# Monetary policy announcements and stock market volatility: a multi-country study

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**Abstract**

We investigate the impact of monetary policy announcements on the stock market volatility. In particular, we investigate the impact of policy rate and quantitative easing announcements of Federal Reserve System, Bank of Canada, Bank of Japan and European Central Bank and the stock market volatility in US, Canada, Japan, UK, Germany, France, Italy and Eurozone as a whole. Quantitative easing announcements increase stock market volatility in their respective countries, but the effect is not significant possibly due to low number of observations. Policy rate meetings increase volatility significantly and this increase is higher for interest rate increases. Volatility five days before the meeting is not affected, but volatility five days after the meeting is decreased. We conclude that the impact of monetary policy announcements on the stock markets during the period 2006 – 2016 was stabilizing.

**JEL Classification:** C22, E44, G14, G15

**Keywords:** news announcements, realized volatility, central bank announcements, stock market volatility

* Lyócsa appreciates the support of the Slovak Grant Agency under Grant No. 1/0406/17. This work was supported by the Slovak Research and Development Agency under Contract No. APVV-14-0357.

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## 1. Introduction

Announcements of macroeconomic news are closely followed by market participants in financial markets. Macroeconomic situation is directly relevant for the valuation of financial assets, and news therefore often tell market participants whether they should update prices upwards or downwards. Due to the large importance of this topic, there already exist a large literature assessing the impact of macroeconomic news announcement on financial markets. The stock market reaction was studied e.g. by Flannery and Protopapadakis (2002), Ehrmann and Fratzscher (2004), Bernanke and Kuttner (2005), and Bekaert and Engstrom (2010). The response of foreign exchange markets was investigated by e.g. Almeida, Goodhart, and Payne (1998), Andersen, Bollerslev, Diebold, and Vega (2003), and Ehrmann and Fratzscher (2005); see Neely and Dey (2010) for a review. The impact of macroeconomic announcements on government bond markets has been investigated in Fleming and Remolona (1997, 1999), Christie-David et al. (2000), Balduzzi, Elton, and Green (2001), Gűrkaynak, Sack, and Swanson (2005), and Beechey and Wright (2009), while other authors have studied several classes of assets, see Boyd, Hu, and Jagannathan (2005), Faust, Rogers, Wang, and Wright (2007) and Bartolini, Goldberg, and Sacarny (2008).

One of the most important types of macroeconomic announcements are announcements of central banks. Market participants pay a lot of attention to monetary policy decisions, see Thorbecke (1997) and Thornton (1998). In this paper, we study impact of central banks' announcements on volatility of equity markets. In particular, we want to find out whether monetary policy decisions have stabilizing or destabilizing impact on equity markets.

Since understanding of volatility is important for market participants, the impact of news announcements on volatility has been investigated previously. Harvey and Huang (1991) and Ederington and Lee (1993) find that volatility increases around macroeconomic announcements. This topic was further studied by Dominigues (1998), Nikkinen and Sahlstrőm (2004), Bauens, Omrane and Giot (2005), Dominigues (2006) Nikkinen, Omran, Sahlstrőm and Äijő (2006), Beine, Laurent and Palm (2009) and many others.

However, previous literature does not offer a satisfactory answer to our question. Firstly, even though previous literature document increase in volatility around news announcements, this cannot be interpreted in such a way that announcements have destabilizing impact on financial markets. The information content of news is usually high, and it is therefore only natural that volatility is high around earnings announcements.

One way how to evaluate whether news announcements have stabilizing or destabilizing impact on financial markets is to investigate whether volatility increases or decreases several days after the announcement. This question has been addressed before, but we argue that it was not answered in a satisfactory way. Originally, this question was addressed within the GARCH framework based on daily data, see e.g. Bomfin (2003), Kim, McKensie and Faff (2004) and

Bauwens, Omrane and Giot (2005). However, volatility models estimated from daily data cannot reliably estimate whether and how much was volatility increased on a particular day.

Later researchers started to utilize implied volatility calculated from option prices, see e.g. Ederington and Lee (1996), Sahlström (2001), Nikkinen and Sahlstrőm (2004), Äijő (2008), Jiang, Konstantinidi and Skiadopoulos (2012), Marshall, Musayev, Pinto and Tang (2012) and Krieger, Mauck and Vazquez (2015). Studies based on implied volatility almost always find that volatility decreases after the announcement of scheduled news. However, this can be caused by the fact that implied volatility is calculated for next 30 days. Since volatility is high during news announcement day, implied volatility is high as long as this 30-day window includes the announcement day, and drops after the announcement day drops out from this 30-day window. Therefore, decrease in the implied volatility after the announcement does not mean that announcement has stabilizing impact.

We utilize realized volatility calculated from high-frequency data. As a result, we have a reliable estimate of volatility for each individual day and we can easily evaluate whether volatility increases or decreases before, during and after monetary policy announcement. High-frequency data has been previously used to evaluate impact of news announcements. However, they are usually used to study market reaction right before and right after the announcement, see e.g. Balduzzi, Elton, and Green (2001). These studies typically find that direct impact of news announcements is concentrated in a very short time window around the announcement.

We study whether stock market volatility is increased or decreased over periods 5 days before, at the day of announcement and 5 days after the monetary policy announcement of central banks in G7 countries. Our contribution is threefold. First, most of the papers studying impact of monetary policy announcements on financial markets study foreign exchange markets, not stock markets. Second, we use a multi-country sample – five central banks and their impact on volatility of eight stock market indices. Third, and most importantly, literature in this field is based on implied volatility, and implied volatility mechanically declines after the scheduled announcements. We utilize realized volatility calculated from high-frequency data and find that monetary policy announcements during the period 2006 – 2016 had stabilizing impact on stock markets – volatility was decreased five days after the announcement. As expected, at the announcement day was volatility increased and this increase was larger for interest rate increases.

The rest of the paper is organized as follows. Section 2 intuitively explains our model using a simulation example. Section 3 describes the data and the methodology; section 4 presents the results; and section 5 concludes.

## 2. Data

Our sample starts from January 2006 and ends in November 2016. We cover G7 countries; it is a group of the seven major advanced economies according to the International Monetary Fund. This group consists of Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States. Our data can be divided in three main categories, namely stock market indices, news announcements from Central Banks (CBs), and exchange rate and interest rate data. As France, Germany and Italy are part of the monetary union, the corresponding stock markets share the same set of news announcements from the European Central Bank (ECB).

### 2.1 Stock market indices

We study the effect of news announcement of CBs to seven stock market indices: S&P 500 (United States), FTSE 100 (United Kingdom), TSX (Canada), NIKKEI 225 (Japan), STOXX 50 (Europe), DAX (Germany), CAC (France), and MIB (Italy). Measures of volatility are pre-calculated measures for the given sample period and are downloaded directly from the Oxford-Man Institute of Quantitative Finance Realized Library[1].

### 2.2 News announcements

We focus on the most important macroeconomic news announcements related to the central banks; target interest rates and quantitative easing. Target interest rate is an essential part of the monetary policy strategy. Many central banks set a target interest rate in effort to influence short-term interest rates. The data were collected from Bloomberg and are described in Table 1.

Table 1 Interest Rate News Announcements

| **Country** | **Event name from Bloomberg** | **Ticker** |
|---|---|---|
| Canada | Bank of Canada Rate Decision | CABROVER Index |
| Eurozone | ECB Main Refinancing Rate | EURR002W Index |
| Japan | BOJ Target Rate | BOJDTR Index |
| United Kingdom | Bank of England Bank Rate | UKBRBASE Index |
| United States | FOMC Rate Decision (Upper Bound) | FDTR Index |

*Source: https://www.bloomberg.com*

In case of Canada and the United Kingdom the data about the target interest rate announcement did not require any adjustments and are easily available for the whole observed period. European central bank reports ECB Main Refinancing Rate, ECB Deposit Facility Rate, and ECB Marginal Lending Facility. We refer only to the first mentioned interest rate because it

[1] http://realized.oxford-man.ox.ac.uk/data/download

is the most important rate and it was reported during the whole observed period, unlike the other two rates. Moreover, all of these rates are announced at the same time. In the United States the federal funds rate is targeted by the Federal Reserve's Federal Open Market Committee (FOMC). In December 2008, the target interest rate was replaced by a target range. We use FOMC Rate Decision (Upper Bound) because Bloomberg uses this label also for the interest rate reported before the introduction of the target range. Therefore, this variable covers the whole observed period. On the other hand, variable representing the lower bound of the interest rate was introduced only after December 2008.

The situation in Japan is also worth mentioning, because it is a bit more complicated. On April 4, 2013 the Bank of Japan has shifted its monetary policy focus to a targeted monetary base via Japanese government bond purchases.[2] On January 29, 2016 the Bank of Japan employed new approach to its monetary policy known as "Quantitative and Qualitative Monetary Easing with a Negative Interest Rate".[3] As a result of these two major changes in monetary policy, there is a gap in our data from April 4, 2013 to January 29, 2016 because no interest rate news was announced. During this period the Bank of Japan targeted monetary base instead of interest rate.

