be fixed and known, a more realistic assumption is that market participants form beliefs about future jump variances, $E_tZ_j^2$, and update these beliefs based on new information. In this case changes in $Var_t(F_T)$ not only reflect the mechanical "dropping-out" of the most recent FOMC jump, but also changes to the jump variance beliefs due to the current policy announcement. Equation (2) generalizes to

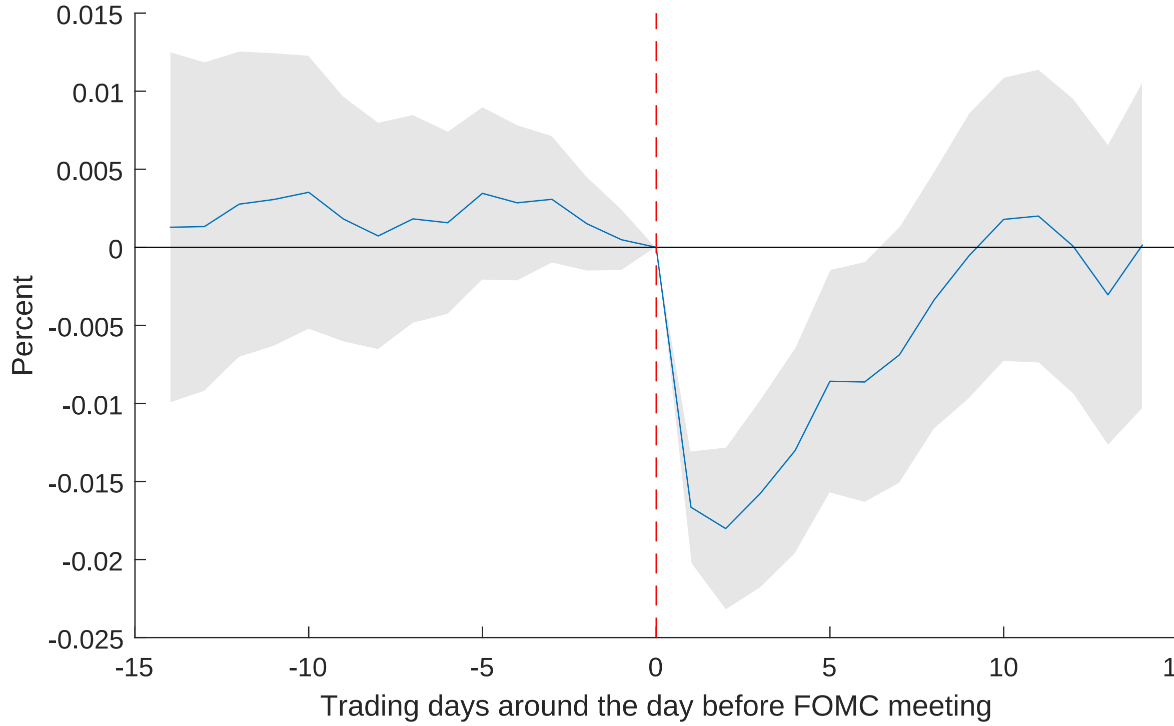
$$epe_{t,T} = \delta\sigma^2 + \sigma_j^2 + \sum_{i:t<\tau_i\leq T} (E_t - E_{t-\delta})Z_i^2, \tag{4}$$

and analogously for $\Delta mpu_{t,T}$. If future jump variance beliefs increase sufficiently as a result of an FOMC announcement, market-based variance and uncertainty would increase. More generally, changes in beliefs contribute additional variation to $epe_{t,T}$ and $\Delta mpu_{t,T}$, both over time and across contracts. This slight generalization of the model is a more plausible description of FOMC jumps and interest rate uncertainty.[27] While the presence of jumps provides an explanation for the tendency of mpu to decline around FOMC announcements, changes in the beliefs about jump variances can explain the substantial variation in Δmpu. Consistent with this interpretation, we show below in Section 3.4 that the biggest changes in mpu occurred when the language regarding forward guidance about future rates was explicitly changed in the FOMC statement.

A separate question regarding the presence of FOMC jumps is whether investors require compensation for the risk due to jumps, that is, whether there are jump risk premia. Appendix C.5 presents some evidence that suggests that jump risk premia may play a role in explaining the systematic decline in uncertainty around FOMC announcements: First, historical volatilities of interest rate changes on FOMC days are much smaller than market-based jump volatilities. Second, a simple option trading strategy designed to benefit from falling uncertainty—short straddle positions around FOMC announcements—yields significantly positive excess returns. While there are some caveats to these results, including the potential role of transaction costs for the profitability of the trading strategy, they provide some suggestive evidence for the presence of jump risk premia.

[27] Another possible but more complicated extension would be to allow for stochastic volatility of the diffusion term, as in Dubinsky et al. (2018).

Figure 3: 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 191 scheduled FOMC announcements from January 1994 to October 2019, excluding the period from July 2007 to June 2009 containing the Global Financial Crisis.

3.3 The FOMC uncertainty cycle

While uncertainty declines markedly on days with FOMC meetings, it increases on average on non-FOMC days. Table 1 shows a large cumulative decline in *mpu* on FOMC days of 3 percentage points, and a sizeable cumulative increase in *mpu* on non-FOMC days amounting to 2 percentage points. As a result uncertainty falls over the entire sample period, as evident in Figure 1. As noted above in Section 3.1, neither macro news nor speeches by FOMC participants increase interest rate uncertainty. While we cannot rule out that other specific events systematically increase policy uncertainty, the creation of uncertainty does not appear to be linked to macro announcements or other policy events. So when is uncertainty actually created?

After the initial drop around FOMC meetings, monetary policy uncertainty tends to steadily increase over the course of the intermeeting period, with most of the increase occurring over the first two weeks. This "FOMC uncertainty cycle" is evident in Figure 3 which plots the average change over the FOMC cycle relative to the day before the FOMC meeting. Specifically the figure shows the cumulative 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.[28] Shaded areas show 95%-confidence intervals for the mean cumulative change using White heteroscedasticity-robust standard errors. The significant one-day decline ($j = 1$) around scheduled FOMC meetings of about two basis points corresponds to the average change on FOMC meetings in the first column of Table 1. Figure 3 then illustrates that the decline continues on the second day after the announcement. But then uncertainty starts to gradually ramp up over the course of the following two weeks, offsetting almost the entire drop in uncertainty.[29] Appendix C.7 shows that our finding of a predictable drop and subsequent ramp-up in uncertainty is robust to the choice of sample period as well as to the treatment of outliers.

The ramp-up of uncertainty over the intermeeting period is consistent with our simple model of FOMC jumps. More distant contracts generally contain more uncertainty as they cover more trading days and more FOMC jumps. Our constant-maturity one-year mpu measure interpolates between two contract expirations, so it contains the uncertainty from the shorter contract plus a share of the additional uncertainty in the longer contract. After an FOMC meeting uncertainty is lower than usual as there are less than average FOMC meetings within the one-year horizon, and over time uncertainty reverts back to normal as the number of FOMC meetings within the horizon normalizes.

The systematic pattern of policy uncertainty over the intermeeting period is markedly

[28]In Figure 3 we only include changes in uncertainty before and after scheduled FOMC meetings, while Appendix C.7 shows that including unscheduled meetings gives similar results.

[29]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.

different than the pattern for the VIX. Appendix C.6 shows (i) the decline in *mpu* on FOMC days is about twice as large as the decline in the VIX, and (ii) the VIX increases in the few days leading up to the FOMC meeting in contrast to the gradual ramp-up in *mpu* over the meeting cycle. That is, the intermeeting period exhibits a much more pronounced pattern of decline and subsequent ramp-up for uncertainty about future short-term rates than for the VIX. To uncover the FOMC uncertainty cycle it is crucial to use a measure of policy uncertainty such as *mpu*.

