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# ECB Announcements and Stock Market Volatility

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## Abstract

This paper documents that ECB announcements increase the stock market volatility in the euro area (EA) on the same day. I consider two volatility measures from January 1998 to May 2019. First, a realized volatility measure uses intraday data for 8 different stock market indices. Second, a range measure approximates volatility using daily prices from 11 national stock market indices. Employing event study methods I find a stronger impact following the global financial crisis starting in 2007. All assets react similarly so that no national peculiarities arise. The effects also spill over to 7 non-EA markets analyzed.

**JEL classification:** E52, E58, G12, G14

**Keywords:** ECB announcements, asset price volatility, event study

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# 1 Introduction

Monetary policy and financial market activity are highly intertwined. Recent asset pricing models like Drechsler et al. (2018) note the relevance of the nominal interest rate set by central banks. A reduction in the nominal rate provides more liquidity which, in turn, leads to higher asset prices and volatility. Uncertainty about the future path of interest rates helps predict future variance of equity returns (Kaminska and Roberts-Sklar (2018)). However, given the lower bound in many economies, the interest rate is usually insufficient to fully understand current developments on financial markets. If the interest rate instrument is not available, then the communication of non-standard monetary policy tools may have a first-order impact on the volatility of financial markets. This indicates the relevance of central bank announcements for asset price volatility, which I empirically assess in this study.

The importance of central bank communication is well-established in the literature (cf. Blinder et al. (2008) for a survey). Yet numerous questions remain open because monetary policy announcements are complex. They occasionally concern aspects beyond the nominal interest rate such as legal regulations, forward guidance and quantitative easing measures. Not only its contents but also the channel of communication plays a role. Gertler and Horvath (2018) detect stock market responses considering various communication tools around scheduled meetings such as speeches, media interviews and conference discussions. Schmeling and Wagner (2019) show that the specific tone inherent to central bank statements moves asset prices. Many event studies document how financial markets react to central bank announcements. Unconventional monetary policy surprises affect the Eurostoxx 50 in Haitsma et al. (2016) while Fausch and Sigonius (2018) detect significant reactions for German stock returns. Policies by the European Central Bank (ECB) boosted equity prices between 2007 and 2012 (Fratzscher et al. (2016)). Relatedly, Georgiadis and Gräb (2016) provide evidence for an increase in equity returns in reaction to ECB's asset purchase program announcements. These studies, however, mainly pay attention to *level* effects on financial markets.

To my knowledge existing event studies have not explicitly addressed financial markets' *volatility* yet. Volatility in financial markets has large implications for real economic activity. Financial volatility represents uncertainty, which hinders economic growth, for example because investors reduce the amount of foreign direct investment in response to an increased uncertainty level. Volatility measures indicate markets' sensitivity, that is whether they are

getting more nervous (volatility increase) or calmer (volatility decrease). A quantification of volatility reactions would be a useful tool for both policy makers and practitioners. It adds important information to any statement about an increase/decrease of an asset in reaction to announcements. The volatility mirrors the immediate reaction on financial markets during an announcement day while the return gives merely the outcome at the end of the trading day. For instance, a rise in a specific asset at the end of the trading day could be either caused by a few transactions leading to a smooth price increase or by many transactions over- and undershooting the final price. The asset's volatility measure reflects which of the two scenarios is more appropriate for the trading day.

Policy makers have been aware of the relevance of their announcements since the early stages of the euro. Willem Duisenberg, former president of the ECB, noted at a press conference on November 2001: '[...] bi-monthly meetings of the Governing Council also lead, every two weeks, to speculation in the markets and higher volatility [...] but we thought that it might inspire some calm in the markets if [...] the monetary policy stance will only take place once a month.[...]' (ECB (2001)). This communication strategy took effect in 2002. In 2015, the ECB further reduced its monetary policy meeting frequency from four to every six weeks. Thus, the ECB follows the Federal Reserve that has eight scheduled meetings per year. Other major central banks recently reduced their quantity of regular meetings as well. In 2016, the Bank of Japan reduced from 14 to 8 meetings and the Bank of England changed from a monthly to an eight-meeting schedule. These adjustments aim to reduce financial volatility. I examine the success of these policy changes, namely whether fewer announcements lead to less volatility. While the paper uses the euro area (EA) as a laboratory to tackle this research question the findings are potentially relevant for other central banks. The focus on the ECB is not only relevant as the EA accounts for about one fifth of world GDP and the euro being an important reserve currency but especially interesting given EA's unique structure of several countries sharing a common central bank.