The second category of news announcements is related to quantitative easing. It is an unconventional monetary policy used by central banks to stimulate their economies when conventional monetary policy is no longer effective. It is often used in situations when interest rates used by central bank are already near zero and there is not a lot of room for even greater decline. Quantitative easing usually consists of purchases of long-term financial assets from banks and other financial institutions. This policy creates additional money in the economy and should lower long-term interest rates.

We selected the events when introduction of quantitative easing or any change in this policy were announced. All selected countries have some experiences with quantitative easing except of Canada. The relevant data were collected manually from the official sites of the central banks.[4]

## 2.3 Exchange rate and interest rate data

Our dataset also contains information about short term interest rates and exchange rates for each country. The data are in daily frequencies and cover the same time period as macroeconomic news announcements. Interest rate is represented by short term 3-month interest rate for each country. Further on, we utilize the so called "effective exchange rate". An effective

[2] http://www.boj.or.jp/en/announcements/release_2013/k130404a.pdf
[3] http://www.boj.or.jp/en/announcements/release_2016/k160129a.pdf
[4] http://www.boj.or.jp/en/mopo/mpmsche_minu/index.htm/#p01
https://www.ecb.europa.eu/press/govcdec/html/index.en.html
https://www.federalreserve.gov/newsevents/press/monetary/2016monetary.htm
http://www.bankofengland.co.uk/monetarypolicy/Pages/decisions.aspx

exchange rate is calculated as a weighted average of the individual exchange rates of a particular country with its main trading partners. It is also known as a trade-weighted exchange rate because the weights are set according to the importance of each partner country's share of trade with the reporting country.

## 3. Methodology

In this section we first describe how we measure volatility of stock markets, next describe our methodology and in the end explain all the explanatory variables used in the analysis.

### 3.1 Volatility estimators

The impact of news announcements on the stock market variance is based on modelling realized measures of daily volatility, which is the variable of interest in this study. The most common estimator of daily volatility in the literature is given by:

$$\sum_{j=1}^{N} r_{i,t,j}^2 \qquad (1)$$

In (1), $r_{i,t,j}$ is the $j^{\text{th}}$ intraday return of $i^{\text{th}}$ stock market index at day $t$. $N$ denotes the number of intraday returns, which is a function of the length of the trading hours and the sampling frequency. However, in the presence of microstructure noise, the estimator given in (1) is biased. Alternatively, one could employ one of several estimators which are consistent even in the presence of some form of the microstructure noise (e.g. Barndorff-Nielsen and Shepard, 2004; Hansen and Lunde, 2006; Shephard and Sheppard, 2010; Andersen et al., 2012). A different empirical strategy which we follow in this study as well was suggested by Patton and Sheppard (2009), who show that different measures might encompass different information and, in turn, advocate for the use of a combination of realized measures. Motivated by these considerations, we we report results for a simple arithmetic average of the following eight realized measures of volatility (Barndorff-Nielsen and Shepard, 2004; Hansen and Lunde, 2006; Shephard and Sheppard, 2010; Andersen et al., 2012):

- 5-minute realized volatility.
- 10-minute realized volatility.
- 5-minute realized kernel.
- 5-minute realized volatility with 1-minute sub-sampling.
- 10-minute realized volatility with 1-minute sub-sampling.
- 5-minute bi-power volatility.
- 5-minute bi-power volatility with 1-minute sub-sampling.
- 5-minute median-truncated volatility.

In all our calculations we use the logarithm of these measures, which is due to the fact that the distribution of realized measures tends to be skewed to the right and is subject to outliers which might have an undesired impact on the results. We denote the combination of realized measures simply as $RV_t$ and refer to it as realized volatility in the subsequent text.

### 3.2 Econometric model

The impact of news announcement on eight stock market indices is evaluated for each index separately via univariate (D)HARX-GARCH models (Heterogeneous AutoRegressive model with eXogenous variables and Generalized AutoRegressive Conditional Heteroskedastic errors). We consider modelling either the realized volatility directly (HARX-GARCH model) or the difference of the realized volatility (DHARX-GARCH model). The choice to model both is motivated by the fact that this enables us to understand how rate announcement affects volatility in a fuller manner: observing the level and changes as well. Also, if we capture the dependence in the level of the volatility series sufficiently, results from both models should be similar, thus strengthening our conclusions. The former specification is as follows:

$$\begin{aligned} RV_t &= \mu_0 + \mu_1 RV_{t-1} + \mu_2 RV_{t-1,t-5} + \mu_2 RV_{t-1,t-22} + \sum\nolimits_{s=1}^{S(i)} \kappa_s EV_s + \sum\nolimits_{c=1}^{C(i)} \delta_c CV_c + z_t \\ z_t &= \left(1 + \theta_1 L^1\right)\varepsilon_t \\ \varepsilon_t &= \sigma_t \eta_t, \quad \eta_t \sim iid\left(0,1\right) \end{aligned} \tag{2}$$

In case of the DHARX-GARCH model, only the dependent variable changes from $RV_t$ to the difference of the realized volatility, e.g. $\Delta RV_t$. In model (2), $\mu$, $\kappa$, $\delta$, and $\theta$ are model parameters. By $EV_s$ we denote **E**vent **V**ariables and by $CV_c$ we denote **C**ontrol **V**ariables (described in more detail in Section 3.3). The variable $RV_{t-1}$ is the lagged realized volatility, while $RV_{t-1,t-5}$, $RV_{t-1,t-22}$ are the average realized volatilities across previous five and twenty two trading days. The lagged realized volatilities tend to capture the weekly and monthly volatility movements and all three should reflect the heterogeneity in investors' dealing frequencies and investment time horizons (Muller et al., 1997; Corsi, 2009).

Even though the lagged realized volatilities and other exogenous variables capture most of the future movement of market volatility, the error term $z_t$ might still be subject to autocorrelation and conditional heteroscedasticity. We therefore model the term $z_t$ as a moving average process ($L$ is the lag operator), while we model the evolution of $\sigma^2_t$ via a suitable GARCH model. Two GARCH models are considered, the standard model of Bollerslev (1986):

$$\sigma_t^2 = \omega + \alpha_1 \varepsilon_{t-1} + \beta_1 \sigma_{t-1}^2 \tag{3}$$

and Nelson's (1991) exponential GARCH model:

$$\ln\left(\sigma_t^2\right) = \omega + \alpha_1 s_{t-1} + \gamma_1\left(\left|s_{t-1}\right| - E\left[\left|s_{t-1}\right|\right]\right) + \beta_1 \ln\left(\sigma_{t-1}^2\right) \quad (4)$$

In specification (4), $s_t$ denotes standardized innovations, and $\alpha_i$ and $\gamma_i$ control for the leverage and sign effects, respectively.

Apart from the standard normal distribution we considered a possibility that $\eta_t$ follows a distribution which can capture the possible asymmetric and leptokurtic properties of the volatility series. Therefore we also used the SU-normal distribution of Johnson (1949a, b) with the probability density function defined as:

$$f(x) = (2\pi)^{-1/2} J e^{-\frac{z^2}{2}} \quad (5)$$

where $z = \varsigma^{-1}(sinh^{-1}(x) - \lambda)$ and $J = \varsigma^{-1}(x^2 + 1)^{1/2}$. $\lambda$ and $\varsigma$ are shape parameters that specify the skewness and kurtosis of the distribution.

Different choices for the process of $\sigma^2_t$ and $\eta_t$ lead to four different models[5]. We prefer models where resulting standardized residuals do not display autocorrelation and conditional heteroscedasticity as indicated by the Escanciano and Lobato (2009) test. If more suitable models remain, we report specification which was preferred according to the Bayesian information criterion (BIC, Schwartz, 1978). In one instance (France), we directly chose the model with lowest BIC as none of the models passed both tests of autocorrelation and conditional heteroscedasticity.

### 3.3 Explanatory variables

In this study we investigate the impact of most relevant news announcements from Central bank(s) on the volatility of corresponding stock markets. In specification (2), $\kappa_s$ coefficients measure the impact of news announcement on the market volatility. For each stock market index we have considered several classes of variables which aim to capture the reactions on the market before, during, and after the event, while also considering the uncertainty about the announcement and also the possible magnitude of the unexpected part of the news announcement. The variables are as follows:

*Key interest rate*

*Before news announcement date*

- $R5B_t^k$ x $RV_{t\text{-}6,t\text{-}10}$. Here, $R5B_t^k$ is a dummy variable with value of 1 if $t$ is a date in a five day window prior to the announcement of event $k$, 0 otherwise. We set $R5B_t^k$ to 1 only if the number of analysts (estimates) was different from 0, thus controlling for un-expected

[5] HAR-GARCH with $\eta_t$ following normal distribution, HAR-GARCH with $\eta_t$ following Johnson's SU distribution, HAR-EGARCH with $\eta_t$ following normal distribution, and HAR-EGARCH with $\eta_t$ following Johnson's SU distribution.

news announcements. The dummy variable is multiplied by $RV_{t\text{-}6,t\text{-}10}$, e.g. the average volatility over five days prior the before news announcement window.

