Online Appendix for "Market-Based Monetary Policy Uncertainty"

Michael D. Bauer, Aeimit K. Lakdawala, and Philippe Mueller

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A Measuring short-rate uncertainty

A.1 Details of SRU calculation

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, one 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, $Var_t(L_T)$. This appendix derives an expression for $Var_t(L_t)$ and then explains the semiparametric method we use to empirically implement this measure.

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 expectations and variance operators. Under this measure the price p_t of a future payoff x_T is $p_t = P_{t,T}E_t(x_T)$, where $P_{t,T}$ is the price of a zero-coupon bond maturing at T. 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.

We now derive an expression relating conditional variance to market prices:

$$
\begin{aligned}
Var_t(L_T) = Var_t(F_{T,T}) &= E_t F_{T,T}^2 - (E_t F_{T,T})^2 = E_t F_{T,T}^2 - F_{t,T}^2 && (1)\\
&= \frac{2}{P_{t,T}} \int_0^\infty c_{t,T}(K) dK - F_{t,T}^2 \\
&= \frac{2}{P_{t,T}} \left(\int_0^{F_{t,T}} p_{t,T}(K) + P_{t,T}(F_{t,T} - K) dK + \int_{F_{t,T}}^\infty c_{t,T}(K) dK \right) - F_{t,T}^2 \\
&= \frac{2}{P_{t,T}} \left(\int_0^{F_{t,T}} p_{t,T}(K) + \int_{F_{t,T}}^\infty c_{t,T}(K) dK \right) && (2)\\
&= 2 \int_0^\infty \left[\frac{c_{t,T}(K)}{P_{t,T}} - \max(0, F_{t,T} - K) \right] dK. && (3)
\end{aligned}
$$

The last equality in the first line follows from the fact that any forward price is a martingale under the forward-T measure.[1] To obtain the second line we use the fact that $x^2 = 2\int_0^\infty \max(0, x - K)dK$ for any $x \geq 0$, so that $E_t F_{T,T}^2 = 2\int_0^\infty E_t \max(0, F_{T,T} - K)dK = \frac{2}{P_{t,T}} \int_0^\infty c_{t,T}(K)dK$. The third line uses put-call-parity $c_{t,T}(K) - p_{t,T}(K) = P_{t,T}(F_{t,T} - K)$.

Expression 2 shows that the conditional variance of future LIBOR can be written as a portfolio of out-of-the-money Eurodollar puts and calls, and it is similar to the well-known formula for the fair strike of a variance swap (e.g., equation (6) in Choi et al., 2017). Expression 3 is useful for implementation, and it resembles the formula for model-free implied volatility of Britten-Jones and Neuberger (2000) and Jiang and Tian (2005). The difference with those existing results is that we focus on the variance of the level, whereas those formulas apply to the variance of logs/returns.[2]

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.

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 puts and calls 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

[1] 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).

[2] Our result resembles the swaption-based conditional variance for swap rates in Trolle and Schwartz (2014).

Gürkaynak et al. (2007).[3] To accurately approximate the integral in (3) we obtain a smooth call-price function $\hat{c}(K)$ by translating observed option prices into Black (1976) implied volatilities (IVs), linearly interpolating the IVs, and translating the fitted IVs back into call prices. For strikes outside the range of observed option prices we use the IV at the bounds of the range. 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). With the smooth function in hand we then calculate the integral in 3 using the trapezoidal rule over a grid of 120 strikes in an interval of ± 3 around $F_{t,T}$.

The maturity of Eurodollar contracts follows a sea-saw pattern due to the fixed expiration dates. We use linear interpolation to construct constant maturities. Specifically, we linearly interpolate the conditional variances to obtain $Var_t(L_{t+h})$ for constant h. 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.

A.2 LIBOR-OIS spread

First we note that derivatives based on the Fed's policy rate, the federal funds rate, are available and could in principle be used for our purpose, eliminating concerns about spreads. But there are a number of practical reasons against using federal funds futures and options for our purpose, mainly that the liquidity and data availability of federal funds options is too limited. For these reasons most empirical work using money market options for analysis of monetary policy has focused on Eurodollar options (Neely, 2005; Swanson, 2006; De Pooter et al., 2021; Bundick et al., 2017).

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 this spread varies over time. 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. Specifically, the LIBOR-OIS spread is the difference between three-month LIBOR and the three-month OIS rate, which is closely tied to the fed funds rate. The reason is that 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

[3] 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.

reflect the market's (risk-neutral) expectation for the fed funds rate over this period.

Table A.1: Summary statistics for LIBOR-OIS and one-year SRU (in basis points)

	LIBOR-OIS		SRU
Subsample	Mean	SD	Mean
Jan-2002 to Jun-2007	11	4	102
Jul-2007 to Jun-2009	89	59	83
Jul-2009 to Oct-2019	20	9	82

Sample period: January 2002 to October 2019.

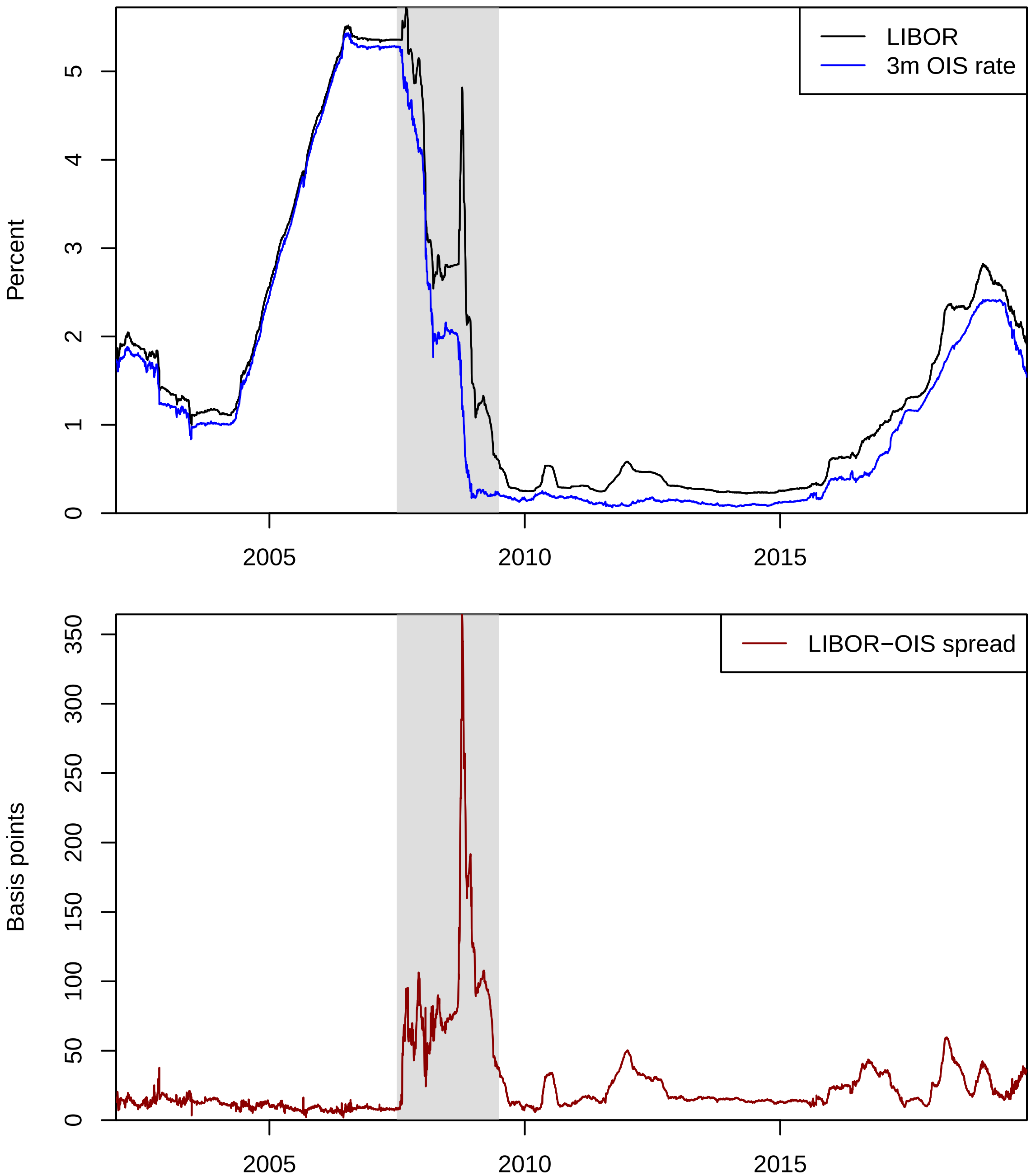
Figure A.1 plots three-month LIBOR and OIS rates in the top panel, and the spread between these rates in the bottom panel. The data for these series comes from Bloomberg, and due to limited availability of historical data for OIS rates we start this sample in January 2002. The shaded area corresponds 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 this paper we consider to be the financial crisis period. Table A.1 reports summary statistics for the LIBOR-OIS spread for the period before, during and after the financial crisis.[4] 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 SRU 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 SRU was thus less useful as a measure of uncertainty about the fed funds rate. 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).