Central bank announcement effects are typically not limited to a special sector but concern the whole economy. Therefore, my analysis focuses on national stock market indices. Sosvilla-Rivero and Morales-Zumaquero (2012) distinguish a different volatility behavior between core and peripheral EA sovereign bond yields. The present study checks whether the same holds for major national stock market indices. In contrast to the work that tries to predict volatility and optimize the quality of forecast models, this study infers asset volatility reactions from crucial

events. News from different sources simultaneously influences asset prices, and a quantification of the effect of a single event on financial markets is not trivial. However, to quantify the central bank's contribution is worthwhile so that a central banker is aware of the consequences for financial stability when uttering a statement related to monetary policy. At the same time, asset price developments can also be a driver of monetary policy. For instance, Cieslak and Vissing-Jorgensen (2017) assess the impact of the stock market on U.S. monetary policy using a textual approach. They find that the Federal Reserve reacts with accommodative communication to low stock market returns. One needs to bear in mind this interplay between financial markets and central bank communication when deducing the influence of ECB's announcements on the stock markets of its respective member economies.

Announcements by the ECB provide new information to the market. On the one hand, this can reduce uncertainty of market participants and thus asset volatility decreases. On the other hand, if the provided information does not meet market participants' expectations, adjustments on the financial market increase the volatility level. The latter is expected because any communication consists of releasing private information to the public. This release is very likely to provoke some market reactions equivalent to an increase in volatility. For instance, credibly announced accommodative measures such as asset purchase programs might further reinforce volatility on financial markets: An increased demand for assets causes more transactions and higher asset prices. Moreover, studies like Fratzscher et al. (2016) support a volatility increase. They prove a significant equity price rise in response to ECB announcements.

The rest of the paper proceeds as follows. Section 2 describes the methodology and the data. Section 3 presents the empirical results comprising robustness checks. The implications of announcements for future volatility will be assessed in Section 4. Section 5 discusses the identification of monetary policy shocks and building on that Section 6 incorporates local projections methods. Section 7 concludes.

## 2 Methodology and Data

To assess the effect of monetary policy on financial markets, I use key stock market indices of different EA economies as dependent variable. This goes beyond studies like Haitzma et al. (2016) that only look at an aggregated European index. Empirical studies typically use European indices or take the German market as a proxy for the EA. Recently, Cieslak and Schrimpf

(2019) use futures of the DAX and 3-month-Euribor around events to construct monetary policy surprises of ECB communication. National equity markets differ in many dimensions such as regulations, market capitalization, number of traded firms and turnover. A separate consideration of national markets thus allows me to compare country-specific effects or to allocate assets to certain groups such as core versus peripheral countries in the EA. Related literature distinguishes core countries and periphery countries. For this data set, core countries are Austria (AU), Belgium (BE), Finland (FI), France (FR), Germany (DE), and the Netherlands (NL). Periphery countries are Greece (GR), Ireland (IR), Italy (IT), Portugal (PT), and Spain (ES). The latter are also referred to as distressed countries in the literature. ECB’s policy communication does not only affect its member countries but potentially extends to non-EA markets, McQuade et al. (2015) for example, find a strong reaction in Eastern European countries. To test for possible spill-over effects, I also include the stock markets of Denmark (DK), Great Britain (GB), Japan (JP), Norway (NW), Sweden (SW), Switzerland (CH), and the United States (US).

Two distinct measures are analyzed in the following. First, a realized volatility measure uses intraday data for selected stock market indices. Second, a (daily) price range measure approximates volatility to enlarge both the observation period and cross-section of stock markets. The section concludes by illustrating both measures.

## 2.1 High-frequency Realized Volatility

In its simplest form realized volatility is defined as the sum of squared log returns

$$RV_t = \sum_{i=1}^n r_{i,t}^2, \quad (1)$$

with  $r_{i,t} = \log(p_{i,t}) - \log(p_{i,t-1})$  for all  $i = 1, \dots, n$  intraday values at day  $t$ . Data for 7 different national EA and 7 non-EA stock market indices as well as the Eurostoxx 50 index are obtained from Heber et al. (2009). They exist at a 5 and 10 minutes frequency.<sup>1</sup> I estimate the ordinary least squares regression

$$RV_t = \alpha + \beta_1 RV_{t-1} + \beta_2 \Delta \ln(MSCI_t) + \gamma ECB_t + \varepsilon_t, \quad (2)$$

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<sup>1</sup>Note that the number of  $n$  per trading day depends on the specific stock market. For example, the German DAX refers to the stock market in Frankfurt, which is open for trade from 8am until 8pm. Considering 5 minutes frequency, this results in  $n = 144$  observations to determine the realized volatility on a particular day.