- $R5B_t^k$ x $VAE_t^k$ is an interaction term, where $VAE_t^k$ is the variance of analysts' estimates of the rate. We have assumed that the higher variance of analyst estimates should lead to higher market volatility before the announcement of the news.
- $R5B_t^k$ x $NA_t^k$ is an interaction term, where $NA_t^k$ is the number of available analyst estimates. We have assumed that the higher the coverage of the event the less uncertain the outcome. Alternatively the increased number of analysts might suggest also a more relevant announcement.

*At news announcement date*

- $R_t^k$ x $RV_{t\text{-}1}$. This is the central variable of interest and it is composed of a simple dummy variable $R_t^k$ with value of 1 if $t$ is a date of the event announcement and the announcement took place during trading hours of the given stock market, otherwise the value of the variable is 0. The dummy variable is multiplied by $RV_{t\text{-}1}$, e.g. the level of volatility day before the event announcement. We expected a positive coefficient which would imply that news announcement increases the uncertainty on the stock market.
- $R_t^k$ x $S_t^k$ (–) is an interaction term, where $S_t^k$ is the magnitude of a surprise of the announcement calculated as: (actual value of the key rate – average of analyst estimates)/(average of analyst estimates) x 100%. The value of the interaction term is 0 if the rate was above of what was expected.
- $R_t^k$ x $S_t^k$ (+) We expected that the larger the surprise the larger the uncertainty on the stock market, but the effect might be asymmetric. If analysts expected a rate increase while in reality rate remained unchanged, the market might react with greater uncertainty as this might suggest that the economy is not in such a good shape as expected by analysts. The value of the interaction term is 0 if the rate was below of what was expected.

*After news announcement date*

- $R1A_t^k$ x $RV_{t\text{-}1}$. Here, $R1A_t^k$ is a dummy variable with value of 1 if $t$ is a date one day after the announcement of the event $k$, 0 otherwise. The dummy variable is multiplied by the volatility level one day before the news announcement, $RV_{t\text{-}1}$. This way, we are controlling for the sudden decrease in the level of volatility due to the fact that the given day corresponds to a day after the news announcement.
- $R5A_t^k$ x $RV_{t\text{-}1}$ is a dummy variable with value of 1 if $t$ is a date in a five day window after the announcement of the event $k$, 0 otherwise. As before, the dummy variable is multiplied by the volatility level one day before the news announcement, $RV_{t\text{-}1}$. This variable is also of central importance to the paper as we are testing whether news announcement has led to a reduction or rather to an increase in the overall level of market uncertainty.

- $R5A_t^k$ x $S_t^k$ (–) is an interaction term, where $S_t^k$ is the magnitude of a surprise of the announcement. The value of interaction terms is 0 if the surprise was positive, i.e. higher rate than expected.
- $R5A_t^k$ x $S_t^k$ (+) The value of interaction terms is 0 if the surprise was negative, i.e. lower rate than expected.

*International development of rates*

- $R5B.W_t^k \times RV_{t-6,t-10}$. Here, $R5B.W_t^k$ is a count variable, which sums $R5B_t^k$ across all other markets in the sample. As monetary policy of central banks in developed countries might indicate monetary policy of other central banks, news announcement of other relevant central banks might influence stock market volatility as well. We multiply the dummy variable by the average volatility over five days prior the before news announcement window ($RV_{t-6,t-10}$).
- $R.W_t^k \times RV_{t-1}$. The variable $R.W_t^k$ is a count variable which sums $R_t^k$ across all other markets, but only if rate announcement on other markets occurred during trading hours of a given market. To account for the market level of volatility, the dummy variable is multiplied by $RV_{t-1}$. We expect a smaller positive coefficient on $R.W_t^k \times RV_{t-1}$ compared to $R_t^k \times RV_{t-1}$, as monetary policy in other countries might be important but not as much as the local policy.
- $R1A.W_t^k \times RV_{t-1}$. The volatility before the event announcement is multiplied by a count variable which sums $R1A_t^k$ across all other markets.
- $R5A.W_t^k \times RV_{t-1}$. The volatility before the event announcement is multiplied by a count variable which sums $R5A_t^k$ across all other markets. We expect that the coefficient should be negative indicating a decrease in the level of uncertainty on the market after news was announced at other Central banks.

*Quantitative easing*

*Local monetary policy on quantitative easing*

- $Q5B_t^k \times RV_{t-6,t-10}$. $Q5B_t^k$ is a dummy variable with value of 1 if $t$ is a date in a five day window before news announcement $k$, related to quantitative easing (the date of this news might not be known to market participants).
- $Q_t^k \times RV_{t-1}$. $Q_t^k$ is a dummy variable with value of 1 if $t$ is a date of the news announcement $k$, but only if it took place during trading hours of the given stock market. We expect positive coefficient loading on $Q_t^k$ variable as quantitative easing might be perceived as a significant monetary policy direction for the whole economy.
- $Q1A_t^k \times RV_{t-1}$. To account for the sudden decrease of the realized volatility we included the dummy variable $Q1A_t^k$ which is equal to 1 one day after the event and 0 otherwise.

- $Q5A_t^k$ *x* $RV_{t\text{-}1}$. To observe whether news related to *QE* has led to the decrease of the realized volatility we used a dummy variable $Q5A_t^k$ with value of 1 if *t* is a date in a five day window after the news announcement *k* related to quantitative easing.

*International monetary policy on quantitative easing*

- $Q5B.W_t^k$ *x* $RV_{t\text{-}6,t\text{-}10}$. $Q5B.W_t^k$ is a count variable which sums $Q5B_t^k$ across all other markets. As before, the main idea is that monetary policy in other developed countries might indicate future monetary policy in the given country and therefore relevant news announcements of other Central banks might have an effect on the local stock market.
- $Q.W_t^k$ *x* $RV_{t\text{-}1}$. $Q.W_t^k$ is a count variable which sums $Q_t^k$ across all other markets, but only if rate announcement on other markets occurred during trading hours of a given market.
- $Q1A.W_t^k$ *x* $RV_{t\text{-}1}$. The count variable $Q1A.W_t^k$ sums $Q1A_t^k$ across all other markets.
- $Q5A.W_t^k$ *x* $RV_{t\text{-}1}$. The count variable $Q5A.W_t^k$ sums $Q5A_t^k$ across all other markets.

Some of the variables were not used for all markets. For example, when the Japanese stock market trades, other stock markets in our sample are inactive. Therefore specification modelling realized volatility on the NIKKEI 225 excludes news announcement variables on other markets (namely $R.W_t^k$ and $Q.W_t^k$). Similarly, when modelling Canadian TSX, we do not have variables related to the *QE* in Canada, as during our sample period, *QE* was only considered in Canada, but not actually employed.

In specification (2), $\delta_c$ coefficients are related to a set of control variables. The motivation for including control variables is that other relevant events might be influencing the level of market volatility on a given day *t*. Therefore all control variables are not lagged and it is assumed that they are exogenous with respect to the market volatility.

Since changes in short-term interest rates and exchange rate can be perceived as a signal of monetary policy, we included simple differences[6] of 90-day money market interest rates denoted as $\Delta IR_t$, and a logarithmic difference of a currency index which measure the appreciation/depreciation of the currency to the currencies of main trading partners and is denoted as $\Delta FX_t$, we included also the squared return ($\Delta FX^2{}_t$) to proxy the uncertainty levels on the foreign exchange market, which might spillover to the equity market. We have also included dummy variables for days-of-the week.

## 4. Results

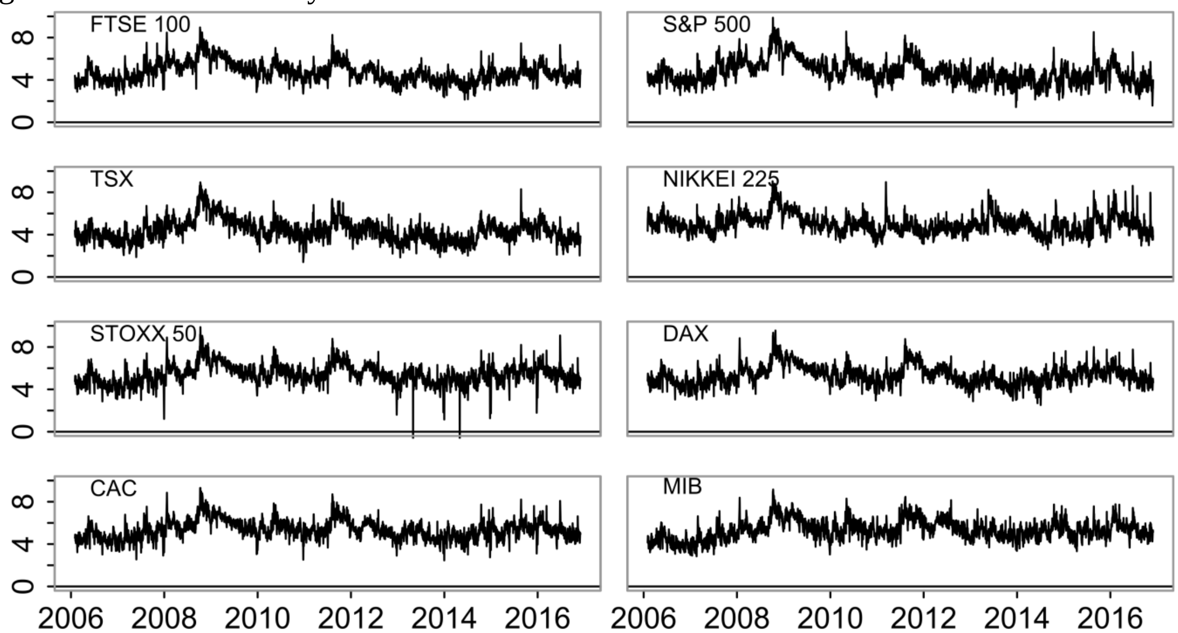
### 4.1 Data and model characteristics

Time series of realized volatility for all the stock markets are plotted in Figure 1. As we can see, volatilities of different stock markets exhibit similar time pattern. Therefore, if we would investigate impact of announcement of one central bank (e.g. FED) on several countries, these