A.3 Comparison of uncertainty measures

We compare our model-free measure of short-rate uncertainty, SRU, with the following alternative market-based measures of short-term interest uncertainty:

[4]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.

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



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

- Basis point volatility (BP vol) is the product of Black IV with the futures price. It is based on the assumption of log-normal prices and uses only ATM option prices in the IV calculation. As for SRU, we linearly interpolate this measure to a constant one-year horizon as well (by interpolating variances). BP vol is also known as "normalised" volatility and empirically almost identical to "normal volatility" which is based on the Bachelier model, that is, on the assumption of a normally distributed price. Because these two measures are almost identical, we only report results for BP vol.

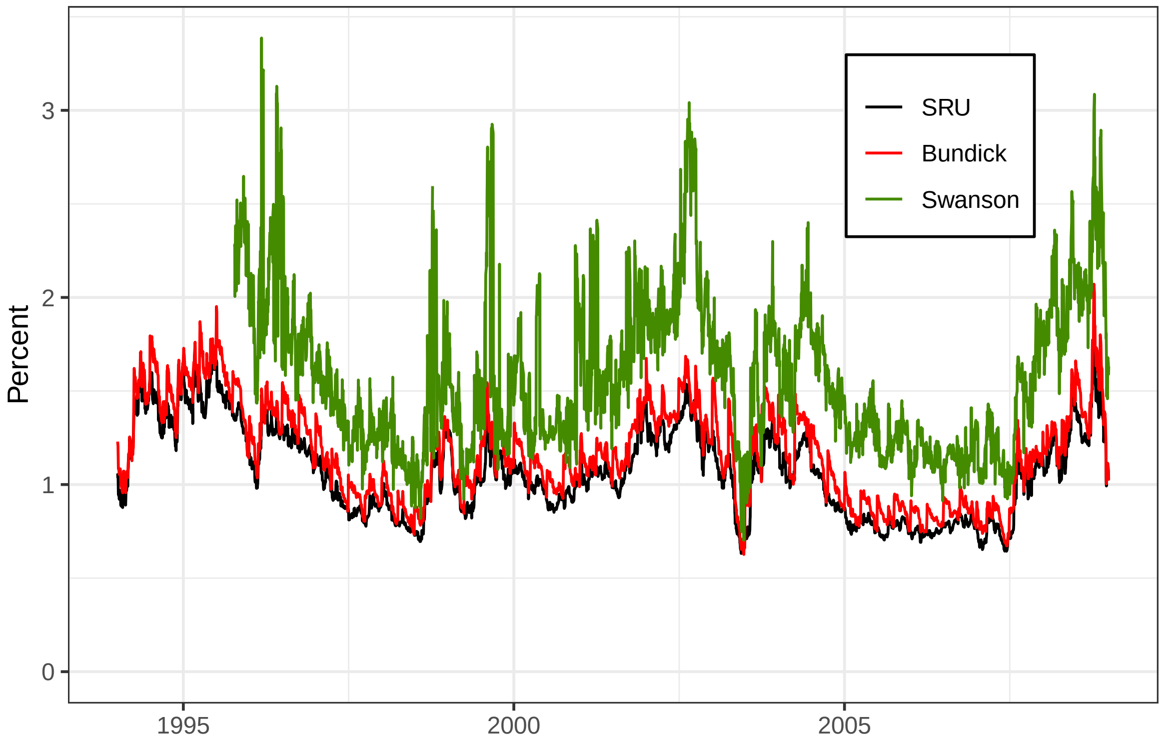
- Bundick et al. (2017) calculate a model-free IV by means of the well-known VIX formula, applied to Eurodollar futures prices. This yields the IV for futures returns, which however is close to the IV for changes in LIBOR, since percent changes and absolute changes are similar for Eurodollar futures prices (which tend to be close to 100). Similarly to our approach, the Bundick measure is also model-free, uses a range of prices across strikes, and, since it uses the VIX, is based on variance swap theory. For our comparison, we use their measure for the four-quarters-ahead Eurodollar contract.

- Swanson (2006) and Swanson and Williams (2014) also calculate a model-free uncertainty measure from Eurodollar option prices, but using a very different approach from ours. They approximate the entire risk-neutral distribution with a flexible non-parametric function, and then measure uncertainty as the interquintile range, i.e., the difference between the 80th and the 20th percentile of this distribution. We use their measure for the four-quarters-ahead Eurodollar contract.

In addition, our comparison in Section 2 of the paper also includes common market-based measures of uncertainty about medium- and long-term rates (e.g., 1y/10y swap rates and long-term Treasury yields).

Figure A.2 visually compares our SRU measure with the Bundick and Swanson measures, over the period from 1994 to 2008 where all three measures are available to us. We do not include BP vol in the figure because its level is very similar to SRU (see Table 1 of the paper). The Bundick measure is quite close to ours, but shows a seesaw pattern due to the changing horizon of the four-quarters-ahead Eurodollar contract. The Swanson measure also has such a seesaw pattern since it also uses a fixed contract, but in addition it is also much more volatile, likely because of the difficulty to approximate the tails of the risk-neutral distribution from the option prices. Measures like ours and the VIX have the benefit that they put weights on option prices that decline with the distance of the strike price from the futures price, and as a result these measures are less affected by measurement error in the tails.

Figure A.2: Alternative option-based uncertainty measures for future 3-month LIBOR



Three daily option-based uncertainty measures for future 3-month LIBOR. *SRU*: the risk-neutral standard deviation ay a one-year horizon. *Bundick*: the model-free IV measure for Eurodollar options from Bundick et al. (2017), approximately measuring uncertainty at a four-quarter horizon. *Swanson*: uncertainty measure of Swanson and Williams (2014) for a four-quarter horizon. Sample period: January 3, 1994, to December 31, 2008.