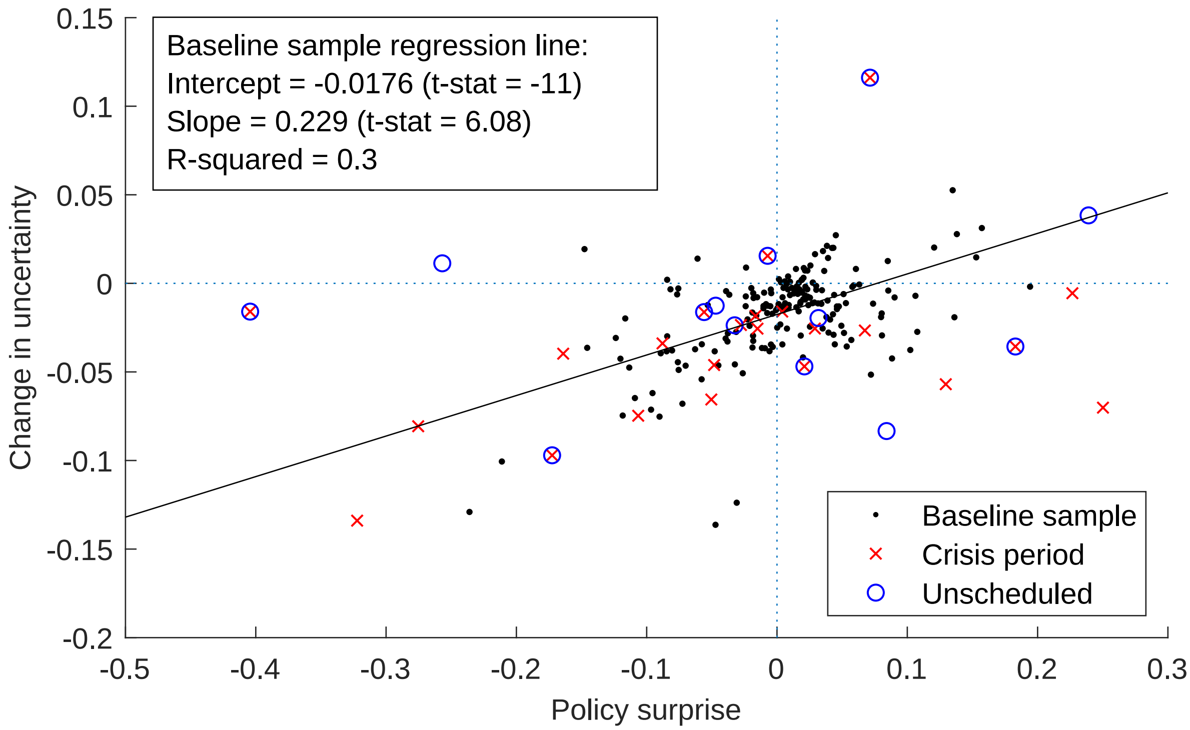
3.4 The role of FOMC policy actions

We have documented that uncertainty declines *on average* around FOMC meetings, but Table 1 and Figure 2 show substantial variation around the mean change. This variation raises the question how policy actions taken at these meetings affect *mpu*, which we now turn to.

First, surprises to the expected path of policy rates (i.e. first moment changes) are positively correlated with changes in uncertainty about future rates. We measure the monetary policy surprise as the first principal component of changes in Eurodollar futures rates for contracts expiring over the next four quarters.[30] We scale this surprise measure so that its effect on the four-quarters-ahead futures rate is equal to one. Thus, a positive surprise indicates that new information on the day of the FOMC announcement causes market participants to revise their expectations about the policy path over the next year upwards. The scatter plot in Figure 4 plots changes in policy uncertainty around FOMC meetings (Δmpu) against the monetary policy surprises (*mps*). It clearly shows the pronounced positive correlation, consistent with the positive (full-sample) correlation between changes in futures rates and uncertainty reported in Section 2.1. That is, a more hawkish policy surprise is associated with a smaller than average decline or even an increase in policy uncertainty, and a dovish policy surprise is associated with a larger than average decline. This positive correlation raises

[30]This is similar to the methodology in Nakamura and Steinsson (2018), except that we use daily (instead of intraday) changes in futures rates in order to be consistent with our daily measure of policy uncertainty.

Figure 4: Monetary policy surprises and changes in uncertainty



Scatter plot of the daily change in monetary policy uncertainty against the policy surprise on FOMC announcement days. The baseline sample consists of scheduled announcements from January 1994 to October 2019 excluding the period from July 2007 to June 2009 containing the Global Financial Crisis. The black line shows the fit from the regression of change in uncertainty on policy surprise for the baseline sample, t-statistics are based on White hetreoskedasticity-robust standard errors.

the question of whether the observed average decline in uncertainty in our sample is simply due to the prevalence of dovish policy surprises. This is not the case, as evident from the negative regression intercept shown in Figure 4, which has the same magnitude and statistical significance as the average change in *mpu* around FOMC reported in Table 1. An implication of this correlation is that estimates of the financial market impact of FOMC announcements should include not only conventional policy surprise measures, but also changes in uncertainty, in order to avoid confounding the effects of changes in first and second moments; we will do so below in Section 4.

Second, policy actions also have substantial effects on uncertainty that are distinct from their effects on the expected policy path. Changes in uncertainty appear to be closely tied to actual FOMC policy communication. Narrative analysis of influential meetings provides strong evidence that financial markets are reacting to changes in forward guidance language embedded in the FOMC statement. Table 3 lists the ten FOMC announcements with the biggest declines and the five announcements with the biggest increases in *mpu*, which are also clearly visible in Figure 2. For each announcement, the table notes a key phrase or aspect of the FOMC statement and its role in the current monetary policy cycle. These most impactful announcements usually came as a result of the change in the forward guidance language in the FOMC statement.

The first phase of explicit forward guidance began in 2003 when the FOMC under Alan Greenspan introduced the "*considerable period*" language at its May meeting to signal more clearly about lower future rates. The introduction of this forward guidance language substantially reduced uncertainty. However, in January 2004 this language was replaced by a phrase *"can be patient"* which lead to an increase in uncertainty. The second phase of explicit forward guidance began during the financial crisis and was marked by clearer messaging about the likely path for the future funds rate. It started with the *"for some time"* language in December 2008, when the FOMC cut rates and indicated in its statement that low rates were here to stay.[31] Then in August 2011 the FOMC introduced calendar-based guidance for the first time with the phrase *"exceptionally low levels for the federal funds rate at least through mid-2013."* This language considerably pushed out the expected date of liftoff from zero and led to the largest decrease in uncertainty in our sample. Large increases in uncertainty occurred when the FOMC announced drastic, unexpected policy action, for example an unscheduled rate cut and concerted actions with other central banks in October 2008, or the first rate hike in years in February 1994. These examples make it clear that large observed changes in *mpu* are typically driven by a change in the forward guidance language contained in the FOMC announcement.[32]

[31]The phrase *"for some time"* was used in subsequent FOMC statements until March 2009 when it was changed to "*for an extended period*".

[32]Interestingly, our *mpu* measure also shows a large decline at the July 1995 FOMC meeting. At this meeting, the FOMC mentioned a numerical target for the federal funds rate in the statement for the very first time.

Table 3 also reports the monetary policy surprise, *mps*, and the positive correlation between policy surprises and changes in uncertainty that we noted previously is clearly evident: for these announcements, Δmpu and *mps* almost always have the same sign. However, it is also evident that the correlation is not perfect: the large declines in *mpu* did not always coincide with large dovish surprises, and vice versa. For example, on 16 December 2008 market participants were somewhat caught off guard by the aggressive cut, which resulted in an expansionary policy surprise together with a large reduction in uncertainty stemming from 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 the introduction of calendar based forward guidance did reduce uncertainty substantially.

This narrative evidence suggests that the FOMC's policy actions caused changes in policy uncertainty, over and above any surprises to the expected policy path. Through the lens of our model of FOMC jumps, FOMC announcements changed investors perceptions about future jump variances and in this way affected market-based uncertainty about future short rates. This has implications for the overall design of monetary policy and for understanding the monetary transmission mechanism. By directly affecting uncertainty around the policy rate, the FOMC may have at its disposal a separate policy tool, provided that uncertainty matters for the transmission of policy actions to financial markets.

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 asset prices.

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

Meeting date	Δmpu	mps	Description
			Top 10 declines in monetary policy uncertainty
09 Aug 2011	-0.136	-0.047	Introduction of calendar based forward guidance: "exceptionally low levels for the federal funds rate *at least through mid-2013*."
16 Dec 2008	-0.134	-0.322	ZLB is reached and introduction of clear forward guidance phrase: "exceptionally low levels of the federal funds rate *for some time*."
06 Jul 1995	-0.129	-0.236	First explicit mention of numerical target for federal funds rate. Also interest rate cut: "...inflationary pressures have receded enough to accommodate a modest adjustment in monetary conditions."
17 Nov 1998	-0.124	-0.031	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"
17 May 1994	-0.101	-0.211	Fed funds target rate increased by 50 bps to "...substantially remove the degree of monetary accommodation which prevailed throughout 1993."
25 Nov 2008	-0.097	-0.173	TALF announcement: "... increase credit availability and support economic activity by facilitating renewed issuance of consumer and small business ABS at more normal interest rate spreads."
15 Oct 1998	-0.083	0.084	FOMC stated that "further easing of the stance of monetary policy was judged to be warranted to sustain economic growth"
18 Mar 2009	-0.081	-0.275	Change in language about low rates to "for an extended period" from previous statement which said "for some time"
06 May 2003	-0.075	-0.090	Introduction of forward guidance phrase: "policy accommodation can be maintained for a considerable period"
29 Oct 2008	-0.075	-0.107	Fed funds target rate cut by 50bps. Confirmation that the FOMC "...will act as needed to promote sustainable economic growth and price stability."
			Top 5 increases in monetary policy uncertainty
Meeting Date	Δmpu	mps	Description
08 Oct 2008	0.116	0.071	Announcement after unscheduled meeting of concerted actions by central banks around the world
28 Jan 2004	0.053	0.135	Change in language to ".. can be patient in removing its policy accommodation" from previous statement which said "..accommodation can be maintained for a considerable period."
18 Apr 1994	0.038	0.240	Unscheduled conference call: "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	0.031	0.157	First rate hike in years in line with the FOMC decision "...to move toward a less accommodative stance in monetary policy..."
28 Mar 1995	0.028	0.138	The FOMC indicated "asymmetric directive also would provide a clear signal of the Committee's intention to resist higher inflation."