[6] The use of simple differences instead of percentage changes is due to the period of negative rates.

results would not be independent. This is evident also in our data. Results for stock indices in Germany, France, Italy and Eurozone are very similar, because the most important explanatory variables are always related to announcements of European Central Bank. This is the reason why we did not include stock indices from other European countries. However, our paper overall does not suffer from this problem, because our sample includes announcements of five independent central banks.

Figure 1 Realized volatility




Descriptive statistics of the key variables are summarized in Table 2. It is worth noting that logarithmic transformation of realized volatility was clearly useful. Even though realized volatility itself is highly skewed (not reported here), logarithm of realized volatility (denoted as *RV* in Table 2 and the remainder of the paper) is less so, with skewness not very different from zero. As is often the case in the finance literature, realized volatility shows high level of persistence as the lowest first order autocorrelation was found for Japan with still considerable 0.770. This supports our choice for modelling volatility via an autoregressive model: the HAR-GARCH model.

As expected, the highest number of analysts covering rate announcements is for the FED. However, variance of analyst estimates seems to be small and based on the raw data, analysts often predict the same. The surprises are reported in *x*100% scale and vary greatly mostly because of small levels of interest rates at the end of our sample period, where even a small deviation from the average of analyst's expectation leads to large percentage changes.

Table 2 Descriptive statistics of key variables

| **United Kingdom** | Rate announcements 127, Quantitative easing indication 9 | | | | | | |
|---|---|---|---|---|---|---|---|
| | Mean | Std.Dev. | Skewness | Kurtosis | Minimum | Maximum | AC1 |
| *RV* | 4.713 | 0.945 | 0.679 | 3.639 | 2.142 | 8.957 | 0.835 |
| *ΔIR x 100* | -0.155 | 2.626 | -25.171 | 1003.630 | -106.500 | 21.250 | 0.316 |
| *ΔFX x 100* | -0.008 | 0.484 | -1.248 | 17.273 | -6.200 | 2.185 | 0.097 |
| *$\Delta FX^2$ x 100 (annualized)* | 5.279 | 5.576 | 3.979 | 41.140 | 0.000 | 98.426 | 0.273 |
| *Variance of analyst estimates* | 0.003 | 0.009 | 5.141 | 31.829 | 0.000 | 0.063 | 0.692 |
| *Surprises* | 0.639 | 9.193 | 9.889 | 109.664 | -25.000 | 100.000 | -0.005 |
| *Number of Analysts* | 52.504 | 8.511 | -1.977 | 12.562 | 0.000 | 68.000 | 0.399 |
| **United States** | Rate announcements 88, Quantitative easing indication 8 | | | | | | |
| | Mean | Std.Dev. | Skewness | Kurtosis | Minimum | Maximum | AC1 |
| *RV* | 4.754 | 1.117 | 0.691 | 3.724 | 1.437 | 9.876 | 0.847 |
| *ΔIR x 100* | -0.106 | 1.171 | -2.114 | 25.902 | -11.800 | 9.500 | 0.724 |
| *ΔFX x 100* | 0.006 | 0.344 | 0.142 | 6.624 | -2.202 | 2.207 | -0.003 |
| *$\Delta FX^2$ x 100 (annualized)* | 3.960 | 3.751 | 2.271 | 12.143 | 0.000 | 35.028 | 0.210 |
| *Variance of analyst estimates* | 0.003 | 0.008 | 3.781 | 17.594 | 0.000 | 0.044 | 0.407 |
| *Surprises* | 0.424 | 11.260 | 5.243 | 56.235 | -50.000 | 92.308 | -0.002 |
| *Number of Analysts* | 76.023 | 33.350 | -0.658 | 2.452 | 0.000 | 135.000 | 0.464 |
| **Canada** | Rate announcements 87, Quantitative easing indication 0 | | | | | | |
| | Mean | Std.Dev. | Skewness | Kurtosis | Minimum | Maximum | AC1 |
| *RV* | 4.383 | 1.015 | 0.767 | 4.118 | 1.408 | 8.943 | 0.808 |
| *ΔIR x 100* | -0.105 | 1.168 | -2.081 | 25.974 | -11.800 | 9.500 | 0.718 |
| *ΔFX x 100* | -0.007 | 0.586 | -0.110 | 6.476 | -3.082 | 3.966 | -0.048 |
| *$\Delta FX^2$ x 100 (annualized)* | 6.674 | 6.485 | 2.219 | 10.870 | 0.000 | 62.955 | 0.242 |
| *Variance of analyst estimates* | 0.003 | 0.006 | 3.060 | 13.529 | 0.000 | 0.036 | 0.178 |
| *Surprises* | -0.883 | 6.419 | -5.819 | 43.180 | -50.000 | 12.500 | -0.070 |
| *Number of Analysts* | 25.391 | 4.787 | -1.476 | 10.501 | 0.000 | 34.000 | 0.369 |
| **Japan** | Rate announcements 100, Quantitative easing indication 5 | | | | | | |
| | Mean | Std.Dev. | Skewness | Kurtosis | Minimum | Maximum | AC1 |
| *RV* | 4.983 | 0.900 | 0.800 | 4.397 | 2.6052 | 9.041 | 0.770 |
| *ΔIR x 100* | -0.094 | 1.155 | -2.067 | 27.123 | -11.800 | 9.500 | 0.718 |
| *ΔFX x 100* | 0.003 | 0.673 | 0.363 | 7.877 | -3.674 | 4.807 | -0.017 |
| *$\Delta FX^2$ x 100 (annualized)* | 7.494 | 7.619 | 2.523 | 13.852 | 0.000 | 76.314 | 0.211 |
| *Variance of analyst estimates* | 6E-04 | 0.002 | 4.634 | 24.789 | 0.000 | 0.014 | 0.65 |
| *Surprises* | 0.033 | 13.24 | 2.560 | 41.913 | -66.67 | 100.000 | -0.29 |
| *Number of Analysts* | 22.71 | 16.17 | 0.310 | 2.212 | 0.000 | 62 | 0.79 |
| **Europe** | Rate announcements 121, Quantitative easing indication 2 | | | | | | |
| | Mean | Std.Dev. | Skewness | Kurtosis | Minimum | Maximum | AC1 |
| *RV-STOXX* | 5.402 | 0.957 | -0.142 | 7.587 | -2.885 | 9.879 | 0.737 |
| *RV-DAX* | 5.334 | 0.924 | 0.518 | 3.743 | 2.522 | 9.557 | 0.806 |
| *RV-CAC* | 5.351 | 0.902 | 0.457 | 3.646 | 2.460 | 9.302 | 0.796 |
| *RV-MIB* | 5.358 | 0.930 | 0.306 | 3.154 | 2.847 | 9.156 | 0.804 |
| *ΔIR x 100* | -0.105 | 1.168 | -2.112 | 25.899 | -11.800 | 9.500 | 0.725 |
| *ΔFX x 100* | 0.000 | 0.371 | -0.322 | 8.521 | -3.106 | 2.541 | -0.020 |
| *$\Delta FX^2$ x 100 (annualized)* | 4.156 | 4.165 | 2.640 | 16.440 | 0.000 | 49.299 | 0.199 |
| *Variance of analyst estimates* | 0.002 | 0.005 | 3.449 | 15.091 | 0.000 | 0.026 | 0.375 |
| *Surprises* | 1.087 | 10.609 | 7.548 | 67.080 | -16.667 | 100.000 | -0.011 |
| *Number of Analysts* | 46.369 | 12.281 | -1.133 | 4.694 | 0.000 | 68.000 | 0.521 |

*Notes: Statistics for Variance of analyst estimates, Surprises and Number of Analysts are calculated for events related to interest rate news announcement.*

Core results from the analysis are presented in Table 3 and Table 4. In Table 3 we report results from the specification where we model daily changes in realized variance. Variables $RV_{t-1}$, $RV_{t-1,t-5}$ and $RV_{t-1,t-22}$ are usually included in the model in order to properly account for time-series properties of the level of volatility. Interestingly, results from Table 3 show, that they are able to explain the behavior of volatility changes as well. The significance of the three volatility coefficients in Table 4 is not surprising and is in accordance with the volatility modelling literature.