B Monetary policy vs. macroeconomic uncertainty

Uncertainty about future short-term interest rates reflects uncertainty about both the macroeconomic outlook and the conduct of monetary policy. Here we present some reduced-form analysis of the relationship between macro uncertainty and our short-rate uncertainty measure, as well as a discussion, based on a simple structural model, of the difficulties of obtaining a meaningful decomposition into these two fundamental sources of uncertainty.

A wide variety of measures has been used in the literature to study macroeconomic uncertainty; for an excellent survey see Cascaldi-Garcia et al. (2020). One particularly influential approach was proposed by Jurado et al. (2015) (JLN), who calculate an econometric measure of macro uncertainty based on the volatility of forecast errors for a wide variety of economic time series. An important advantage of this method is that—in contrast to other widely used uncertainty measures based on volatility or text analysis—it removes predictable variation in the data, and is thus consistent with a definition of uncertainty as the extent to which the future is unpredictable. Recently, a real-time version of this uncertainty measure was proposed by Rogers and Xu (2019), who observe that ex-post and real-time estimates of uncertainty using this method can differ quite a bit.

Table B.1 shows regressions of monthly averages of SRU on these macro uncertainty proxies. Over the full sample period from January 1990 to June 2020, the JLN measure is essentially uncorrelated with SRU. The Rogers-Xu measure however, which is only available from September 1999 to October 2018, is significantly positively related to SRU, with an R^2 of 0.36. For comparability, we also estimate the regression for the JLN measure over a sample period starting in 1999, which yields a significantly positive relationship and an R^2 of 0.31.

Table B.1: Regressions of SRU on macro uncertainty measures

	JLN	JLN	Rogers-Xu	SPF PGDP
Intercept	-0.35	-2.35	-0.55	0.47
	[0.20]	[1.77]	[1.37]	[2.78]
Slope	1.40	3.46	14.07	0.64
	[0.76]	[2.41]	[3.98]	[2.94]
R^2	0.04	0.31	0.36	0.16
Observations	366	258	230	123
Sample	Monthly	Monthly	Monthly	Quarterly
	1990:M1–2020:M6	1999:M1–2020:M6	1999:M9–2018:10	1990:Q1–2020:Q1

Regressions of SRU on different measures of macroeconomic uncertainty: the 12-month-ahead macro uncertainty measure of Jurado et al. (2015)(JLN), the corresponding real-time uncertainty estimate from Rogers and Xu (2019), and the dispersion in the four-quarter-ahead forecasts for the GDP price index in the Survey of Professional Forecasters (SPF). t-statistics in squared brackets are based on Newey-West standard errors with automatic lag selection.

We also consider wide variety of survey-based uncertainty proxies, using forecast dispersion in the quarterly Survey of Professional Forecasters for various macro variables and forecast horizons. The only measure that we found to have a significantly positive relationship with (quarterly averages of) SRU is the dispersion about the GDP price index.[5] This measure has an R^2 of 0.16.

These results suggest that some modest amount of the low-frequency variation in SRU could be driven by changes in macroeconomic uncertainty. But because the correlations are generally small, we have found that the residual short-rate uncertainty from these regressions

[5] All other measures we considered were not significantly correlated with SRU, with the only exception being the dispersion about the near-term forecasts for the level of nominal GDP, which were significantly negatively correlated with SRU.

generally still tends to exhibits the cyclical and trend behavior that is evident in Figure 1 of the paper. In any event, our main analysis generally focuses on uncertainty changes around FOMC announcements and not on these low-frequency patterns.

It is worth noting, however, that these reduced-form estimates may well overstate the importance of macroeconomic uncertainty for variation in short-rate uncertainty, for at least two reasons. First, the most popular macro uncertainty proxies, such as the one by JLN, are based on a wide range of macro time series that also include financial variables including interest rates. Because of this overlap, the correlation of "pure" macro uncertainty (i.e., uncertainty only about non-financial macroeconomic variables) is likely smaller than what we estimate. Second, there is also a causation running from monetary policy uncertainty to macroeconomic uncertainty, because uncertainty around the economic outlook is in turn affected by the actions and reactions of monetary policy. In other words, how unpredictable the future course of the macroeconomy is depends also on how unpredictable the central bank is. This is another reason why the strength of the statistical relationship between proxies for macro and short-rate uncertainty documented in Table B.1 likely overstates the true causal importance of macroeconomic uncertainty for SRU.

We can make these issues more concrete in the context of a simple structural model, the canonical three-equation New Keynesian model. The Phillips curve, IS curve and a monetary policy rule are:

$$\pi_t = \beta E_t \pi_{t+1} + \kappa y_t + u_t \tag{4}$$

$$y_t = E_t y_{t+1} + \gamma \left(i_t - E_t \pi_{t+1} \right) + g_t \tag{5}$$

$$i_t = \alpha \pi_t + \beta y_t + \varepsilon_t, \tag{6}$$

where π_t is inflation, y_t is the output gap, i_t is the short-term nominal interest rate, u_t is a supply or cost-push shock, g_t is a demand shock, and ε_t is a monetary policy shock. In this simple model, monetary policy uncertainty comes from ε_t while macro uncertainty comes from u_t and g_t. For simplicity, we are ignoring other potential sources of monetary policy uncertainty which could come from changes in the policy rule. The conditional variance of the short rate is

$$Var_t[i_{t+h}] = \alpha^2 Var_t[\pi_{t+h}] + \beta^2 Var_t[y_{t+h}] + Var_t[\varepsilon_{t+h}] + \text{covariance terms} \tag{7}$$

Clearly, short-rate uncertainty is driven by monetary policy uncertainty, but also by uncertainty about inflation and the output gap. This is the main reason why the time series of SRU cannot be interpreted as being driven only by monetary policy uncertainty. A more subtle issue is that macroeconomic variables are endogenous to monetary policy, and thus $Var_t[\pi_{t+h}]$ and $Var_t[y_{t+h}]$ are also affected by monetary policy uncertainty.[6] The consequence is that a decomposition of SRU into monetary policy and macro uncertainty could not be accomplished with a reduced-form analysis that uses empirical proxies for $Var_t[\pi_{t+h}]$ and $Var_t[y_{t+h}]$ to directly estimate equation (7). Such a decomposition, similar in principle to the regressions in Table B.1, would tend to overstate to important of macroeconomic uncertainty for short-rate uncertainty. An accurate decomposition using different uncertainty proxies would require estimation of a structural model. We view this as a promising avenue for future research.

An alternative approach for measuring policy uncertainty that has been used successfully in the literature is to estimate a policy rule such as equation (6) as a stochastic volatility model (Creal and Wu, 2017; Fernández-Villaverde et al., 2015). The estimated volatility series of the residual can then serve as a proxy for monetary policy uncertainty. This is a fundamentally different route than using market-based measures (or other observable proxies) of uncertainty about the policy instrument, as we do in our paper.

A separate issue is that both approaches—either using uncertainty proxies and an estimated structural model, or estimating equation (6) using stochastic volatility methods—require data that is generally available only at monthly or lower frequencies. Therefore, they are of little use for the purpose of our paper, which is to investigate *high-frequency changes* in monetary policy uncertainty around FOMC announcements and their role for the transmission of policy actions to financial markets.