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.

4.1 Event study regressions

We estimate the financial market effects of monetary policy actions on FOMC announcement days using the event-study approach common in this literature (Gürkaynak et al., 2005b; Nakamura and Steinsson, 2018) and three different regression specifications. We start with 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 (see Section 3.4). Next, we add to this regression the daily change in uncertainty, Δmpu, to estimate its direct effect on asset prices while controlling for its correlation with mps. Finally, we further add an interaction effect between mps and the level of uncertainty on the day before the FOMC announcement (mpu_{-1}), to study whether the prevailing level of uncertainty affects the financial market response to policy surprises.[33] Our sample includes 191 scheduled FOMC announcements from January 1994 to October 2019, excluding the period from July 2007 to June 2009 containing the Global Financial Crisis.

Table 4 reports regression estimates for changes in nominal (top panel) and real (bottom panel) five- and ten-year Treasury yields. We use nominal yields from Gürkaynak et al. (2007) and TIPS yields from Gürkaynak et al. (2010). Due to data availability the sample for TIPS yields starts from February 1999. For nominal yields the first specification confirms the well-established result that policy surprises have sizeable and significant effects. The second regression shows a statistically significant and positive response of yields to Δmpu—an increase in mpu results in an increase in long-term yields, over and above the effect of the policy surprise. A one standard deviation increase in the mpu measure raises the five- and ten-year nominal yields by around 1.5 bps. The first columns in the bottom panel of Table 4 show that policy surprises drive real yields as well, as found in Hanson and Stein (2015) and Nakamura and Steinsson (2018). In addition to this, we find that changes in mpu also have a

[33]To economize on space in our tables, we do not report the estimated regression intercept, or the coefficient on the lagged level of uncertainty, which we include in the third regression specification to accurately estimate the interaction effect.

Table 4: Transmission of uncertainty to Treasury yields

	Response of nominal yields					
	5 year yield			10 year yield		
mps	0.67	0.56	1.10	0.47	0.35	0.62
	[15.76]	[10.62]	[7.38]	[9.32]	[5.69]	[3.81]
Δmpu		0.51	0.70		0.64	0.78
		[2.50]	[3.20]		[2.67]	[3.07]
mps x mpu_{-1}			-0.49			-0.25
			[-3.50]			[-1.48]
R^2	0.53	0.56	0.61	0.32	0.37	0.40
	Response of real (TIPS) yields					
	5 year yield			10 year yield		
mps	0.51	0.38	1.62	0.43	0.32	1.19
	[5.83]	[4.36]	[3.97]	[6.68]	[4.76]	[3.93]
Δmpu		0.83	0.99		0.72	0.84
		[2.85]	[3.50]		[3.11]	[3.44]
mps x mpu_{-1}			-1.31			-0.91
			[-3.18]			[-2.79]
R^2	0.21	0.27	0.39	0.22	0.28	0.38

Regressions of daily changes in nominal and real 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 (measured on day before announcement) of uncertainty (mpu_{-1}) on FOMC announcement days. In the third specification we also include mpu_{-1} in the regression but don't report its coefficient to economize on space (as for all estimated constants). In brackets are t-statistics based on White heteroscedasticity-robust standard errors. The sample for nominal yields contains 191 scheduled FOMC announcements from January 1994 to October 2019. The sample for real yields (151 announcements) is February 1999 to October 2019. Both exclude the period from July 2007 to June 2009 containing the Global Financial Crisis.

statistically significant direct effect on real yields that is similar in magnitude to the effect on nominal yields. While the average effect of Δmpu for both nominal and real yields is modest, certain FOMC announcements caused large changes in uncertainty, as documented in Section 3. For example, mpu dropped by 13.6 bps around the 9 August 2011 FOMC meeting, and our estimates indicate that this change in mpu accounted for almost half the actual decline of 20 bps in the nominal and 18 bps in the real 10 year Treasury yield on that day. In Section 4.3 below we discuss a risk-based mechanism for understanding the effects of changes in uncertainty on long-term yields.

Estimates for our third specification reveal that the response of nominal and real bond yields to *mps* depends on the level of monetary policy uncertainty on the day before the FOMC meeting (mpu_{-1}). The interaction coefficients are negative, meaning that yields respond more strongly to monetary policy surprises when uncertainty is low. To gauge the magnitude of the effect, we use the 25^{th} and 75^{th} percentiles of *mpu* to classify "low" and "high" uncertainty periods. In response to a 100 basis point contractionary monetary policy surprise, the five-year (ten-year) nominal yield increases by 83 (56) bps when uncertainty is low but only by 48 (35) bps when uncertainty is high. The dependence of the real yield response on uncertainty is even more pronounced. The five-year (ten-year) real yield increases by 91 (69) bps when uncertainty is low but only by 20 (19) bps when uncertainty is high. In Section 4.3 we provide an explanation of this result using a signal extraction framework.

In addition to the effects on Treasury yields, monetary policy uncertainty also matters for asset prices throughout the financial markets. Table 5 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 relative to Bernanke and Kuttner (2005) and Gürkaynak et al. (2005b).[34] More importantly, the next two columns show that stock prices fall when monetary policy uncertainty rises. A one standard deviation increase in *mpu* reduces stock prices by 0.3%, indicating that the effect is economically meaningful in addition to being statistically significant.

Table 5 also documents that the VIX and thus stock market volatility 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 0.7 percentage points. Moreover, accounting for uncertainty increases the R^2 of the VIX regression to 0.22 compared to only 0.04 with just the policy surprise. Our results

[34] 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 (2019). But using the higher frequency policy surprise does not affect how stock prices respond to uncertainty, which is the main focus here.

Table 5: Transmission of uncertainty to stock and foreign exchange market

	S&P 500			VIX			Dollar Index		
mps	-3.44	-1.72	-10.67	4.26	-0.09	16.68	2.56	1.80	11.75
	[-3.68]	[-1.41]	[-3.19]	[2.95]	[-0.04]	[3.01]	[4.36]	[2.84]	[4.41]
Δmpu		-8.74	-10.93		22.13	26.74		3.72	5.93
		[-1.77]	[-2.18]		[1.72]	[1.96]		[1.94]	[3.84]
mps x mpu_{-1}			8.39			-15.68			-9.15
			[2.74]			[-2.71]			[-4.39]
R^2	0.06	0.10	0.14	0.04	0.15	0.22	0.13	0.15	0.33

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 Section 4 for details), on the monetary policy surprise (mps), the change in uncertainty (Δmpu), and the policy surprise interacted with the ex-ante level (measured on day before announcement) of uncertainty (mpu_{-1}) on scheduled FOMC announcement days. In the third specification we also include mpu_{-1} but don't report its coefficient to economize on space (as for all estimated constants). In brackets are t-statistics based on White heteroscedasticity-robust standard errors. The sample contains 191 scheduled FOMC announcements from Janury 1994 to October 2019, excluding the period from July 2007 to June 2009 containing the Global Financial Crisis. For the regressions using the dollar index, the sample ends in December 2017 due to data availability.

here and in Section 3.3 suggest that changes in monetary policy uncertainty are a crucial factor driving changes in the VIX around FOMC announcements.

To estimate the transmission of uncertainty to the foreign exchange market we use a US dollar index, calculated as a foreign exchange portfolio that goes short the G9 currencies and long the US dollar.[35] Due to data availability, the sample for the exchange rate regression ends in December 2017. 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 the US dollar. Again, the table shows a statistically significant and economically meaningful additional impact of Δmpu. A one standard deviation rise in uncertainty leads to an appreciation of the US Dollar index by 0.15%.

The level of uncertainty plays an important role in the transmission of monetary policy surprises to stock and foreign exchange markets as well. For all three asset prices, the interaction coefficients are statistically significant and imply substantial differences in responses

[35] 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, as in Lustig et al. (2011).

depending on whether uncertainty is high or low. The asset price response is more muted when uncertainty is high. For example after a 100 bps contractionary *mps*, stock prices fall 6% when uncertainty is low (25^{th} percentile) but only by 1.5% when uncertainty is high (75^{th} percentile).