Diagnosis tests showed that error term should be modelled as an MA(1) process. This is captured by the term $\varepsilon_{t-1}$. Moreover, error term exhibited heteroscedasticity and we therefore model it as a GARCH model, see variance equation in the lower part of each table. For most of the stock markets, GARCH(1,1) model is sufficient and via our modelling framework (see Section 3.2) the use of the EGARCH model was preferred only for the S&P500 and TSX stock markets. Diagnostic tests (in the bottom of both tables) show that residuals from our models have in most cases satisfactory properties, an exception is for French CAC market index's volatility, where standardized residuals still showed some presence of conditional heteroskedasticity.

### 4.2 Events

The results are presented in Table 3 and Table 4. In order to ease the exposition, the main results from these tables are also presented in Figure 2 and Figure 3. We therefore advise the reader to first get an overview from these figures, and only afterwards look at the Table 3 and Table 4.

First we discuss the impact of interest rate announcements in their respective countries. During the 5-day period before the announcement we see no significant increase or decrease in realized volatility for all the countries. Similarly, we find no impact of variance of analysts' expectation and number of analysts on the pre-announcement volatility either.

On the announcement day, we observe that the volatility of the stock market is increased in all the countries. We investigate also the importance of the interest rate surprise. In order to allow asymmetric response to positive and negative surprises, we include also interaction terms $R_t^k$ x $S_t^k$ (+) and $R_t^k$ x $S_t^k$ (–). If the sign of $R_t^k$ x $S_t^k$ (+) is positive, or the sign of $R_t^k$ x $S_t^k$ (–) is negative, it should be interpreted in such a way that large surprise cause larger increase in volatility. However, these coefficients are significant only for the US and UK. In case of US, the larger the positive news are, the smaller is increase in volatility at the announcement day. Size of negative news does not seem to matter. In case of UK, volatility increase is largest for large surprises. However, the impact is much stronger for negative then for positive surprises. When we look at all the countries together, we conclude that volatility increase is higher particularly for negative interest rate surprises (i.e. actual rate cut might be expected more than rate increase).

After the interest rate meeting we observe a decrease in volatility. Note that the first term, $R1A_t^k$ x $RV_{t\text{-}1}$, captures decrease in volatility right after the announcement day. We are not particularly interested in this term, because it is highly expected that volatility will be lower on a day after the announcement than it was at the day of announcement. In other words, this decrease can be considered as a mechanical result of increase in volatility on the announcement day.

However, it is important to control for this decrease in volatility, as instead, we are interested in the term $R5A_t^k$ x $RV_{t\text{-}1}$ (volatility level 5 days after the event day) which does not suffer from this problem. We find that coefficient of this variable is negative for all the counties, but not always significant. In other words, on average, compared to the level of volatility before the event day, the volatility 5 days after the interest rate announcement decreased, but this effect is not very strong. We include also terms $R5A_t^k$ x $S_t^k$ (+) and $R5A_t^k$ x $S_t^k$ (–) to capture whether the response depends on the interest rate surprise. We find that decrease in volatility is larger after positive interest rate surprises, and smaller after negative interest rate surprises. As before, it appears that actual rate cuts were less expected.

Realized volatility on stock markets seems to be increasing also during days, when interest rate announcements are made by central banks in other countries. However, this effect is significant only in the UK and Canada. This result is very intuitive. Canada has strong ties to US, and UK has strong ties to EU, and therefore one would expect that particularly these countries will respond to announcement of foreign central banks. Most likely, Canada is strongly responding to the FED announcements and UK is strongly responding to the ECB announcements.

Volatility five days before the foreign central banks' announcements is not influenced by these announcements except for Canada, where the volatility increased during the 5-day window before the event. Similarly, we do not observe change in the volatility five days after the announcement, except for the Eurozone, where volatility decreases.

### 4.3 Realized volatility and quantitative easing

We also study how quantitative easing related to stock market volatility. Interestingly, at the day of the announcement it was found that only stock market in Japan tends to have a strong volatility (increases) reaction, but not in other countries. On the contrary, quantitative easing of foreign central banks increases volatility in basically all countries except Japan. This suggests that the Japanese financial system is largely segmented from rest of the developed world. On the other hand, quantitative easing in other countries has caused changes in volatility in neither domestic, nor foreign stock markets. We do not observe significant increase or decrease of volatility after the quantitative easing announcements.