C A simple model of FOMC jumps

We specify a simple model of short-term interest rates that treats FOMC announcements as short-rate jumps occuring at deterministic times, as in Piazzesi (2001). Our model is essentially the classic Bachelier model, in which asset price changes are normally distributed, augmented with deterministic jumps. We specify the model for the LIBOR rate L_t which follows the stochastic differential equation

$$dL_t = \sigma dW_t + dJ_t, \quad J_t = \sum_{j=1}^{N_t} Z_j, \tag{8}$$

[6] To see this more formally, gather the three variables into $Z_t \equiv (\pi_t, y_t, i_t)$ and the three shocks into $E_t \equiv (u_t, g_t, \varepsilon_t)$, the solution to this model can be written as $Z_t = \Psi Z_{t-1} + \Gamma E_t$. Thus π_t and y_t will explicitly depend on ε_t which will make $Var_t[\pi_{t+h}]$ and $Var_t[y_{t+h}]$ depend on $Var_t[\varepsilon_{t+h}]$

where $W_t \sim N(0,t)$ 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.[7] The market-based variance of FOMC jumps is σ_j^2. The solution to (8) is $L_t = L_0 + \sigma W_t + \sum_{j=1}^{N_t} Z_j$, and the conditional variance of the future short rate is

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

where the sum is over all jumps occurring after time t up to and including T. This expression shows us what our option-based variance measure captures, according to this simple model: the (scaled) diffusion variance plus the sum of all the jump variances for all FOMC meetings until the contract's expiration date.

The model has strong implications for changes around FOMC meetings. If t is the day of FOMC meeting j (so that $t = \tau_j$) we have

$$\Delta Var_t L_T = Var_t L_T - Var_{t-\delta} L_T = -\delta\sigma^2 - \sigma_j^2 < 0,$$

where δ is one trading day measured in years (about 1/250). For days without FOMC meetings the change in the variance is just $-\delta\sigma^2$. That is, the model predicts that the conditional variance should decline more on FOMC days than on other days. For changes in $SRU_{t,T}$, the square root of the conditional variance, around the day of FOMC meeting j we have

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

where the σ_i^2's are the variances for the remaining FOMC jumps after date τ_j until T. Our baseline measure of SRU shown in Figures 1 and 2 of the paper is a constant-horizon measure calculated by interpolating multiple contracts while the equation above is for a fixed contract expiration.

C.1 Evidence for FOMC jumps and resolution of uncertainty

Table C.1 reports evidence for changes around FOMC announcements in the variance and uncertainty for each individual Eurodollar contract ED1 to ED6. The top panel shows summary statistics for changes in the variance, $\Delta Var_t L_T$, and the bottom panel for changes in uncertainty, $\Delta SRU_{t,T}$. The means are all negative and strongly significant. The medians are

[7] All distributions are specified under a market-based/risk-neutral probability measure.

Table C.1: Summary statistics for changes around FOMC announcements across contracts

	ED1	ED2	ED3	ED4	ED5	ED6
Changes in conditional variance						
Mean	-0.009	-0.017	-0.026	-0.033	-0.037	-0.041
t-statistic	-8.861	-9.602	-8.745	-8.286	-7.743	-8.054
Median	-0.004	-0.008	-0.015	-0.016	-0.020	-0.024
Standard deviation	0.013	0.025	0.042	0.056	0.068	0.072
Changes in SRU						
Mean	-0.019	-0.018	-0.019	-0.018	-0.017	-0.017
t-statistic	-11.791	-12.434	-10.916	-10.126	-9.130	-9.003
Median	-0.013	-0.013	-0.015	-0.013	-0.013	-0.013
Standard deviation	0.021	0.020	0.024	0.025	0.027	0.026
Observations	177	197	197	197	197	194
Fraction negative	0.09	0.12	0.19	0.15	0.19	0.19

Summary statistics for daily changes around FOMC announcements in variance ($\Delta Var_{t,T}L_T$, top panel) and uncertainty ($\Delta SRU_{t,T}$, bottom panel). t-statistics are calculated using White heteroskedasticity-robust standard errors. Sample: 197 scheduled FOMC meetings between January 1994 and September 2020, excluding the period from July 2007 to June 2009 containing the Global Financial Crisis (some observations are missing for contracts ED1 and ED6 due to option data availability).

higher because of the fat left tails. The average decline in SRU is between 1.5 and 1.9 bps, in line with the results in Section 3 for the one-year measure.

Through the lens of our simple model, uncertainty decreases every day due to a shortening of the horizon, but it decreases by more around FOMC meetings. Thus, for understanding the importance of FOMC jumps we need to compare days with FOMC meetings to other days. Table C.2 shows results for regressions of changes in variance and SRU on a dummy variable for days with FOMC announcements. The estimated intercepts show that the average change in uncertainty on non-FOMC days is negative, in line with the prediction of the model. (This contrasts with the results in Table 2 which do not show an average decline for non-FOMC days, since those results are based on our one-year uncertainty measure.) The dummy coefficients implz that the decline around FOMC meetings is much larger than on other days, and that the difference has very high statistical significance, consistent with Table 1. For changes in conditional variance, in the top panel, these coefficients estimate the average of the negative jump variances, $-\sigma_j^2$, and the table also reports the implied average jump volatility, which range from 8 to 19 bps. These numbers are substantially larger than the average decline in SRU due to FOMC announcements ("resolution of uncertainty") which is around 1.5 bps. The reason is that these measure something quite different, namely the changes in the market-based

Table C.2: FOMC days vs. non-FOMC days across contracts

	ED1	ED2	ED3	ED4	ED5	ED6
Changes in conditional variance						
Constant	-0.001	-0.002	-0.003	-0.004	-0.005	-0.005
	[-11.85]	[-10.97]	[-9.54]	[-8.64]	[-7.50]	[-6.15]
FOMC dummy	-0.007	-0.015	-0.023	-0.028	-0.032	-0.037
	[-7.40]	[-8.18]	[-7.51]	[-7.09]	[-6.67]	[-7.05]
R^2	0.028	0.022	0.019	0.015	0.013	0.012
Memo: estimated jump vol.	0.084	0.122	0.152	0.167	0.179	0.192
Changes in SRU						
Constant	-0.003	-0.003	-0.003	-0.003	-0.002	-0.002
	[-15.88]	[-13.07]	[-11.37]	[-10.47]	[-9.21]	[-7.76]
FOMC dummy	-0.015	-0.015	-0.016	-0.016	-0.015	-0.014
	[-9.60]	[-10.37]	[-9.22]	[-8.53]	[-7.74]	[-7.75]
R^2	0.038	0.025	0.022	0.019	0.016	0.014
Observations	4922	6228	6230	6230	6230	6176

Regressions of changes in variance ($\Delta Var_{t,T}L_T$, top panel) and uncertainty ($\Delta SRU_{t,T}$, bottom panel) on a dummy variable for days with FOMC announcements. t-statistics in squared brackets are calculated using White heteroskedasticity-robust standard errors. Sample period: January 1994 and September 2020, excluding the period from July 2007 to June 2009 covering the Global Financial Crisis (some observations are missing for contracts ED1, ED2 and ED6 due to option data availability).

standard deviation for the future short rate, as opposed to the jump volatility of a typical FOMC meeting. The jump model is helpful in interpreting these quantities. Overall, the sizeable positive jump variances and systematic decline in uncertainty around FOMC days are consistent with the presence of substantial FOMC jumps.[8]

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.2 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 some other types of jumps.

[8]This analysis gives us "*ex post* estimates" of the FOMC jump variance, a term originating 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.