The results presented in Table 4 and 5 are robust across a variety of specifications. In our baseline sample, we excluded announcements that were either unscheduled or occurred in the financial crisis period. Including these two sets of dates does not materially change the results (not shown). The results are also robust to different choices of the monetary policy surprise. Using higher-frequency (30-minute window) or lower-frequency (2-day window) changes has little effect on our results (not shown). In Appendix Section D we report two additional sets of robustness checks. First, we follow the specification of Hanson and Stein (2015) which studies the effect of FOMC announcements on nominal and real forward rates using changes in the 2 year yield as *mps*. Table D.1 shows that results are similar for both the effect of changes in uncertainty and the interaction effects with *mps*. Second, in Table D.2 we report results for a specification that uses the target and path factors of Gürkaynak et al. (2005b), who showed that two separate factors are useful for accurately characterizing monetary policy surprises. Again, the results are similar, both for changes in uncertainty and for the interaction effects. Even when controlling for the policy surprise, i.e., for shifts in first moments, in this more flexible two-dimensional way, there is a clear separate role for uncertainty and second moments in the monetary policy transmission.

4.2 Unconventional monetary policy announcements

The results presented in this section excluded the Global Financial Crisis period. Of course, this was an episode where the FOMC started unconventional policies like quantitative easing (QE) and relied more on other unconventional policies like 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 major FOMC announcements, following a large and growing literature including, among many others, Gagnon et al. (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 we follow Raskin (2013) and Swanson (2017).

Table 6: 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	-0.10	-0.17	-0.22	-0.21	0.65	-3.80	-0.67
12/16/2008	QE1/FG	-0.13	-0.32	-0.16	-0.17	5.01	-4.39	-2.35
3/18/2009	QE1/FG	-0.08	-0.27	-0.47	-0.52	2.06	-0.74	-2.82
11/3/2010	QE2	-0.03	0.00	-0.04	0.04	0.37	-2.01	-0.56
8/9/2011	FG	-0.14	-0.05	-0.19	-0.21	4.63	-12.94	-1.54
9/21/2011	MEP	0.00	0.06	0.02	-0.08	-2.98	4.46	1.64
1/25/2012	FG	-0.02	0.00	-0.09	-0.08	0.86	-0.60	-0.46
9/13/2012	QE3/FG	-0.02	0.00	-0.04	-0.03	1.62	-1.75	-0.54
12/12/2012	FG	0.00	0.01	0.02	0.06	0.04	0.38	-0.21
6/19/2013	Taper Tantrum	0.01	0.04	0.17	0.14	-1.39	0.03	0.93
12/17/2014	FG	-0.01	0.03	0.08	0.08	2.01	-4.13	0.97
3/18/2015	FG	-0.04	-0.08	-0.15	-0.12	1.21	-1.69	-1.90
9/17/2015	FG	-0.04	-0.08	-0.12	-0.09	-0.26	-0.21	-0.53
Std. dev. (full sample)		0.03	0.08	0.09	0.08	1.15	2.09	0.49

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.

The event-study estimates in Table 6 show that changes in policy uncertainty are a highly relevant second dimension of the Fed's recent unconventional policy announcements, including 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). These announcements also lowered the uncertainty around the expected policy path very substantially, as mpu fell by about 3-4 standard deviations, including the decline of about 13 bps on December 16, 2008, which is the second largest drop in our sample. Thus, signaling worked not only through first but also through second moments of the perceived distribution of future policy rates, which may help explain the very large effects on other asset prices.[36] Another major FOMC policy action was the introduction of calendar-based FG on August 9, 2011, which caused a modest dovish policy surprise but a dramatic decline in policy uncertainty, indeed the 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 and significant asset price responses to the Fed's explicit FG language can be explained by the dramatic shift in the second moment of the perceived distribution of the future policy rate: The policy rate was already at the zero lower bound and thus changes in the second moment caused by the FOMC announcement became particularly important. Similarly, other FG announcements also generally reduced policy uncertainty and supported financial market conditions. On the flipside, 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 *mpu* increased, Treasury yields jumped and stock prices dropped. Finally, the SEP releases coinciding with the FOMC announcements in March and September 2015, discussed in more detail in Swanson (2017), featured dovish interest rate projections relative to market expectations, and lowered both the expected path as well as the uncertainty around this path. Long-term Treasury yields fell significantly in response, a final example of the impact of forward guidance on asset prices—this time in the form of the SEP dot plot—through changes in the second moments of the distribution of future policy rates.

[36] 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.

4.3 Understanding the asset price response

We have documented two channels through which uncertainty matters for monetary transmission to financial markets, related to (i) changes in uncertainty due to the FOMC announcement, and (ii) the prevailing level of uncertainty before the FOMC announcement. Here we provide possible explanations for these two channels.

The first channel is that higher uncertainty lowers bond prices, stock prices, and the value of foreign currencies vis-a-vis the dollar (since yields and the dollar value rise). A simple risk-based explanation provides a rationale for this channel. Standard asset pricing theory implies that expected excess returns depend on the negative covariance of returns with the stochastic discount factor (SDF). As pointed out by Hanson and Stein (2015), the factors driving this covariance are the uncertainty about future returns, the uncertainty about the SDF, and the correlation. Our results are consistent with effects of higher uncertainty on risk premia: If changes in uncertainty about future short rates (*mpu*) are related to uncertainty about the returns of the above-mentioned asset classes, then higher short-rate uncertainty raises expected excess returns/risk premia and lowers asset prices.[37]

In Table 7 we provide evidence that is supportive of this risk-based explanation. It shows that estimates of the term premium in five- and ten-year Treasury yields, taken from Kim and Wright (2005)and Adrian et al. (2013) exhibit a strong positive response to changes in *mpu*. These results are generally consistent with the findings of Bundick et al. (2017), who estimate positive effects of changes in monetary policy uncertainty on term premia in Treasury yields.[38]

[37]Specifically, for gross return R_{t+1}, risk-free rate R_t^f, and SDF M_{t+1}, absence of arbitrage implies

$$E_t R_{t+1} - R_t^f = -Cov_t(M_{t+1}, R_{t+1})/E_t M_{t+1}.$$

The risk premium increases and the current asset price declines if the covariance between M_{t+1} and R_{t+1} becomes more negative, which could arise due to (a) higher $\sigma_t(R_{t+1})$, (b) higher $\sigma_t(M_{t+1})$, (c) a more negative correlation, or a combination of these factors. If higher *mpu* coincides with higher conditional return volatility $\sigma_t(R_{t+1})$ then asset prices will fall. Another risk-based channel could work through higher $\sigma_t(M_{t+1})$, which would simultaneously raise both the variance risk premia inherent in our *mpu* measure as well as the risk premia in all other financial assets.

[38]There are several differences between our empirical frameworks, including the dependent variable, the uncertainty measure, the sample choice, and most importantly the fact that we control for changes in the expected policy path, measured by *mps*, which is important since changes in first and second moments of

Table 7: Response of term premia to monetary policy uncertainty

	ACM Term Premium				KW Term Premium			
	5 year		10 year		5 year		10 year	
mps	0.09	0.00	0.00	-0.12	0.21	0.16	0.22	0.16
	[2.09]	[-0.06]	[0.03]	[-1.72]	[9.67]	[6.20]	8.75	[5.10]
Δmpu		0.49		0.60		0.24		0.32
		[2.72]		[2.56]		[2.27]		[2.48]
R^2	0.03	0.11	0.00	0.06	0.37	0.42	0.30	0.37

Regressions of daily changes in term premia on 5 and 10 year Treasury yields (ACM from Adrian et al. (2013) and KW from Kim and Wright (2005)) on the monetary policy surprise mps and the change in uncertainty Δmpu on FOMC announcement days. Constants are included in the regressions but not reported here. In brackets are t-statistics based on White heteroscedasticity-robust standard errors. The sample contains 191 scheduled FOMC announcements from January 1994 to October 2019, excluding the period from July 2007 to June 2009 containing the Global Financial Crisis.

They suggest that higher uncertainty affects asset prices by raising risk premia.

Our estimates of the asset price effects of changes in mpu are therefore consistent with a risk-based explanation from standard asset pricing models. In addition, our findings may also contribute to an explanation of the effects of the conventional monetary policy surprise (mps) on asset prices, which the literature has found to be surprisingly large (Gürkaynak et al., 2005a; Hanson and Stein, 2015). Since conventional policy surprises are positively correlated with changes in uncertainty, additional effects of these surprises on asset prices may come from indirect effects of uncertainty on risk premia. While Hanson and Stein (2015) question that policy surprises increase term premia by changing uncertainty based on the observation that "little evidence exists for it in the data" (p. 442), we have provided exactly this evidence in Figure 4. Moreover, Tables 4 and 5 show that the response of asset prices to mps declines once we control for Δmpu in the event study regression. Accounting for changes in monetary policy uncertainty can provide an explanation for the puzzle why policy surprises cause such large swings in asset prices.