Table 3 DHAR-GARCH model

| | US | UK | JP | CA | EU | DE | FR | IT |
|---|---|---|---|---|---|---|---|---|
| *constant* | **0.028**$^{a}$ | 0.020 | 0.017 | 0.020 | 0.004 | 0.007 | 0.012 | 0.036 |
| $\varepsilon_{t-1}$ | **-0.389**$^{d}$ | **-0.308**$^{c}$ | **-0.451**$^{d}$ | **-0.298**$^{d}$ | **-0.184**$^{b}$ | **-0.221**$^{c}$ | **-0.166**$^{b}$ | **-0.199**$^{b}$ |
| $RV_{t-1}$ | **-0.134**$^{d}$ | **-0.282**$^{b}$ | **-0.152**$^{b}$ | **-0.337**$^{d}$ | **-0.399**$^{d}$ | **-0.353**$^{d}$ | **-0.423**$^{d}$ | **-0.368**$^{d}$ |
| $RV_{t-1,t-5}$ | 0.004 | 0.128 | -0.006 | **0.141**$^{d}$ | **0.234**$^{b}$ | **0.176**$^{b}$ | **0.254**$^{d}$ | **0.194**$^{b}$ |
| $RV_{t-1,t-22}$ | **0.118**$^{d}$ | **0.135**$^{d}$ | **0.134**$^{d}$ | **0.181**$^{d}$ | **0.151**$^{d}$ | **0.164**$^{d}$ | **0.154**$^{d}$ | **0.155**$^{d}$ |
| $\Delta IR_{t-1}$ | -0.005 | **0.008**$^{d}$ | 0.006 | 0.007 | -0.007 | -0.004 | -0.002 | -0.006 |
| $\Delta FX_{t-1}$ | **0.063**$^{b}$ | 0.006 | **0.107**$^{d}$ | **-0.050**$^{b}$ | 0.031 | 0.028 | **0.045**$^{a}$ | 0.030 |
| $\Delta FX^{2}_{t-1}$ | 0.001 | 0.002 | **0.004**$^{c}$ | 0.000 | 0.000 | 0.001 | -0.001 | 0.001 |
| *Before interest rate meeting* | | | | | | | | |
| $R5B_t^k$ x $RV_{t-6,t-10}$ | -0.011 | -0.011 | -0.005 | -0.005 | -0.009 | -0.005 | -0.005 | 0.004 |
| $R5B_t^k$ x $VAE_t^k$ | 2.005 | -0.348 | -7.942 | 1.141 | -1.383 | -0.104 | -0.606 | -2.752 |
| $R5B_t^k$ x $NA_t^k$ | 0.000 | 0.001 | 0.001 | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 |
| *At interest rate meeting* | | | | | | | | |
| $R_t^k$ x $RV_{t-1}$ | **0.101**$^{d}$ | **0.020**$^{a}$ | **0.023**$^{b}$ | **0.039**$^{a}$ | **0.045**$^{d}$ | **0.048**$^{d}$ | **0.041**$^{d}$ | **0.050**$^{d}$ |
| $R_t^k$ x $S_t^k$ (–) | 0.002 | **-0.021**$^{d}$ | -0.005 | -0.016 | -0.009 | -0.010 | -0.010 | -0.009 |
| $R_t^k$ x $S_t^k$ (+) | **-0.007**$^{d}$ | **0.001**$^{d}$ | 0.000 | -0.008 | 0.008 | 0.003 | 0.006 | 0.004 |
| *After interest rate meeting* | | | | | | | | |
| $R1A_t^k$ x $RV_{t-1}$ | **-0.032**$^{c}$ | -0.018 | -0.007 | -0.015 | -0.008 | -0.007 | -0.006 | -0.021 |
| $R5A_t^k$ x $RV_{t-1}$ | **-0.015**$^{a}$ | -0.003 | **-0.010**$^{a}$ | -0.001 | **-0.014**$^{b}$ | **-0.013**$^{b}$ | **-0.013**$^{b}$ | -0.004 |
| $R5A_t^k$ x $S_t^k$ (–) | **0.007**$^{b}$ | **-0.009**$^{c}$ | **0.007**$^{d}$ | 0.009 | -0.001 | -0.002 | -0.001 | -0.002 |
| $R5A_t^k$ x $S_t^k$ (+) | **0.002**$^{b}$ | **-0.004**$^{d}$ | **0.002**$^{b}$ | 0.007 | **-0.005**$^{d}$ | **-0.005**$^{b}$ | **-0.004**$^{b}$ | **-0.004**$^{b}$ |
| *International development of rates* | | | | | | | | |
| $R5B.W_t^k$ x $RV_{t-6,t-10}$ | 0.005 | 0.001 | 0.003 | **0.007**$^{a}$ | -0.002 | -0.001 | -0.001 | 0.001 |
| $R.W_t^k$ x $RV_{t-1}$ | -0.034 | **0.015**$^{a}$ | | **0.064**$^{d}$ | 0.003 | 0.002 | 0.003 | 0.002 |
| $R1A.W_{tk}$ x $RV_{t-1}$ | 0.002 | 0.003 | -0.004 | -0.011 | 0.009 | 0.008 | 0.004 | 0.006 |
| $R5A.W_{tk}$ x $RV_{t-1}$ | 0.000 | 0.001 | 0.002 | 0.003 | **-0.008**$^{b}$ | -0.005 | -0.005 | -0.005 |
| *Quantitative easing (QE)* | | | | | | | | |
| $Q5B_t^k$ x $RV_{t-6,t-10}$ | 0.007 | 0.005 | 0.022 | | -0.002 | -0.014 | -0.015 | -0.015 |
| $Q_t^k$ x $RV_{t-1}$ | 0.020 | 0.024 | **0.178**$^{d}$ | | -0.006 | 0.023 | 0.031 | 0.047 |
| $Q1A_t^k$ x $RV_{t-1}$ | -0.025 | 0.012 | -0.048 | | -0.054 | -0.115 | -0.086 | **-0.151**$^{c}$ |
| $Q5A_t^k$ x $RV_{t-1}$ | -0.030 | -0.008 | -0.014 | | 0.004 | 0.003 | 0.006 | -0.009 |
| *International QE* | | | | | | | | |
| $Q5B.W_t^k$ x $RV_{t-6,t-10}$ | **0.018**$^{c}$ | 0.004 | 0.011 | **0.016**$^{b}$ | **0.019**$^{b}$ | **0.019**$^{b}$ | **0.019**$^{b}$ | 0.014 |
| $Q.W_t^k$ x $RV_{t-1}$ | | 0.026 | | **0.080**$^{b}$ | 0.002 | -0.001 | 0.001 | 0.016 |
| $Q1A.W_t^k$ x $RV_{t-1}$ | 0.007 | -0.002 | **-0.037**$^{b}$ | -0.028 | -0.016 | -0.014 | -0.013 | -0.031 |
| $Q5A.W_t^k$ x $RV_{t-1}$ | **-0.020**$^{b}$ | 0.001 | -0.005 | 0.008 | 0.009 | 0.006 | 0.007 | 0.009 |
| $Mon_t$ | **-0.141**$^{d}$ | **-0.197**$^{d}$ | -0.026 | **-0.075**$^{b}$ | **-0.177**$^{d}$ | **-0.185**$^{d}$ | **-0.192**$^{d}$ | **-0.239**$^{d}$ |
| $Tue_t$ | **0.117**$^{c}$ | **0.094**$^{b}$ | **0.063**$^{a}$ | **0.074**$^{b}$ | **0.105**$^{c}$ | **0.116**$^{d}$ | **0.121**$^{d}$ | **0.159**$^{d}$ |
| $Thu_t$ | 0.036 | **0.116**$^{d}$ | **0.114**$^{c}$ | 0.010 | **0.114**$^{d}$ | **0.100**$^{c}$ | **0.100**$^{d}$ | **0.080**$^{b}$ |
| $Fri_t$ | **-0.061**$^{b}$ | **0.064**$^{b}$ | **0.076**$^{b}$ | **-0.090**$^{c}$ | **0.055**$^{a}$ | **0.050**$^{a}$ | **0.083**$^{c}$ | **0.068**$^{b}$ |
| $\omega$ | -0.034 | **0.051**$^{a}$ | 0.011 | **-0.127**$^{c}$ | **0.093**$^{a}$ | 0.021 | 0.024 | **0.015**$^{b}$ |
| $\alpha$ | **0.031**$^{b}$ | **0.090**$^{b}$ | **0.043**$^{b}$ | **0.063**$^{d}$ | **0.161**$^{d}$ | **0.074**$^{c}$ | **0.075**$^{c}$ | **0.046**$^{d}$ |
| $\beta$ | **0.973**$^{d}$ | **0.665**$^{d}$ | **0.915**$^{d}$ | **0.900**$^{d}$ | **0.506**$^{b}$ | **0.837**$^{d}$ | **0.824**$^{d}$ | **0.890**$^{d}$ |
| $\gamma$ | 0.087 | | | **0.058**$^{b}$ | | | | |
| $\lambda$ | **0.917**$^{d}$ | **0.256**$^{b}$ | **0.889**$^{d}$ | **0.342**$^{c}$ | 0.106 | **0.505**$^{c}$ | **0.195**$^{b}$ | **0.610**$^{c}$ |
| $\varsigma$ | **2.797**$^{d}$ | **2.052**$^{d}$ | **2.102**$^{d}$ | **2.353**$^{d}$ | **1.570**$^{d}$ | **2.372**$^{d}$ | **1.910**$^{d}$ | **2.866**$^{d}$ |
| *Diagnostics* | | | | | | | | |
| SC | 0.812 | 0.497 | 0.807 | 0.858 | 0.863 | 0.953 | 0.671 | 0.537 |
| $SC^2$ | 0.419 | 0.145 | 0.151 | 0.215 | 0.645 | 0.058 | 0.050 | 0.396 |
| Sign bias test (joint effect) | 0.837 | 0.183 | 0.516 | 0.694 | 0.432 | 0.272 | 0.023 | 0.003 |
| Log Likelihood | -2104.3 | -1654.8 | -1868.7 | -2097.3 | -1955.6 | -1841.3 | -1791.0 | -1884.3 |
| Bayesian Information Criterion | 1.661 | 1.326 | 1.534 | 1.655 | 1.536 | 1.455 | 1.405 | 1.488 |
| Correlation fitted vs. observed | 0.487 | 0.530 | 0.505 | 0.523 | 0.561 | 0.532 | 0.543 | 0.542 |
| # observations | 2719 | 2728 | 2626 | 2706 | 2747 | 2744 | 2770 | 2740 |

*Note: Subscripts $^{d}$, $^{c}$, $^{b}$, $^{a}$ denote significance at the 0.1%, 1%, 5%, 10% significance level. SC and $SC^2$ are p-values from the Escanciano and Lobato (2009) test on first order autocorrelation and conditional heteroscedasticity. In row Sign bias test (joint effect) we report p-value also.*