C.2 Extending the model: beliefs about jump variances

Taken literally, the model implies that (i) market-based variance should always decline around FOMC meetings, (ii) variation in the declines over time are only due to differences in the jump variances σ_j^2, and (iii) all contracts should exhibit identical declines. However, (i) uncertainty sometimes increases around FOMC announcements (for about 10-20% of the announcements), (ii) the variability of changes in conditional variance appears larger than can plausibly be explained by differences in jump variances σ_j^2, and (iii) different Eurodollar contracts do not deliver identical jump variance estimates. Regarding the last point: The means in Table C.1 differ notably across contracts, and the first principal component explains only 87% of the variation of daily changes in conditional variance. The empirical deviations from the model's implications seem larger than what could be attributed to market noise or measurement error.

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, $E_t Z_j^2$, and update these beliefs based on new information. In this case changes in $Var_t L_T$ 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. With this generalization, we have

$$\Delta Var_t L_T = -\delta\sigma^2 - \sigma_j^2 + \sum_{i:t<\tau_i\leq T} (E_t - E_{t-\delta}) Z_i^2. \tag{9}$$

(Here, σ_j^2 is the most recent belief of the jump variance, i.e., $\sigma_j^2 = E_{t-\delta} Z_j$. Note that $t = \tau_j$.) If future jump variance beliefs increase sufficiently as a result of an FOMC announcement, market-based uncertainty can increase. More generally, changes in beliefs contribute additional variation to market-based variance and SRU, both over time and across contracts. The FOMC dummy regressions still yield valid estimates of (the negative) average jump variances to the extent that the belief updates average to about zero. While the presence of jumps provides an explanation for the tendency of SRU to decline around FOMC announcements, changes in the beliefs about jump variances can explain why there is substantial variation in uncertainty changes around FOMC announcements, including a fair number of days with increases in uncertainty. This slight generalization of the model is therefore a more plausible description of FOMC jumps and interest rate uncertainty.[9]

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

C.3 Jump risk premia

A question that naturally arises from our analysis of FOMC jumps is whether there are 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. The negative of the mean change in conditional variance around FOMC meetings reported in Table C.1 corresponds to volatilities between 9 and 20 bps. Here we want to include not only the jumps but also the diffusion part, which is why we use the mean changes in market-based variances in Table C.1 (the average of $-\delta\sigma^2 - \sigma_j^2$), instead of the dummy coefficients in Table C.2 (the average of $-\sigma_j^2$). By contrast, the standard deviations of daily changes in three-month LIBOR around FOMC announcements is only 1.5 bps; including the crisis period and all unscheduled FOMC announcements increases this volatility but only to 1.9 bps. The fact that historical volatilities are so much smaller than 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.

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.

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 with Eurodollar options 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. [10] Table C.3 reports summary statistics for both relative returns and absolute returns for this option strategy. Average returns are

[10] Such a position has a small but non-zero exposure to movements in the underlying price. It is possible but in our case not necessary to construct delta-neutral straddle portfolios, meaning that they are unaffected by marginal movements in the underlying price, see Ederington and Lee (1996).

Table C.3: Returns on Eurodollar option straddles around FOMC announcements

	ED1	ED2	ED3	ED4	ED5	ED6
Relative returns						
Mean	-9.1	-4.5	-3.0	-2.3	-2.1	-1.6
Median	-8.3	-4.2	-2.8	-2.2	-1.7	-1.4
SD	11.9	6.1	4.5	4.1	3.7	3.3
Skewness	-0.3	-0.6	0.1	-0.5	-3.2	-0.9
Kurtosis	5.5	7.6	7.4	19.4	23.5	14.7
t-statistic	-10.8	-10.5	-9.2	-7.8	-8	-6.8
Sharpe ratio	2.2	2.1	1.8	1.6	1.6	1.4
Absolute returns						
Mean	-1.3	-1.3	-1.4	-1.4	-1.4	-1.3
Median	-1	-1	-1	-1	-1	-1
SD	1.8	1.9	2.2	2.2	2.4	2.4
Skewness	-0.8	-0.7	-0.6	-1.1	-1.4	-0.8
Kurtosis	6.3	6.7	5.6	6.7	8	6.7
t-statistic	-10.2	-10	-8.6	-8.7	-8.5	-7.9
Sharpe ratio	2.1	2	1.7	1.7	1.7	1.6
Observations	197	197	197	197	197	194

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 annualised 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. Sample period: Jan-1994 to Sep-2020, excluding the period from Jul-2007 to Jun-2009 covering the Global Financial Crisis.

significantly negative, with mean relative returns ranging from about -2 to -9 percent across contracts (with larger negative returns at short horizons, due to smaller straddle prices), and mean absolute returns around -1.4 bps. 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 annualise 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 2.2 at shorter contracts, suggesting high risk-adjusted average returns to short straddle positions around FOMC meetings.[11]

[11] 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).

By comparison, the pre-FOMC announcement returns in Lucca and Moench (2015) have annualised 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 very liquid. While bid-ask spreads are typically 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, 2020). We leave a more detailed analysis of the profitability of our proposed trading strategy to practitioners and future research.

D Additional empirical results for Section 3

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

The following evidence speaks to the question of whether short-rate uncertainty gets resolved before or after the actual FOMC announcement. We show that MPU is only weakly correlated with the pre-FOMC drift in the stock market documented by Lucca and Moench (2015). 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 MPU and the pre-FOMC drift, as shown in Table D.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 MPU of only 0.3 bps. Recall that the average fall in MPU is 1.6 bps and the standard deviation is 2.5 bps. We have also rerun our main results orthogonalizing MPU 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.

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

	Feb-1994 to Dec-2017	Feb-1994 to Mar-2011
	excl. crisis	incl. crisis
pre-FOMC drift	-0.004	-0.006
	[-1.61]	[-3.66]
Constant	-0.016	-0.020
	[-7.37]	[-7.93]
R^2	0.010	0.058
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.

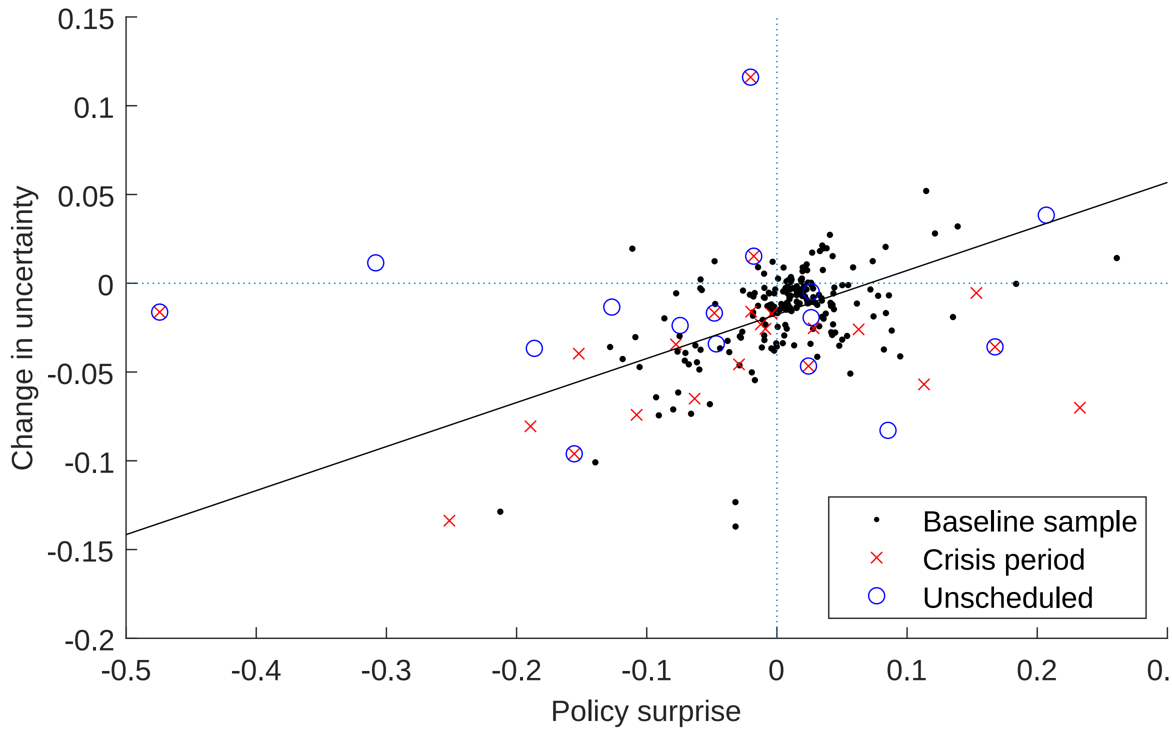
D.2 FOMC first moment surprises and policy uncertainty