The second channel we document is that high policy uncertainty mutes the effects of a monetary policy surprise on asset prices, while low uncertainty leads to a significantly

future short rates are correlated (see Section 3).

stronger impact. This result can be rationalized using the logic of signal extraction (for a formal argument, see Appendix E). Market participants form their forecasts of future asset prices and fundamentals based on a variety of signals, including signals from the Fed about the expected path of future policy rates. Under general conditions, the weight put on the signal from the Fed increases in the precision of that signal. Thus when monetary policy uncertainty is low (precision of the signal is high), market participants will revise their forecasts more in response to the information in the public signal (i.e. policy surprise). Vice versa, in the presence of high policy uncertainty, signals from the Fed are less precise and thus elicit a more muted reaction of asset prices.

Recent work by Benamar et al. (2019) documents a seemingly contradictory result, that asset prices respond more strongly to macroeconomic news when uncertainty is high. However, this result is based on a fundamentally different uncertainty measure, related to investors' information demand and their private signals, rather than the variance of a public signal. The theoretical framework in Benamar et al. (2019) is consistent with the implication that asset prices respond more strongly to news when the public signal is more informative.

Our results in Table 4 are consistent with recent results of De Pooter et al. (2018), who also document a stronger response of Treasury yields to monetary policy surprises when market-based uncertainty is low. While De Pooter et al. (2018) point to the risk-taking behavior of financial intermediaries in the Treasury bond market as a possible explanation, our results in Table 5 document similar patterns for stock and foreign exchange markets. Our simple signal-extraction logic has the appeal that it provides an explanation for the empirical relevance of uncertainty across different asset markets.

5 Conclusion

While the macro-finance literature has mainly studied the effects of changes in the first moment of the distribution of the future policy rate, this paper provides new evidence that the second moments of this distribution also have important consequences for financial markets. FOMC announcements have substantial effects on uncertainty: on average they tend to lower it as part of a systematic FOMC uncertainty cycle, but depending on the nature of the announcements they have differential effects on uncertainty. Monetary policy uncertainty matters for the transmission of policy actions to financial markets in two ways: 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 larger effects on asset prices when monetary policy uncertainty is lower. Taken together, this evidence indicates the presence of an uncertainty channel of the transmission of monetary policy to financial markets.

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 et al. (2019) and Bundick et al. (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.

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Appendix

A Derivation of mpu

To derive an expression relating variance to market prices, first note that

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

The last equality in equation (A.1) follows from the fact that any forward price is a martingale under the forward-T measure.[39] Similar to Martin (2017), we use the fact that $x^2 = 2\int_0^\infty \max(0, x-K)dK$ for any $x \geq 0$, and obtain

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

Plugging this expression into equation (A.1) yields

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

The second line uses put-call-parity $c_{t,T}(K) - p_{t,T}(K) = P_{t,T}(F_{t,T} - K)$.

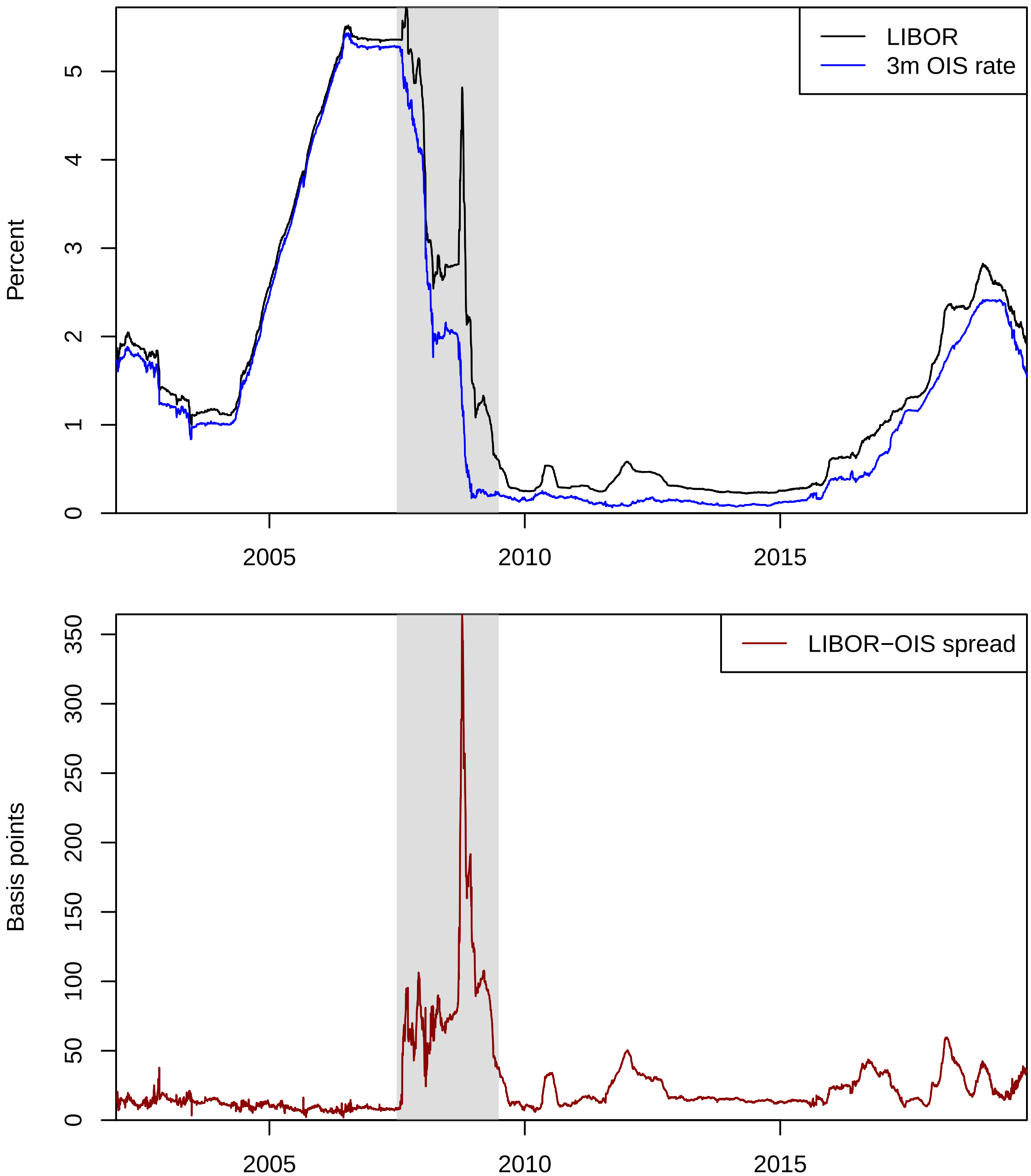
B LIBOR-OIS spread

The LIBOR-OIS spread is the the difference of between three-month LIBOR and a three-month rate closely tied to the fed funds rate. The fed funds rate measures the rate on overnight loans, hence it is not comparable to three-month LIBOR. 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.

Figure B.1 plots three-month LIBOR and OIS rates in the top panel, and the spread between these rates in the bottom panel. The data for these series comes from Bloomberg, and due to limited availability of historical data for OIS rates we start this sample in January 2002. The shaded area corresponds to the period from July 2007 to June 2009, the episode of elevated financial stress and an abnormally large LIBOR-OIS spread which for the purpose of

[39] Here we treat $F_{t,T}$ as a forward price, although Eurodollar futures have daily settlement and $F_{t,T}$ is a futures price (and thus a martingale only under the risk-neutral measure).

Figure B.1: Three-month LIBOR and OIS rates



Shaded area: July 2007 to June 2009. Sample period: January 2002 to October 2019.

Table B.1: Summary statistics for LIBOR-OIS and one-year *mpu* (in basis points)

	LIBOR-OIS		*mpu*
Subsample	Mean	SD	Mean
Jan-2002 to Jun-2007	11	4	102
Jul-2007 to Jun-2009	89	59	82
Jul-2009 to Oct-2019	20	9	85

Sample period: January 2002 to October 2019.

this paper we consider to be the financial crisis period. Table B.1 reports summary statistics for the LIBOR-OIS spread for the period before, during and after the financial crisis.[40]

C Additional results for Section 3

C.1 Resolution of uncertainty and FOMC pre-announcement drift

We investigate the relationship between changes in uncertainty and the pre-announcement drift. Hu et al. (2019) document a tight link between drop in the VIX and the pre-FOMC stock market drift, in line with the finding that the VIX falls before the announcement. By contrast, there is only a very weak link between changes in *mpu* and the pre-FOMC drift, as shown in Table C.1. For the Lucca and Moench (2015) sample, the coefficient is statistically significant, but for the period from 1994 to 2017 the coefficient is insignificant. In both sample periods, the R^2 is very low, and for the 1994-2017 period it is only 0.01. In addition to the weak correlation, the size of the effect is also small: For the 1994-2017 period a pre-FOMC drift of around 50bps is associated with a drop in the *mpu* of only 0.3 bps. Recall that the average fall in *mpu* is 1.7 bps and the standard deviation is 2.6 bps. We have also rerun our main results orthogonalizing our Δmpu measure with respect to the pre-FOMC stock market drift and found essentially identical results. Thus overall, most of the variation in *mpu* appears to be unrelated to the pre-announcement drift in the stock market, consistent with the view that policy uncertainty changes after the release of the statement.