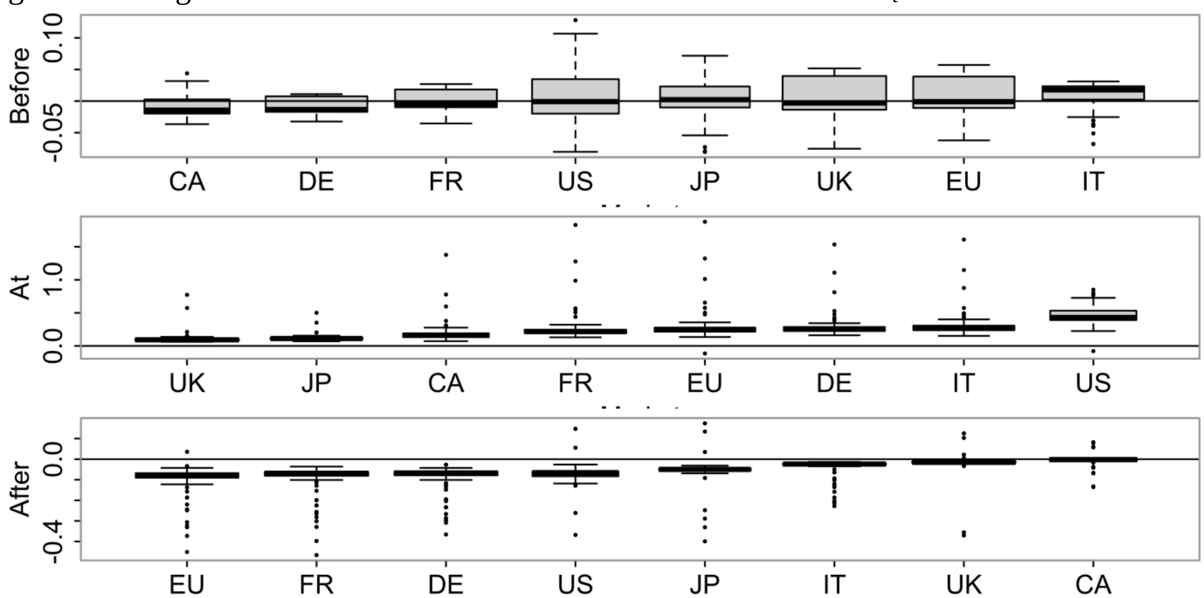
Table 4 HAR-GARCH model

| | US | UK | JP | CA | EU | DE | FR | IT |
|---|---|---|---|---|---|---|---|---|
| *constant* | **0.138**$^{d}$ | **0.145**$^{d}$ | **0.284**$^{d}$ | **0.201**$^{c}$ | **0.309**$^{d}$ | **0.209**$^{d}$ | **0.266**$^{d}$ | **0.288**$^{d}$ |
| $\varepsilon_{t-1}$ | **-0.398**$^{d}$ | **-0.315**$^{d}$ | **-0.431**$^{d}$ | **-0.303**$^{d}$ | **-0.195**$^{c}$ | **-0.228**$^{d}$ | **-0.166**$^{c}$ | **-0.179**$^{c}$ |
| $RV_{t-1}$ | **0.875**$^{d}$ | **0.725**$^{d}$ | **0.816**$^{d}$ | **0.666**$^{d}$ | **0.606**$^{d}$ | **0.652**$^{d}$ | **0.573**$^{d}$ | **0.605**$^{d}$ |
| $RV_{t-1,t-5}$ | **-0.007**$^{d}$ | 0.117 | 0.016 | **0.128**$^{d}$ | **0.219**$^{c}$ | **0.168**$^{d}$ | **0.249**$^{d}$ | **0.212**$^{d}$ |
| $RV_{t-1,t-22}$ | **0.104**$^{d}$ | **0.118**$^{d}$ | **0.101**$^{d}$ | **0.159**$^{d}$ | **0.113**$^{d}$ | **0.135**$^{d}$ | **0.121**$^{d}$ | **0.121**$^{d}$ |
| $\Delta IR_{t-1}$ | -0.008 | **0.007**$^{c}$ | -0.002 | -0.001 | **-0.020**$^{b}$ | -0.013 | -0.013 | **-0.017**$^{a}$ |
| $\Delta FX_{t-1}$ | **0.062**$^{a}$ | 0.005 | **0.107**$^{d}$ | **-0.048**$^{b}$ | 0.033 | 0.030 | **0.045**$^{a}$ | 0.029 |
| $\Delta FX^{2}_{t-1}$ | 0.001 | **0.003**$^{a}$ | **0.005**$^{d}$ | 0.001 | 0.000 | 0.001 | 0.000 | 0.002 |
| *Before interest rate meeting* | | | | | | | | |
| $R5B_t^k \times RV_{t-6,t-10}$ | -0.008 | -0.008 | -0.005 | 0.000 | -0.009 | -0.004 | -0.005 | 0.003 |
| $R5B_t^k \times VAE_t^k$ | 2.920 | 0.449 | -8.834 | 2.383 | 0.832 | 1.554 | 1.291 | -0.634 |
| $R5B_t^k \times NA_t^k$ | 0.000 | 0.000 | 0.001 | -0.001 | 0.001 | 0.000 | 0.000 | 0.000 |
| *At interest rate meeting* | | | | | | | | |
| $R_t^k \times RV_{t-1}$ | **0.098**$^{d}$ | **0.020**$^{a}$ | **0.026**$^{b}$ | **0.033**$^{a}$ | **0.045**$^{d}$ | **0.048**$^{d}$ | **0.041**$^{d}$ | **0.051**$^{d}$ |
| $R_t^k \times S_t^k\,(-)$ | 0.000 | **-0.023**$^{d}$ | -0.006 | -0.011 | -0.009 | -0.010 | -0.010 | -0.009 |
| $R_t^k \times S_t^k\,(+)$ | **-0.008**$^{d}$ | **0.005**$^{d}$ | -0.000 | -0.002 | 0.007 | 0.002 | 0.006 | 0.004 |
| *After interest rate meeting* | | | | | | | | |
| $R1A_t^k \times RV_{t-1}$ | **-0.034**$^{c}$ | -0.017 | -0.009 | -0.020 | -0.008 | -0.006 | -0.005 | -0.018 |
| $R5A_t^k \times RV_{t-1}$ | -0.015 | -0.004 | **-0.010**$^{a}$ | -0.000 | **-0.015**$^{b}$ | **-0.013**$^{b}$ | **-0.013**$^{b}$ | -0.006 |
| $R5A_t^k \times S_t^k\,(-)$ | **0.007**$^{d}$ | **-0.009**$^{d}$ | **0.007**$^{d}$ | 0.013 | -0.001 | -0.002 | -0.000 | -0.020 |
| $R5A_t^k \times S_t^k\,(+)$ | **0.002**$^{d}$ | **-0.003**$^{d}$ | **0.002**$^{c}$ | 0.011 | **-0.005**$^{b}$ | **-0.005**$^{b}$ | **-0.005**$^{b}$ | **-0.004**$^{a}$ |
| *International development of rates* | | | | | | | | |
| $R5B.W_t^k \times RV_{t-6,t-10}$ | **0.006**$^{b}$ | 0.002 | 0.003 | **0.007**$^{a}$ | -0.001 | -0.001 | 0.000 | 0.000 |
| $R.W_t^k \times RV_{t-1}$ | -0.041 | **0.015**$^{a}$ | | **0.058**$^{d}$ | 0.003 | 0.001 | 0.003 | 0.001 |
| $R1A.W_{tk} \times RV_{t-1}$ | 0.003 | 0.004 | -0.003 | -0.009 | **0.009**$^{a}$ | 0.008 | 0.005 | 0.007 |
| $R5A.W_{tk} \times RV_{t-1}$ | 0.000 | 0.001 | 0.001 | 0.002 | **-0.009**$^{b}$ | -0.006 | **-0.006**$^{a}$ | -0.006 |
| *Quantitative easing (QE)* | | | | | | | | |
| $Q5B_t^k \times RV_{t-6,t-10}$ | 0.009 | 0.007 | 0.020 | | 0.002 | -0.011 | -0.011 | -0.008 |
| $Q_t^k \times RV_{t-1}$ | 0.023 | 0.028 | **0.179**$^{d}$ | | 0.001 | 0.028 | 0.036 | 0.049 |
| $Q1A_t^k \times RV_{t-1}$ | -0.021 | 0.015 | -0.044 | | -0.048 | -0.110 | -0.078 | **-0.143**$^{c}$ |
| $Q5A_t^k \times RV_{t-1}$ | -0.026 | -0.006 | -0.020 | | 0.010 | 0.008 | 0.012 | -0.004 |
| *International QE* | | | | | | | | |
| $Q5B.W_t^k \times RV_{t-6,t-10}$ | **0.019**$^{c}$ | 0.005 | **0.012**$^{a}$ | **0.018**$^{b}$ | **0.022**$^{b}$ | **0.021**$^{c}$ | **0.021**$^{b}$ | **0.018**$^{a}$ |
| $Q.W_t^k \times RV_{t-1}$ | | 0.028 | | **0.086**$^{b}$ | 0.008 | 0.004 | 0.006 | 0.022 |
| $Q1A.W_t^k \times RV_{t-1}$ | 0.009 | -0.003 | **-0.032**$^{b}$ | -0.026 | -0.013 | -0.012 | -0.011 | -0.027 |
| $Q5A.W_t^k \times RV_{t-1}$ | -0.019 | 0.002 | -0.006 | **0.010**$^{a}$ | 0.012 | 0.008 | 0.009 | 0.012 |
| $Mon_t$ | **-0.176**$^{d}$ | **-0.224**$^{d}$ | **-0.089**$^{c}$ | **-0.125**$^{b}$ | **-0.211**$^{d}$ | **-0.211**$^{d}$ | **-0.219**$^{d}$ | **-0.268**$^{d}$ |
| $Tue_t$ | **0.078**$^{d}$ | **0.061**$^{a}$ | -0.023 | 0.018 | **0.072**$^{b}$ | **0.089**$^{c}$ | **0.092**$^{c}$ | **0.121**$^{d}$ |
| $Thu_t$ | -0.003 | **0.083**$^{c}$ | 0.031 | **-0.045**$^{a}$ | **0.080**$^{b}$ | **0.074**$^{b}$ | **0.072**$^{b}$ | 0.045 |
| $Fri_t$ | **-0.095**$^{b}$ | 0.035 | 0.016 | **-0.140**$^{c}$ | 0.022 | 0.025 | **0.057**$^{b}$ | 0.038 |
| $\omega$ | **-0.045**$^{a}$ | **0.054**$^{a}$ | 0.023 | **-0.168**$^{c}$ | 0.089 | 0.022 | 0.026 | **0.015**$^{b}$ |
| $\alpha$ | **0.022**$^{a}$ | **0.094**$^{c}$ | 0.058 | **0.062**$^{c}$ | **0.156**$^{c}$ | **0.075**$^{c}$ | **0.078**$^{c}$ | **0.045**$^{d}$ |
| $\beta$ | **0.964**$^{d}$ | **0.645**$^{d}$ | **0.856**$^{d}$ | **0.868**$^{d}$ | **0.524**$^{b}$ | **0.832**$^{d}$ | **0.808**$^{d}$ | **0.890**$^{d}$ |
| $\gamma$ | **0.103**$^{d}$ | | | **0.071**$^{b}$ | | | | |
| $\lambda$ | **0.879**$^{d}$ | **0.278**$^{b}$ | **0.890**$^{d}$ | **0.328**$^{b}$ | **0.108** | **0.492**$^{c}$ | **0.195**$^{b}$ | **0.658**$^{c}$ |
| $\varsigma$ | **2.790**$^{d}$ | **2.085**$^{d}$ | **2.114**$^{d}$ | **2.357**$^{d}$ | **1.565**$^{d}$ | **2.413**$^{d}$ | **1.917**$^{d}$ | **2.950**$^{d}$ |
| *Diagnostics* | | | | | | | | |
| SC | 0.766 | 0.473 | 0.961 | 0.829 | 0.711 | 0.968 | 0.594 | 0.563 |
| $SC^2$ | 0.536 | 0.135 | 0.192 | 0.277 | 0.520 | 0.057 | 0.052 | 0.403 |
| Sign bias test (joint effect) | 0.924 | 0.160 | 0.693 | 0.788 | 0.365 | 0.3401 | 0.044 | 0.006 |
| Log Likelihood | -2101.4 | -1650.6 | -1853.5 | -2090.6 | -1942.9 | -1835.3 | -1782.0 | -1876.2 |
| Bayesian Information Criterion | 1.659 | 1.323 | 1.522 | 1.650 | 1.527 | 1.450 | 1.398 | 1.482 |
| Correlation fitted vs. observed | 0.876 | 0.873 | 0.812 | 0.850 | 0.800 | 0.850 | 0.845 | 0.851 |
| # observations | 2719 | 2728 | 2626 | 2706 | 2747 | 2744 | 2770 | 2740 |