The scatter plot in Figure D.1 plots changes in policy uncertainty around FOMC meetings (MPU) against our baseline measure of first moment monetary policy shocks (MPS). The figure shows a clear positive correlation, consistent with the positive correlation between changes in futures rates and uncertainty reported in Section 2. We report the coefficients from regressing MPU on MPS in the first column of Table D.2, and the slope coefficient is very strongly statistically significant.

The literature has also used other event-study measures of FOMC policy surprises. The second column of Table D.2 reports estimates of regressions of MPU on the target and path factors of the monetary surprise from Gürkaynak et al. (2005). Both are significantly positively related to changes in uncertainty, but the association is much stronger for the path factor. The third column of Table D.2 shows results for regressions on the target factor and the delphic and odyssean forward guidance factors of Andrade and Ferroni (2021), which are identified based on their correlation with changes in TIPS breakeven inflation rates. Both forward guidance factors are similarly strongly related to changes in uncertainty.

The positive correlation between MPS and MPU raises the question of whether the average decline in uncertainty around FOMC announcements is simply due to the prevalence of dovish policy surprises. Since MPS is the first principal component and therefore has a zero mean by construction, we answer this question by calculating an alternative surprise

Figure D.1: 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 full sample consists of FOMC announcements from January 1994 to September 2020, the baseline sample excludes unscheduled announcements and also excludes 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.

measure that is not demeaned. This surprise series, which is scaled in the same way as MPS has a sample mean of -0.011, reflecting the well known fact that the FOMC's policy surprises have been dovish on average. The intercept of a regression of MPU on this surprise measure shows that this average dovishness cannot explain the mean decline in uncertainty: The estimated intercept is -0.014 with a t-statistic of -9.6, which is very similar in terms of magnitude and statistical significance to the sample mean of MPU reported in Table 2 of the paper. This is also true in individual regressions of MPU on rate changes for each futures contract that constitutes the MPS surprise measure—the intercept remains roughly the same size and strongly statistically significant. To conclude, the resolution of uncertainty that we have emphasised is not driven by any mechanical correlation with the first moment surprise.

Table D.2: Monetary policy surprises and uncertainty

	1/94 to 9/20	1/94 to 9/20	2/99 to 9/20
MPS	0.197		
	[5.67]		
GSS Target		0.061	
		[2.11]	
GSS Path		0.224	
		[6.32]	
AF Target			0.135
			[3.34]
AF Delphic			0.146
			[2.89]
AF Odyssean			0.151
			[2.15]
Constant	-0.016	-0.016	-0.014
	[-10.48]	[-10.74]	[-8.81]
Observations	197	197	157
R-squared	0.27	0.31	0.17

Regression of the daily change in monetary policy uncertainty on first moment policy surprises on FOMC announcement days. The first column ("MPS") uses our baseline monetary surprise measure, the second column ("GSS") shows the regression when we use the Gürkaynak et al. (2005) target and path factors and the third column ("AF") shows the results when we use the Andrade and Ferroni (2021) target, delphic and odyssean factors. The sample consists of scheduled FOMC announcements from January 1994 to September 2020, excluding the period from July 2007 to June 2009 containing the Global Financial Crisis. The sample for the third column starts from February 1999 due to availability of breakeven inflation data. In brackets are t-statistics based on White hetreoskedasticity-robust standard errors.

D.3 Macroeconomic data releases and uncertainty

Here we show the impact of macroeconomic data releases on uncertainty, and compare them to FOMC announcements. Table D.3 reports in the first column the results of a regression of daily changes in SRU 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 0.8 bps, which is strongly significant. However, this is still only about half as large as the decline due to scheduled FOMC meetings of 1.6 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 standardised differences between the data release and the consensus expectations.[12] The second column shows that after controlling for the average change in SRU 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 uncertainty, but there is no systematic relationship between large macroeconomic news surprises and changes in uncertainty. Overall, this evidence shows that FOMC announcements are far more important for short-rate uncertainty than macroeconomic news.

D.4 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 D.4 below we show the summary statistics for changes in SRU 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 SRU 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.

D.5 FOMC uncertainty cycle

Here we investigate in more detail the FOMC uncertainty cycle documented in Figure 3 of the paper. While the evidence for the decline around the FOMC meeting is generally quite sharp and can be explained based on FOMC jumps—see also Appendix C—it is much less clear why uncertainty ramps up over the first two weeks of the intermeeting cycle.

Part of the reason for the FOMC uncertainty cycle documented in the paper is somewhat mechanical: As evident from our simple model, more distant derivative contracts generally contain more uncertainty than shorter contracts, mainly because they cover more FOMC meetings, and also because of general uncertainty (diffusion variance). The one-year SRU 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 announcement, uncertainty is lower than usual as there are less than average FOMC meetings within the one-year horizon. Over the intermeeting cycle, the number of announcements

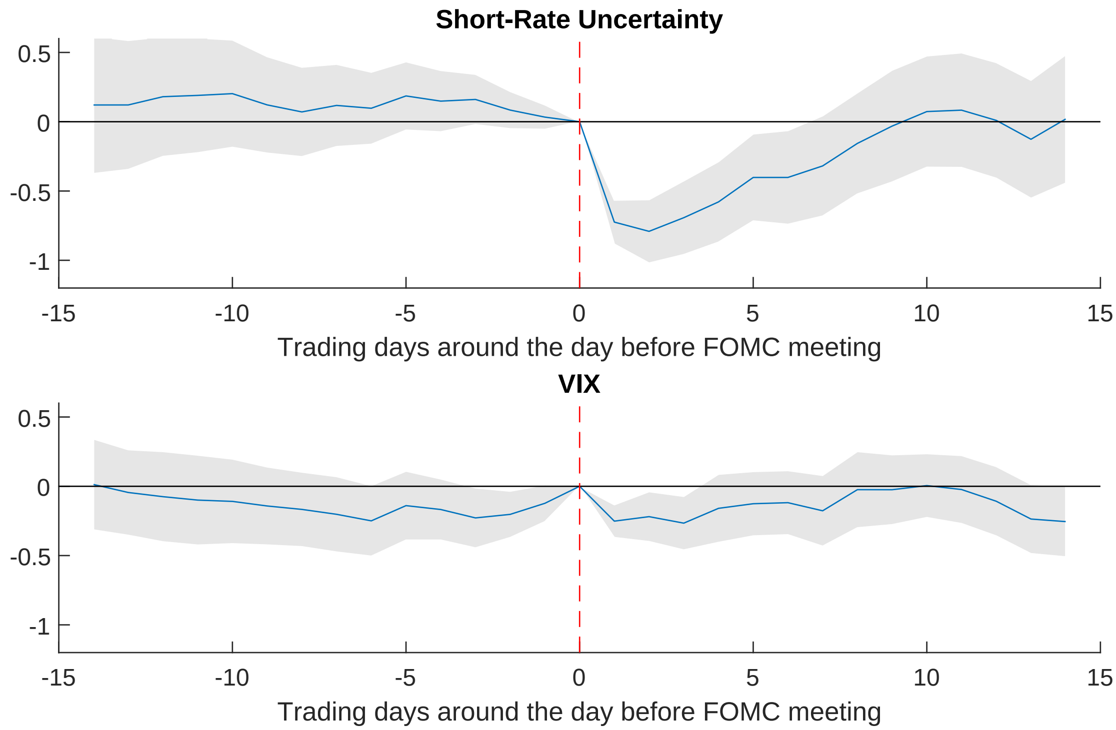
[12] The consensus expectations are available from the widely used survey by Action Economics, the successor to Money Market Services.