C.2 Macroeconomic data releases and policy uncertainty

Here we show the impact of macroeconomic data releases on policy uncertainty, and compare them to FOMC announcements. Table C.2 reports in the first column the results of a regression of daily changes in *mpu* on dummies for days with six major macro news releases, as well as for scheduled FOMC announcements. Some macro releases also lead to a significant decline in uncertainty, but of smaller magnitude than scheduled FOMC announcements. Among the macro releases, the employment report is associated with the largest decline of 1.0 bps, which

[40]The standard deviation of one-year changes in the LIBOR-OIS spread, arguably the statistic that is most closely comparable to our conditional one-year-ahead standard deviation of future LIBOR, was generally similar to the standard deviation of the level of the LIBOR-OIS spread.

Table C.1: Change in monetary policy uncertainty and pre-FOMC drift

	Jan-1994 to Dec-2017	Jan-1994 to Mar-2011
	excl. crisis	incl. crisis
pre-FOMC drift	-0.004	-0.006
	[-1.64]	[-3.72]
Constant	-0.016	-0.020
	[-7.42]	[-7.96]
R^2	0.010	0.059
Observations	176	138

Regression of change in monetary policy uncertainty on the pre-FOMC drift in the stock market on scheduled FOMC days. The pre-FOMC drift is measured as the cumulative change in the S&P 500 futures index in a 24 hour window leading up to the announcement time (typically 2:15pm). The first column covers a sample from January 1994 to December 2017, excluding the period from July 2007 to June 2009 covering the global financial crisis. The second column shows results for the sample of Lucca and Moench (2015), from January 1994 to March 2011. In brackets are t-statistics calculated using White heteroskedasticity-robust standard errors.

is strongly significant. However, this is still only about half as large as the decline due to scheduled FOMC meetings of 1.8 bps. No macro release leads to a similarly large resolution of uncertainty as FOMC announcements.

This result is also confirmed by regressions when we include the actual surprise component of the news release interacted with the dummies. The news surprise for macro announcements are the standardized differences between the data release and the consensus expectations.[41] The second column shows that after controlling for the average change in *mpu* on news days, the surprise itself does not have big effects on uncertainty. The third column replaces the surprise with the absolute value of the surprise. Larger surprises on FOMC days reduce *mpu*, but there is no systematic relationship between large macroeconomic news surprises and changes in *mpu*. Overall, this evidence shows that FOMC announcements are far more important for short-rate uncertainty than macroeconomic news.

C.3 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 C.3 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.

[41] The consensus expectations are available from the widely used survey by Action Economics, the successor to Money Market Services.

C.4 FOMC dummy regressions across contracts

To focus on the differences between days with FOMC meetings and other days, Table C.4 shows results for regressions of $epe_{t,T}$ (top panel) and $\Delta mpu_{t,T}$ (bottom panel) on a dummy for FOMC days.[42] The dummy coefficient in the top panel indicates a sizeable and highly significant average jump variance, ranging from 0.008 to 0.04, which in volatility terms is 9 to 20 bps. The bottom panel shows that the average decline in uncertainty around FOMC meetings is significantly larger than on other days, consistent with Table 1.

According to our model non-FOMC days only experience diffusion variance $\delta\sigma^2$, but more generally these days also exhibit jumps in interest rates, mainly due to macro announcements such as the release of the employment report by the Bureau of Labor Statistics (Johannes, 2004; Kim and Wright, 2014). The estimates in Table C.4 indicate that FOMC jumps lead to much larger changes in market-based variance than on other days, even though many of these other days also include jumps.

C.5 Jump risk premia

If market-based estimates of jump variances differ from actual, real-world variance of FOMC jumps, this would suggest that investors require compensation for bearing jump risk that drives a wedge between the two. It turns out that market-based volatility around FOMC announcements is indeed substantially larger than historical volatility, suggesting the likely presence of jump risk premia. Using the variance estimates reported in the top panel of 2, the implied market-based volatilities range from 10 to 21 basis points for the mean, and from 7 to 16 bps for the median.[43] By contrast, over our sample of 176 FOMC meetings, the standard deviations of daily changes in three-month LIBOR, the three-month T-bill rate and the two-year Treasury yield is only 1.6, 4.5 and 5.2 basis points, respectively.[44] The fact that historical volatilities are so much smaller than, and less than half as large as market-based volatilities is quite striking. Given the pronounced interest rate risk investors are exposed to around FOMC announcements, it seems plausible that jump risk premia play a role in accounting for this difference.[45] However, changes in future jump variance beliefs are another factor that likely

[42] The estimated intercept in Table C.4 shows that for any specific Eurodollar contract, the average change in variance/mpu on non-FOMC days is negative. The reason is the fixed expiration date for each contract which leads to a decline in option-based uncertainty as the maturity of the contract decreases. Because for our one-year mpu measure the horizon is constant by construction, so in Table 1 there is no mechanical decline due to a shortening horizon.

[43] For an accurate comparison, we want to capture the whole market-based volatility around FOMC announcements, including not only the jumps but also the diffusion part. Thus we use the means/medians for changes in market-based variances in Table 2, instead of the regression coefficients in Table C.4.

[44] Intraday changes in the yields for on-the-run three-month and two-year Treasury yields around the FOMC announcements have standard deviations of 3.3 and 4.8 bps, respectively. Changing the sample period to include the crisis period and/or unscheduled meetings only marginally increases the standard deviations.

[45] In a similar comparison of option-based and historical jump volatilities for stock returns around earning announcements, Dubinsky et al. (2018) find that return volatility under the market-based measure is 8.2% and thus slightly higher than the return volatility under the phyiscal measure of 7.4%. Our relative differences in volatility are an order of magnitude larger, suggesting that jump risk premia are quantitatively much more important for interest rate movements around FOMC announcements than they are for stock returns around company earnings announcements.

contributes to changes in market-based variances, see equation (4). These changing beliefs may therefore also be part of the explanation why market-based estimates of jump variances are substantially larger than historical jump variances.

To obtain sharper evidence on the presence of jump risk premia we ask whether investors can profitably exploit the pattern we have documented using an option-trading strategy. If the market-based jump volatilities are truly larger than historical jump volatilities, then writing straddles should be a profitable strategy, similar to the case of earnings announcements in Dubinsky et al. (2018). We calculate returns on straddle positions around scheduled FOMC announcements, that is, on a position including both a call and a put contract with the same, at-the-money strike price. Table C.5 reports summary statistics for both relative returns and absolute returns for this option strategy. Average returns are significantly negative, with mean relative returns ranging from about -2 to -9 percent across Eurodollar contracts (with larger negative returns at short horizons, due to smaller straddle prices), and mean absolute returns around -1.4 basis points. There is some skewness, with median returns slightly above mean returns, and high excess kurtosis as often observed in daily financial market returns. The key statistic is the Sharpe ratio, which we calculate for a short straddle strategy and annualize in the same way as Lucca and Moench (2015) using $\sqrt{8}$ times the per-meeting Sharpe ratio, since there are typically eight scheduled FOMC meetings per year. The Sharpe ratios are large, ranging from about 1.4 at longer contracts to 2.1 at shorter contracts, suggesting high risk-adjusted average returns to short straddle positions around FOMC meetings.[46] By comparison, the pre-FOMC announcement returns in Lucca and Moench (2015) have annualized Sharpe ratios around 1.1. These results suggest that investors might potentially be able to profitably exploit the systematic declines in interest-rate uncertainty round FOMC announcements, consistent with the presence of FOMC jump risk premia.

Like Dubinsky et al. (2018), we do not systematically account for transaction costs in our calculation, as our data includes daily settlement prices but not bid/ask prices. At-the-money option contracts for near-term expirations—those where short straddles are most profitable—tend to be the very liquid. While bid-ask spreads tend to be on the order of 0.5 to 1.0 basis points and would seem to eat up most of the returns. trading costs in liquid option markets tend to be much lower than quoted bid-ask spreads (Muravyev and Pearson, 2016). We leave a more detailed analysis of the profitability of our proposed trading strategy to practitioners and future research.