*Note: Subscripts $^{d}$, $^{c}$, $^{b}$, $^{a}$ denote significance at the 0.1%, 1%, 5%, 10% significance level. SC and $SC^2$ are p-values from the Escanciano and Lobato (2009) test on first order autocorrelation and conditional heteroscedasticity. In row Sign bias test (joint effect) we report p-value also.*

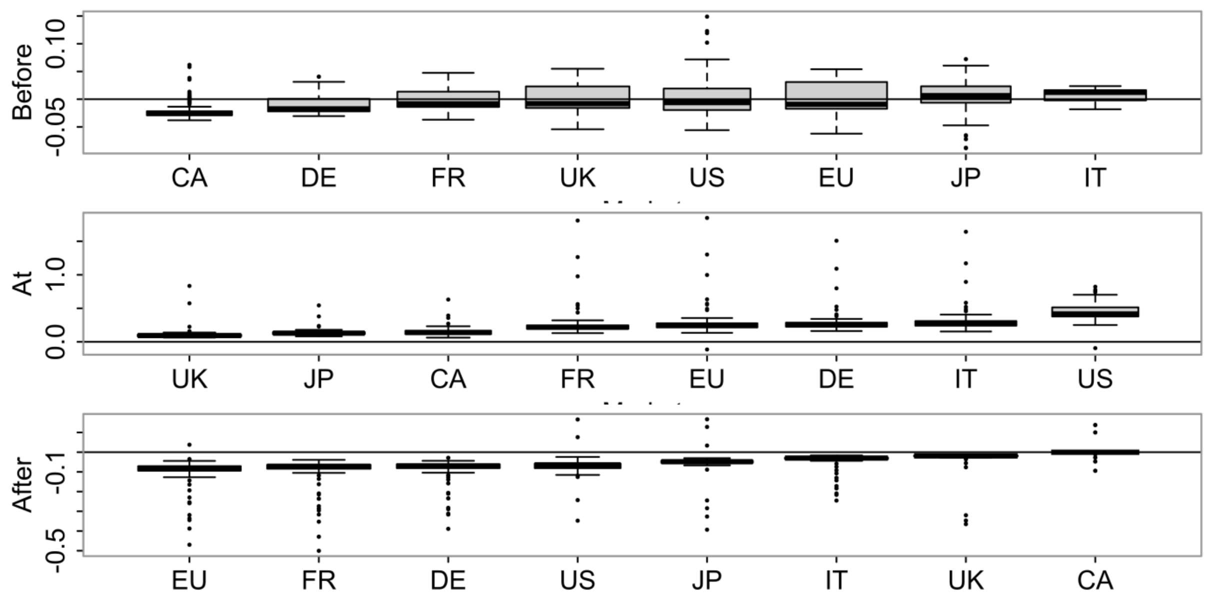
The answer to our core research question, whether central banks' announcements have stabilizing or destabilizing effect on the stock markets, we have graphically summarized our results in Figure 2 (Figure 3). Regardless of whether we model changes or level of the realized volatility, the average impact for central bank announcements on volatility is not significant before the announcement, positive during the announcement day and negative during the 5-day period after the announcement. The reactions appear to be strongest for the US and European markets.

Figure 2 Average effects before/at/after rate announcement on the $\Delta RV_t$




*Notes: All effects are calculated only for the corresponding event period using coefficients from Table 3. In case of the before period we calculated* $\kappa_1^* \; x \; (R5B_t^k \; x \; RV_{t-6,t-10}) + \kappa_2^* \; x \; (R5B_t^k \; x \; VAE_t^k) + \kappa_3^* \; x \; (R5B_t^k \; x \; NA_t^k)$ *only for dates that fall into the "before interest rate meeting", where* $\kappa_j^*$ *are estimated coefficients. The resulting effects are plotted as boxplots. At the event day the plotted values come from* $\kappa_4^* \; x \; (R_t^k \; x \; RV_{t-1}) + \kappa_5^* \; x \; (R_t^k \; x \; S_t^k\,(-)) + \kappa_6^* \; x \; (R_t^k \; x \; S_t^k\,(+))$*, and for after the event day period, the values are* $\kappa_7^* \; x \; (R5A_t^k \; x \; RV_{t-1}) + \kappa_8^* \; x \; (R5A_t^k \; x \; S_t^k\,(-)) + \kappa_9^* \; x \; (R5A_t^k \; x \; S_t^k\,(+))$.

Figure 3 Average effects before/at/after rate announcement on the $RV_t$




*Notes: All effects are calculated only for the corresponding event period using coefficients from Table 4. In case of the before period we calculated* $\kappa_1^* \times (R5B_t^k \times RV_{t-6,t-10}) + \kappa_2^* \times (R5B_t^k \times VAE_t^k) + \kappa_3^* \times (R5B_t^k \times NA_t^k)$ *only for dates that fall into the "before interest rate meeting", where* $\kappa_j^*$ *are estimated coefficients. The resulting effects are plotted as boxplots. At the event day the plotted values come from* $\kappa_4^* \times (R_t^k \times RV_{t-1}) + \kappa_5^* \times (R_t^k \times S_t^k(-)) + \kappa_6^* \times (R_t^k \times S_t^k(+))$*, and for after the event day period, the values are* $\kappa_7^* \times (R5A_t^k \times RV_{t-1}) + \kappa_8^* \times (R5A_t^k \times S_t^k(-)) + \kappa_9^* \times (R5A_t^k \times S_t^k(+))$.

## 5. Conclusion

In this paper, we investigated the impact of monetary policy announcement on stock market volatility. Monetary policy announcements belong to most important macroeconomic news. Not surprisingly, significant research has been devoted to study these events. However, research analyzing the impact of these events on the volatility of the stock markets is relatively scarce, and particularly when it comes to cross-country studies and realized volatility. We therefore analyze a rather broad data sample covering five central banks and stock markets in US, Canada, Japan, UK, Germany, France, Italy and Eurozone as a whole.

Our most important contribution is how we approach this problem. Previous studies have analyzed an impact of news announcements on volatility of financial markets utilizing either GARCH models, or implied volatility. However, GARCH models are based on one price observation per day, and therefore cannot estimate volatility precisely. Implied volatility is not suitable for this purpose for other reason. On a day of scheduled macroeconomic announcement, implied volatility should drop simply because implied volatility captures volatility over following 30-day time period. Therefore, by observing drop in implied volatility we cannot conclude whether event had stabilizing or destabilizing impact.

In order to avoid both these obstacles we utilized realized volatility calculated from high-frequency data. High frequency data has been previously used in connection with monetary policy announcements in order to evaluate immediate impact of these announcements. We, on the contrary, are interested on the longer term impact monetary policy announcements. In particular, we study the impact of these events on realized volatility five days before, five days after and at the day of announcement.

Even though response of stock market volatility to central bank announcements to some extend vary across countries, we can draw several conclusions that hold in general. As expected, volatility increases on the day of the announcement. During the 5-day period before the announcements is volatility neither increased nor decreased. Most importantly, we find that volatility is decreased during the 5-day period after the announcement. We therefore conclude that monetary policy had stabilizing impact on the stock market during the investigated period 2006 – 2016.

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