with  $RV_t \in \{rv_{5,t}, rv_{10,t}\}$  representing the 5 and 10 minutes frequency realized volatilities, respectively. The constant  $\alpha$  captures the influence of unobserved factors. Two control variables are used. To account for possible trends in the data, this day's volatility  $RV_t$  is dependent on that of the previous day  $RV_{t-1}$ . The change of the logarithmic prices of the country-specific Morgan Stanley Capital International (MSCI) Index  $\Delta \ln(MSCI_t)$  controls for other surprises than monetary policy.<sup>2</sup> All variables are obtained from Datastream.<sup>3</sup>

Further control variables such as surveys on expectations of financial traders could refine the analysis. For instance, the Ifo Business Climate Index represents beliefs on the German economy while the Economic Sentiment Indicator by the European Commission captures developments on the European level. However, those indicators are issued monthly and a transformation to a daily frequency would bias the results. Moreover, to be suitable for my study such a control variable should be available from 1998 onwards at a daily frequency. Relevant macroeconomic releases such as monthly unemployment statistics or quarterly GDP growth figures commonly differ from their predicted values and constitute surprises that potentially affect asset price movements. These releases take place at dates at the end of the month. In contrast, monetary policy announcements are spread throughout the month. They typically do not occur at the very last day of a month which cushions the concern of an overlap with macroeconomic news.

The dummy variable  $ECB_t$  captures all of the ECB's press releases during the observation period taking the value of 1 on such a day, and 0 otherwise. It measures the impact of the announcements on asset's volatility. To guarantee an objective choice of announcements, I include every press release on monetary policy from the ECB's homepage. This approach is in line with studies like Brusa et al. (2019) which exclude unscheduled announcements and rely on central banks' website as the only source of announcements. Consequently, information on forward guidance, asset purchase announcements, interest rates, legal regulations and so forth are all equally weighted. The error term is  $\varepsilon_t \sim (0, \sigma^2)$ .

An ECB announcement gives private information to the market. Asset markets should immediately react and exhibit an increased volatility during that day. This hypothesis translates into the expectation of  $\gamma > 0$ .

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<sup>2</sup>One might argue that incorporating a national stock market index is problematic due to double accounting considerations. Two arguments weaken this objection. First, a simple first-difference measure does not conflict a volatility measure. Second, the results are robust to an inclusion of global measures. See Section 3.3 for details.

<sup>3</sup>See the descriptive statistics in Table A3 in the Appendix for details.

## 2.2 Daily price range

To be able to compare more economies for a longer period, I take the prices of national stock market indices and construct a range measure which acts as a cautious proxy of volatility. This measure allows me to start the analysis from the beginning of the EA in 1998 and to include the markets of Austria, Ireland, Greece, Portugal as well. The latter is essential for a comprehensive study of the core/periphery pattern.

The range measure is defined as the difference between the maximum price  $p_t^{max}$  and the minimum price  $p_t^{min}$  during a day divided by the opening price  $p_t^{open}$  to make the values comparable across the different country indices:  $range_t = \frac{p_t^{max} - p_t^{min}}{p_t^{open}}$ . It is a simple approximation to daily volatility because it depicts the daily price range taking into consideration the intraday highest and lowest price. In this way a high number reflects a high fluctuation while a low number represents a steady development during that day. Taking into account more observations during the day would not add further information to the range. Additionally, the typical trading pattern likely biases the results. High trading activity at the beginning and at the end of the trading day contrasts with low activity at lunch time.

Accordingly, I replace the dependent variable  $RV_t$  in Eq. (2) by  $range_t$  giving

$$range_t = \alpha + \beta_1 range_{t-1} + \beta_2 \Delta \ln(MSCI_t) + \gamma ECB_t + \varepsilon_t. \quad (3)$$

Country-specific volatility indices measure the implied volatility, that is the expected fluctuations on derivative markets during a defined future horizon (typically 30 days). They exist only for a few national stock markets and are available for a shorter period than the original market indices. Nonetheless, I incorporate the respective volatility indices of the DAX 30, CAC 40, AEX, and Eurostoxx 50 as dependent variables, too. The reasoning is as follows. A variation of these indices is a valid measure of volatility because it refers to the degree of change in market participants' expectations. If the announcements change market expectations then the prices of options change which, in turn, alter the respective volatility index. Hence, the degree of this change reflects the impact of the new information provided by the ECB.