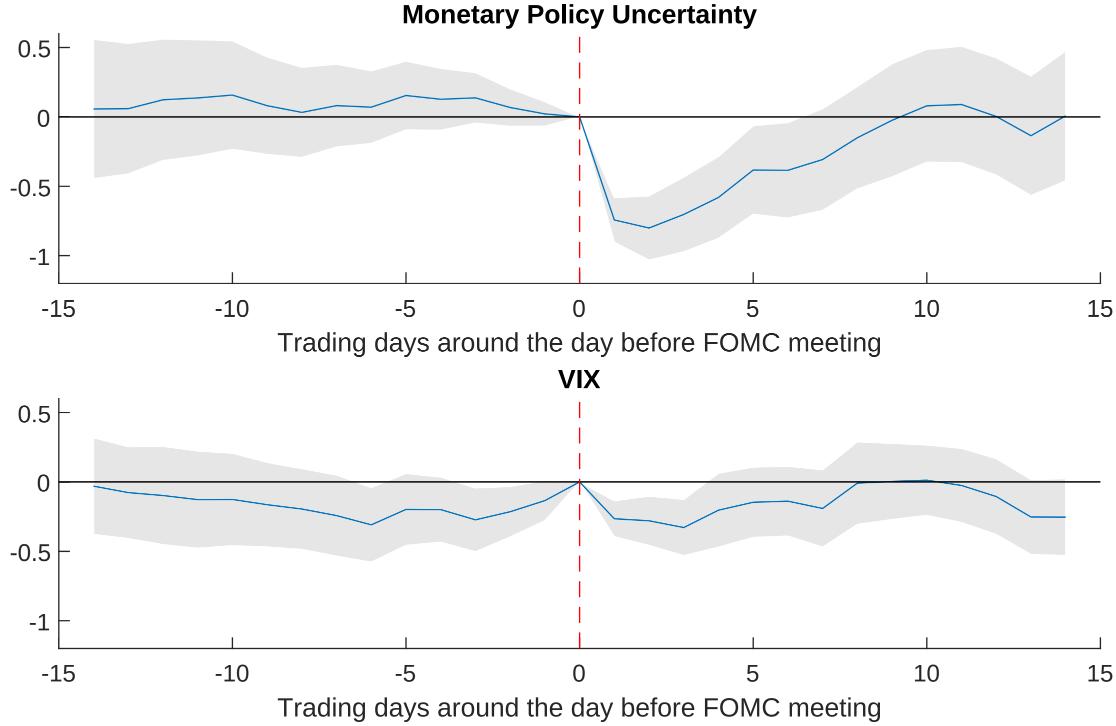
C.6 FOMC uncertainty cycle and VIX

Here we investigate how changes in *mpu* over the FOMC meeting cycle compare to changes in the VIX. Figure C.1 plots 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.

Fernandez-Perez et al. (2017), Amengual and Xiu (2018) and Gu et al. (2018) show that the VIX tends to fall on FOMC days, but the decline in policy uncertainty is substantially larger. The average one-day decline in the VIX is about 0.4 standard deviations, while *mpu* falls on average by about 0.8 standard deviations after FOMC announcements. A plausible

[46] In additional, unreported results we have found very similar results for separate pre- and post-crisis samples (with slightly larger Sharpe ratios before than after the crisis).

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

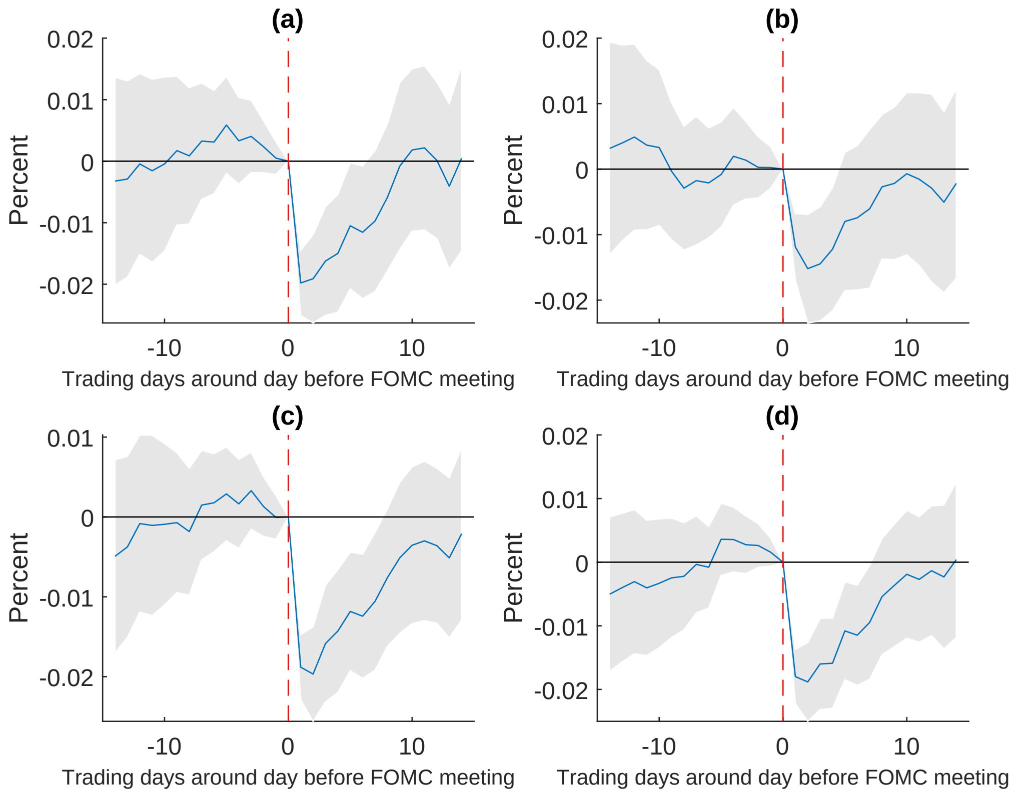


The figure shows the average change in monetary policy uncertainty (top panel) and VIX (bottom panel) on trading days around the FOMC announcement, relative to the day before the FOMC announcement day (shown with dashed red line). Both series are normalized to show changes relative to the standard deviation 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 191 scheduled FOMC announcements from January 1994 to October 2019.

explanation for the much larger decline in *mpu* is that it more directly measures the uncertainty about monetary policy, whereas there are many drivers of uncertainty in the stock market, including not only uncertainty about interest rates/discount rates but also about future cash flows/earnings, as well as shifts in investor sentiment. The FOMC directly controls short-term interest rates, whereas its effects on the stock market are much less immediate. This argument supports the conclusion that changes in monetary policy uncertainty around FOMC announcements are an important underlying driver of changes in stock market uncertainty as measured by the VIX.

A second crucial difference lies in the ramp-up pattern for the VIX vs. *mpu*. The VIX typically increases in the days shortly before an FOMC meeting, consistent with the results documented in Hu et al. (2019). This contrasts with the pattern for *mpu*, which tends to increase over the two weeks after an FOMC meeting.

Figure C.2: 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 October 2019. Panel (c) uses the full sample including the crisis period and 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.

C.7 Robustness of pattern over FOMC meeting cycle

The pattern of on FOMC uncertainty cycle is robust across a variety of dimensions. We present four robustness checks in figure C.2. 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 October 2019. 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 including both the financial crisis period and including unscheduled meetings, 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.

D Additional results for Section 4

Tables D.1 and D.2 present additional results for the transmission of monetary policy uncertainty to financial markets.

E Signal extraction model for understanding interaction effects

Consider that market's prior belief (before the FOMC announcement) about an asset's (unobservable) payoff y given by

$$y \sim N(\mu_y, \sigma_y^2) \tag{E.1}$$

The FOMC meeting announcement is represented by a public signal x

$$x = y + \eta, \quad \text{with } \eta \sim N(0, \sigma_\eta^2) \tag{E.2}$$

After observing the public signal, the market's updated expectation about the payoff is

$$E(y|x) \;=\; \frac{\sigma_\eta^2}{\sigma_y^2 + \sigma_\eta^2}\mu_y + \frac{\sigma_y^2}{\sigma_y^2 + \sigma_\eta^2}x \tag{E.3}$$

The market's expectation is a weighted average of their prior information and the public signal with the weights depending on the informativeness of the two sources of information. The dependent variable in our regression analysis is the change in the asset price on FOMC announcement days. This is captured by the update in the expectation for the asset payoff after observing the public signal given by

$$E(y|x) - E(y) = \frac{\sigma_y^2}{\sigma_y^2 + \sigma_\eta^2}\,[x - \mu_y] \tag{E.4}$$

where $[x - \mu_y]$ is surprise component of the public signal (i.e. monetary policy surprise). The regression with interaction coefficients measures how the response of asset prices to monetary policy surprise depends on the variance of the public signal (i.e. monetary policy uncertainty). Denoting $s_x = [x - \mu_y]$ and $s_y = (E(y|x) - E(y))$, it is straightforward to show that this interaction coefficient is negative.

$$\frac{\partial^2 s_y}{\partial s_x\,\partial\sigma_\eta^2} = \frac{-\sigma_y^2}{\left(\sigma_y^2 + \sigma_\eta^2\right)^2} < 0 \tag{E.5}$$

In other words, asset prices respond less to the information in the monetary policy surprise when the monetary policy uncertainty is high.