priced in the one-year uncertainty, and with it the measured uncertainty, therefore tends to gradually increase.

The graphical evidence in Figure 3 suggests that the increase in uncertainty appears stronger over the first two weeks after the meeting than over the rest of the cycle. To provide additional evidence on this issue, we consider the dynamics of the change in uncertainty derived from fixed-expiration Eurodollar contracts. We regress these daily changes on dummy variables for the number of days since the last FOMC announcements: whether an announcement happened on the same day, 1-5 trading days before, 6-10 days before, etc., up to 25 days. Table D.5 shows the regression results. The negative constant captures the average decline in uncertainty due to the passage of time, that we should expect from these fixed-expiration measures (see also Table C.2). The negative coefficient on the FOMC dummy reflects the resolution of uncertainty. The coefficients on the weekly dummies estimate how the average change in uncertainty during the weeks after the FOMC announcement differs from the average (the negative intercept). For the first two weeks, the coefficients are significantly positive (with the exception of the shortest contract, ED1), which implies that this is when uncertainty primarily ramps up after the decline around the FOMC announcement. In sum, perceived uncertainty and/or jump risk premia decline below "normal" right after an announcement, possibly due to guidance from the FOMC and a shifting focus of investors, before reverting back within the first two weeks of the intermeeting cycle.

It is also interesting to compare changes in SRU over the FOMC meeting cycle to changes in the VIX. Figure D.2 plots changes in SRU (top panel) and the VIX (bottom panel) over the FOMC cycle, normalised in each case by the full-sample standard deviation of daily changes. The VIX tends to fall on FOMC days, as documented in Fernandez-Perez et al. (2017), Amengual and Xiu (2018) and Gu et al. (2018). However, the decline in short-rate uncertainty is substantially larger. The average one-day decline in the VIX is about 0.4 standard deviations, while SRU falls on average by about 0.8 standard deviations after FOMC announcements. The VIX also does not show a pronounced ramp-up pattern—the VIX has a very modest increase in the days leading up to the FOMC meeting, consistent with the results documented in Hu et al. (2019). Overall, the uncertainty cycle—the drop around FOMC meetings and the subsequent ramp-up in uncertainty—is much more dramatic for SRU than for the VIX. A plausible explanation for the much larger decline and clear ramp-up pattern in SRU 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

Figure D.2: Changes in short-rate uncertainty and VIX over the FOMC meeting cycle



The figure shows the average change in SRU (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 normalised 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 197 scheduled FOMC announcements from January 1994 to September 2020.

on the stock market are much less immediate. This is a possible explanation for why the systematic pattern of SRU over the FOMC meeting cycle is much more pronounced than for the VIX.

E Additional results for Section 4

Tables E.1 and E.2 present additional results for the transmission of monetary policy uncertainty to financial markets. The first table shows the transmission of MPU to Treasury forwards (both nominal and real) following the specification of Hanson and Stein (2015), which uses a two-day window around the FOMC announcement and uses the 2-year rate as the measure of monetary policy surprise. Our results continue to show an important role for monetary policy uncertainty consistent with our baseline specification. The second table shows the transmission of uncertainty to yields, stock and foreign exchange market controlling for broader measures of monetary policy surprise, specifically the target and path factors of Gürkaynak et al. (2005). Again, the importance of MPU for transmission of monetary policy actions to financial markets remains both economically and statistically significant.

F 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)) plus two key dates from the Federal Reserve's response to the pandemic. For the FG events we follow Swanson (2021).

The event-study estimates in Table F.1 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.[13] 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

[13] 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.

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. The SEP releases coinciding with the FOMC announcements in March and September 2015, discussed in more detail in Swanson (2021), 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.

Finally, the table also shows two dates from 2020. The March meeting where FOMC lowered the rate to zero and September meeting which gave specific guidance about staying at the zero lower bound. Both meetings lowered uncertainty and moved financial markets, with the March meeting having a susbstantially bigger effect.[14]

G Signal extraction model

Here we provide a simple signal extraction model for news about asset prices. The goal is to explain the importance of the level of uncertainty for the magnitude of the asset price response to monetary policy surprises—the interaction effects—that we documented in Section 4 of the paper.

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

$$y \sim N(\mu_y, \sigma_y^2) \tag{10}$$

[14]The announcement in September 2020, with substantially revised forward guidance language as a result of the new policy framework, affected policy expectations and uncertainty at longer horizons, due to the nature of the guidance. As a result, our one-year uncertainty measure changed only little, and the two-year yield was unchanged. However, additional unreported results show a pronounced decline in longer-term expectations and uncertainty, as measured by Eurodollar futures rates and option-based uncertainty.

The FOMC meeting announcement is represented by a public signal x

$$x = y + \eta, \quad \text{with } \eta \sim N(0, \sigma_\eta^2) \tag{11}$$

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

$$E(y|x) \;=\; \frac{\sigma_\eta^2}{\sigma_y^2 + \sigma_\eta^2}\mu_y + \frac{\sigma_y^2}{\sigma_y^2 + \sigma_\eta^2}x \tag{12}$$

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

$$E(y|x) - E(y) = \frac{\sigma_y^2}{\sigma_y^2 + \sigma_\eta^2}(x - \mu_y) \tag{13}$$

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.

$$\frac{\partial^2 s_y}{\partial s_x \, \partial \sigma_\eta^2} = \frac{-\sigma_y^2}{\left(\sigma_y^2 + \sigma_\eta^2\right)^2} < 0 \tag{14}$$

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

It is helpful to compare our findings and explanation to recent work by Benamar et al. (2021), which documents that asset prices respond more strongly to macroeconomic news when uncertainty is high. While this results would seem to stand in contrast with our findings, it 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. In fact, the theoretical framework in Benamar et al. (2021) is consistent with the implication that asset prices respond more strongly to news when the public signal is more informative. This implication is the one we focus on.