Table C.2: The response of monetary policy uncertainty to news releases

	Dummy	Surprise	Abs. surprise
Sched. FOMC	-0.018	0.012	-0.009
	[-8.83]	[4.97]	[-1.92]
Employment	-0.008	0.013	0.008
	[-3.96]	[3.44]	[1.21]
CPI	-0.002	0.002	0.003
	[-1.24]	[1.15]	[1.32]
PPI	-0.003	0.003	0.001
	[-2.76]	[2.46]	[0.39]
Retail Sales	-0.001	0.002	0.001
	[-0.85]	[1.90]	[1.01]
GDP	0.001	-0.001	0.006
	[0.37]	[-0.41]	[1.52]
ISM	0.006	0.003	0.001
	[3.77]	[2.12]	[0.36]
Constant	0.001	0.001	0.001
	[2.71]	[2.76]	[2.73]
R^2	0.035	0.066	0.043

Regression of change in monetary policy uncertainty on news release days. The first column reports results for a regression with dummy indicators for each news release. For the second column, we add the surprise components of the news release as regressors, and report the coefficients on the surprise component (the coefficients on the dummies are omitted). For "FOMC" the surprise is the first principal component of changes in futures rates, as explained in Section 3.1. For the macro releases, the surprise is the standardized difference between the released number and the consensus forecast from Action Economics/Money Market Services. For the employment report, we use non-farm payrolls, for CPI and PPI we use headline inflation, retail sales are the total sales including automobiles, "GDP" is the advance GDP release, and "ISM" is the Institute for Supply Management manufacturing survey. The third column reports results for a regression which uses absolute values of surprises instead of the actual surprises. The sample period is January 1994 to December 2017, excluding the period from July 2007 to June 2009 covering the Global Financial Crisis, with 5541 daily observations. In brackets are t-statistics calculated using White heteroskedasticity-robust standard errors.

Table C.3: Summary statistics for days with speeches by FOMC members

	All speeches	Greenspan	Bernanke	Yellen
Observations	2137	120	156	60
Mean	0.00	-0.00	0.00	-0.00
t-stat (mean)	0.71	-1.58	0.63	-1.23
Median	0.00	-0.00	0.00	-0.00
Standard deviation	0.02	0.02	0.03	0.01
Skewness	2.32	-0.45	-1.00	-1.15
Kurtosis	36.95	4.55	21.11	6.13
Minimum	-0.21	-0.06	-0.21	-0.06
Maximum	0.34	0.04	0.16	0.03
Cumulative change	0.74	-0.29	0.24	-0.13

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 speech days of the previous three Fed chairs. The sample period is from January 1994 to December 2017.

Table C.4: Comparing FOMC days to non-FOMC days across Eurodollar contracts

	ED1	ED2	ED3	ED4	ED5	ED6
Ex-post estimate of jump varianes						
Constant	0.001	0.002	0.003	0.004	0.005	0.005
	[11.47]	[10.77]	[9.19]	[8.31]	[7.20]	[5.98]
FOMC dummy	0.008	0.015	0.023	0.030	0.034	0.038
	[7.50]	[8.25]	[7.57]	[7.16]	[6.70]	[7.04]
R^2	0.032	0.024	0.020	0.016	0.013	0.012
Daily change in monetary policy uncertainty						
Constant	-0.003	-0.003	-0.003	-0.003	-0.002	-0.002
	[-15.63]	[-12.95]	[-10.95]	[-9.92]	[-8.71]	[-7.40]
FOMC dummy	-0.016	-0.016	-0.017	-0.016	-0.015	-0.015
	[-9.72]	[-10.47]	[-9.32]	[-8.69]	[-7.76]	[-7.67]
R^2	0.043	0.028	0.024	0.020	0.017	0.015
Observations	4655	5907	5909	5909	5909	5886

Regressions of changes in variance/uncertainty on dummies for FOMC meetings, for the ex-post estimate $epe_{t,T} = Var_{t-\delta}(F_T) - Var_t(F_T)$ in the top panel, and $\Delta mpu_{t,T} = \sqrt{Var_t(F_T)} - \sqrt{Var_{t-\delta}(F_T)}$ in the bottom panel. The sample period is from Jan-1994 to Oct-2019, excluding the period from Jul-2007 to Jun-2009 covering the Global Financial Crisis. The number of observations differs across contracts due to option data availability. In brackets are t-statistics calculated using White heteroskedasticity-robust standard errors.

Table C.5: Returns on Eurodollar option straddles around FOMC announcements

	ED1	ED2	ED3	ED4	ED5	ED6
Relative returns						
Mean	-9.0	-4.5	-3.0	-2.4	-2.1	-1.6
Median	-8.3	-4.2	-2.8	-2.2	-1.7	-1.4
SD	12	6.1	4.6	4	3.7	3.2
Skewness	-0.3	-0.5	0.2	-0.6	-3.3	-0.7
Kurtosis	5.4	7.3	7.2	20.3	24.4	15.2
t-stat	-10.4	-10.4	-9	-8.3	-8.1	-6.8
Sharpe ratio	2.1	2.1	1.8	1.7	1.6	1.4
Absolute returns						
Mean	-1.3	-1.4	-1.4	-1.4	-1.5	-1.3
Median	-1	-1	-1	-1	-1	-1
SD	1.8	2	2.3	2.3	2.5	2.4
Skewness	-0.7	-0.3	-0.3	-1	-1.3	-0.7
Kurtosis	6	6.6	5.7	6.4	7.6	6.4
t-stat	-10	-9.6	-8.3	-8.8	-8.5	-7.6
Sharpe ratio	2	1.9	1.7	1.8	1.7	1.5
Observations	193	197	197	197	197	193

Summary statistics for returns on option straddles with at-the-money contracts around scheduled FOMC meetings. The top panel reports relative returns in percent, and the bottom panel reports absolute returns in basis points. The holding period is one day, from the close on the day before the meeting to the close on the day of the meeting. The Sharpe ratios are calculated for short straddles and are annualized by multiplying by $\sqrt{8}$ because there are about 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. The sample period is from Jan-1994 to Oct-2019, excluding the period from Jul-2007 to Jun-2009 covering the Global Financial Crisis.

Table D.1: Hanson and Stein (2015) regressions for Treasury forward rates

	Nominal				Real			
	5 year		10 year		5 year		10 year	
mps	1.04	1.64	0.54	0.61	1.05	2.56	0.41	0.32
	[10.14]	[4.89]	[5.75]	[1.95]	[5.77]	[5.30]	[2.31]	[0.53]
Δmpu		1.25		0.60		1.04		0.48
		[4.09]		[1.68]		[4.00]		[1.56]
mps x mpu_{t-1}		-1.03		-0.25		-2.02		-0.03
		[-2.93]		[-0.72]		[-2.92]		[-0.05]
R^2	0.38	0.49	0.13	0.16	0.31	0.44	0.08	0.10

Event study regressions for forward rates on FOMC announcement days, using the variable definitions of Hanson and Stein (2015). Regressions of two-day changes in Treasury forward rates on (i) the monetary policy surprise mps (measured 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_{-1}). In the second specification we also include mpu_{-1} but don't report its coefficient to economize on space (as for all estimated constants). In brackets are t-statistics based on White heteroscedasticity-robust standard errors. The sample contains 151 scheduled FOMC announcements from February 1999 to October 2019, excluding the period from July 2007 to June 2009 containing the Global Financial Crisis.

Table D.2: Response of asset prices to uncertainty, controlling for target and path factor

	5 year yield	10 year yield	Stock	VIX	Dollar
Target Factor	0.87	0.20	-17.63	33.50	14.21
	[4.85]	[0.71]	[-2.93]	[3.41]	[3.10]
Path Factor	2.00	1.57	-5.58	-0.70	14.16
	[8.61]	[6.16]	[-1.04]	[-0.11]	[5.10]
Δmpu	0.46	0.56	-11.34	28.38	5.07
	[2.86]	[2.68]	[-2.20]	[2.04]	[3.43]
Target x mpu_{-1}	-0.09	0.22	13.61	-30.63	-10.61
	[-0.53]	[0.78]	[2.57]	[-3.17]	[-2.96]
Path x mpu_{-1}	-1.20	-0.95	5.23	-1.61	-11.50
	[-5.64]	[-3.88]	[0.97]	[-0.27]	[-4.96]
R^2	0.72	0.51	0.15	0.23	0.36

Regressions of daily changes in various asset prices on the target and path factor from Gürkaynak et al. (2005b), the change in uncertainty (Δmpu), and the target and path factors interacted with the ex-ante level (measured on day before announcement) of uncertainty (mpu_{-1}) on scheduled FOMC announcement days. We also include mpu_{-1} but don't report its coefficient to economize on space (as for all estimated constants). In brackets are t-statistics based on White heteroscedasticity-robust standard errors. The sample contains 191 scheduled FOMC announcements from January 1994 to October 2019, excluding the period from July 2007 to June 2009 covering the Global Financial Crisis. The dollar index sample (176 announcements) ends in December 2017.