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Table D.3: The response of uncertainty to news releases

	Dummy	Surprise	Abs. surprise
FOMC	-0.018	0.012	-0.009
	[-8.77]	[5.00]	[-1.89]
Employment	-0.008	0.013	0.008
	[-3.97]	[3.46]	[1.21]
CPI	-0.002	0.002	0.003
	[-1.25]	[1.16]	[1.30]
PPI	-0.003	0.003	0.001
	[-2.78]	[2.48]	[0.40]
Retail Sales	-0.001	0.002	0.001
	[-0.88]	[1.91]	[0.98]
GDP	0.001	-0.001	0.006
	[0.39]	[-0.41]	[1.48]
ISM	0.006	0.003	0.001
	[3.76]	[2.10]	[0.36]
Constant	0.001	0.001	0.001
	[2.71]	[2.76]	[2.73]
Obs	5541	5541	5541
R^2	0.035	0.066	0.042

Regression of change in SRU 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. For the macro releases, the surprise is the standardised 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 D.4: 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	-1.22
Standard deviation	0.02	0.02	0.03	0.01
Cumulative change	0.74	-0.29	0.24	-0.13

Summary statistics for the change in short-rate uncertainty (SRU) 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 D.5: Changes in uncertainty after FOMC meetings

	ED1	ED2	ED3	ED4	ED5	ED6
Constant	-0.30	-0.33	-0.35	-0.38	-0.34	-0.36
	[-6.09]	[-6.88]	[-6.66]	[-6.56]	[-5.71]	[-5.43]
FOMC	-1.58	-1.46	-1.54	-1.47	-1.42	-1.08
	[-9.45]	[-9.62]	[-8.58]	[-7.81]	[-7.24]	[-5.40]
W1	0.03	0.18	0.22	0.26	0.21	0.22
	[0.43]	[2.62]	[2.88]	[3.12]	[2.49]	[2.33]
W2	0.07	0.18	0.23	0.29	0.29	0.32
	[0.99]	[2.43]	[2.83]	[3.38]	[3.29]	[3.37]
W3	-0.12	-0.04	-0.03	0.02	-0.06	0.06
	[-1.70]	[-0.56]	[-0.33]	[0.21]	[-0.63]	[0.60]
W4	-0.11	0.02	0.04	0.03	0.05	0.09
	[-1.61]	[0.26]	[0.52]	[0.40]	[0.64]	[0.98]
W5	-0.08	0.01	0.03	0.08	0.10	0.14
	[-1.11]	[0.15]	[0.38]	[0.99]	[1.13]	[1.51]
R^2	0.041	0.028	0.026	0.023	0.020	0.013
Observations	4872	6178	6180	6180	6180	5364

Regressions of changes in uncertainty ($\Delta SRU_{t,T}$) from fixed-expiration Eurodollar contracts, multiplied by 100, on dummy variables for days with FOMC announcements (FOMC), with an FOMC meeting 1-5 trading days ago (W1), 6-10 days ago (W2), etc. t-statistics in squared brackets are calculated using White heteroskedasticity-robust standard errors. Sample period: January 1994 and September 2020, excluding the period from July 2007 to June 2009 covering the Global Financial Crisis (some observations are missing for contracts ED1, ED2 and ED6 due to option data availability).

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

	Nominal				Real			
	5 year		10 year		5 year		10 year	
MPS	1.03	1.52	0.57	0.45	1.05	2.58	0.41	0.36
	[11.80]	[5.08]	[7.74]	[1.90]	[5.82]	[5.36]	[2.34]	[0.60]
MPU		0.87		0.51		1.06		0.50
		[3.41]		[1.96]		[4.14]		[1.66]
MPS x SRU_{-1}		-0.68		0.01		-2.03		-0.07
		[-2.26]		[0.02]		[-2.95]		[-0.11]
R^2	0.43	0.50	0.17	0.19	0.30	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 (MPU), and (iii) MPU interacted with the level of short-rate uncertainty on the day before the FOMC meeting (SRU_{-1}). In the second specification we also include SRU_{-1} but don't report its coefficient to economise on space (as for all estimated constants). In brackets are t-statistics based on White heteroscedasticity-robust standard errors. The sample for nominal forwards contains 197 scheduled FOMC announcements from February 1994 to September 2020 while the sample for the real forwards contains 157 observations from February 1999 to September 2020, Both exclude the period from July 2007 to June 2009 containing the Global Financial Crisis.

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

	5 year yield	10 year yield	Stock	VIX	Dollar
Target Factor	-0.17	-0.22	-7.64	13.35	1.54
	[-0.82]	[-0.83]	[-1.19]	[1.31]	[0.31]
Path Factor	1.37	0.82	-10.62	15.85	13.29
	[9.24]	[4.60]	[-2.82]	[2.66]	[6.42]
MPU	0.59	0.69	-11.06	27.57	5.52
	[3.20]	[3.00]	[-2.15]	[1.99]	[3.90]
Target x SRU_{-1}	0.14	0.15	5.71	-11.07	-1.46
	[0.97]	[0.69]	[1.21]	[-1.51]	[-0.40]
Path x SRU_{-1}	-0.60	-0.32	8.46	-15.50	-10.12
	[-4.57]	[-1.81]	[2.42]	[-2.46]	[-5.94]
R^2	0.67	0.44	0.13	0.21	0.34

Regressions of daily changes in various asset prices on the target and path factor from Gürkaynak et al. (2005), the change in uncertainty (MPU), and the target and path factors interacted with the ex-ante level (measured on day before announcement) of uncertainty (SRU_{-1}) on scheduled FOMC announcement days. We also include SRU_{-1} but don't report its coefficient to economise on space (as for all estimated constants). In brackets are t-statistics based on White heteroscedasticity-robust standard errors. The sample contains 197 scheduled FOMC announcements from January 1994 to September 2020, excluding the period from July 2007 to June 2009 covering the Global Financial Crisis. The dollar index sample (176 announcements) ends in December 2017.

Table E.3: Response of term premia to monetary policy uncertainty

	ACM Term Premium				KW Term Premium			
	5 year		10 year		5 year		10 year	
MPS	0.07	-0.01	-0.03	-0.13	0.20	0.14	0.21	0.14
	[1.97]	[-0.24]	[-0.49]	[-2.04]	[6.19]	[4.08]	6.20	[3.71]
MPU		0.43		0.52		0.27		0.36
		[2.68]		[2.42]		[2.55]		[2.70]
R^2	0.02	0.10	0.00	0.06	0.30	0.36	0.25	0.32

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 policy uncertainty MPU 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 197 scheduled FOMC announcements from January 1994 to September 2020, excluding the period from July 2007 to June 2009 containing the Global Financial Crisis.

Table F.1: Event study of quantitative easing and forward guidance

Date	Event	MPU	MPS	5y yld	10y yld	S&P 500	VIX	Dollar
11/25/2008	QE1	-0.10	-0.16	-0.22	-0.21	0.65	-3.80	-0.67
12/16/2008	QE1/FG	-0.13	-0.25	-0.16	-0.17	5.01	-4.39	-2.35
3/18/2009	QE1/FG	-0.08	-0.19	-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	-0.03	-0.19	-0.21	4.63	-12.94	-1.54
9/21/2011	MEP	0.00	0.05	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	0.01	-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	-0.06	-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
3/15/2020	FG	-0.03	-0.05	-0.21	-0.23	-12.77	24.86	-0.24
9/16/2020	FG	-0.01	0.02	0.01	0.01	-0.46	0.45	
Std. dev. (full sample)		0.03	0.08	0.08	0.08	1.67	2.63	0.60

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). MPU are daily changes in monetary policy uncertainty, MPS is the monetary policy surprise based on changes in Eurodollar futures rates.