## 2.3 Descriptive Statistics

Starting with the introduction of the euro, I examine a period longer than 20 years to establish whether there is a long-term persistence independent of the financial crisis. This contributes to



the literature as most related studies begin their analysis from 2007 onwards (e.g. Fratzscher et al. (2016), Georgiadis and Gräb (2016), Sosvilla-Rivero and Morales-Zumaquero (2012)). The data availability varies across the countries and measures meaning that one has to interpret the long-term results with caution. Specifically, data for  $range_t$  are available between January 1998 and May 2019, while the observations of  $rv_{5,t}$  and  $rv_{10,t}$  start in January 2000.

The visual representation of the applied dependent variables appears stationary. Figure 1 and Figure 2 serves as an example for the German stock market. The other assets' series are not reported because they behave similarly. The realized volatility and range measures show a similar pattern. For instance, they both peak during the dot.com bubble in 2001 and during the financial crisis in 2008. The volatility declines since 2010 and exhibits lower volatility peaks in the close past. The advantage of realized volatility over the range measure is that intraday data should better proxy the behavior of the financial market during an announcement day. Nonetheless, the subsequent results are very similar for both specifications supporting the use of the range measure as a proxy. Moreover, the range measures are highly correlated with its respective realized volatility counterparts (correlation coefficients around 0.78 for all indices except for Finland where it is only 0.42).

[Figure 1 and Figure 2 about here]

Since the augmented Dickey Fuller (ADF) unit root test is rejected it is deemed appropriate to work with level data.<sup>4</sup> In contrast, the ADF test for the MSCI does indicate integration of order 1. Therefore, its (logarithmic) first-differences are justified. The Breusch-Godfrey and White test indicate autocorrelation and heteroskedasticity, respectively, in this data set. To cope with these properties, I use standard errors according to Newey and West (1987)<sup>5</sup>.

The correlation coefficients of the dependent variables in Tables A2 and A3 in the Appendix give additional insights. The positive signs throughout the correlation coefficients indicate that European markets move in the same direction. Therefore, all stocks should be affected in the same direction as well – merely the extent differs, which this paper aims to identify. Specifically by exploiting a large cross-section I intend to test for groups that are more sensitive to ECB announcements than others. For example I expect stronger impacts in periphery markets than in core markets and comparatively low effects in non-EA markets. The former builds on the

<sup>4</sup>Using first differences or growth rates slightly deteriorates the significance of the results (available upon request). However, the overall results remain unchanged confirming the subsequent conclusions.

<sup>5</sup>The maximum lag length in the autocorrelation structure is adjusted according to the Bartlett Kernel with  $T^{\frac{1}{3}}$  for each regression.

established research on government bond yields. Those are highly intertwined with stock prices. The later takes into account that non-EA markets should rather react to communications of their own central bank. Due to a larger sample, the discussion that follows focuses on the coefficients of  $range_t$ , however, the relationships are similar for those of  $RV_t$ . Varying cross-European correlation coefficients ranging between 0.4 and 0.9 motivate to evaluate distinct effects across different markets. For instance, high coefficients around 0.9 exist for German vis-à-vis Dutch and French stock markets whereas the market of Greece has a correlation lower than 0.5 with respect to the other assets. The coefficients also indicate spill-over effects. In general, the correlations are higher for European markets. While Japan has relatively low coefficients the market of Great Britain seems to show a similar volatility behavior with respect to the stock markets of core countries (around 0.8). The only noticeable difference between  $range_t$  and  $RV_t$  is the case of Finish  $RV_t$  showing coefficients lower than 0.2 with respect to the other markets (exception is neighbor country Sweden with a very high value of 0.92). Table A3 reveals that the Greek market has the highest average range and the German market has the highest average realized volatility. However, these figures do not necessarily hint at the potential degree ECB announcements affect the national stock markets because this information is only one of many that moves financial markets.

### 3 Results

First, I present the findings for the full sample to quantify the overall effect. Second, the data are split up into a pre-crisis and a post-crisis period. Finally, several robustness checks support the validity of these findings.

#### 3.1 Long-term period

Table 1 displays the results of the realized volatility specification defined in Eq. (2) for 8 different stock indices using a 5 and a 10 minutes frequency, respectively. The last day's volatility has a great positive impact on this day's volatility in all cases proving the previously detected autocorrelation. In contrast, the logarithmic change of the country-specific MSCI significantly reduces the volatility.<sup>6</sup> Regarding the ECB announcements, the economies seem to be equally affected with similar estimators and significance levels. For instance, a press release by the ECB

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<sup>6</sup>The Finish stock market forms an exception.

increases both  $DE_5$  and  $FR_5$  by around 0.006 bps, on average. ECB's press releases significantly bolster realized volatility for both the 5 and the 10 minutes frequency measure during the sample period. It is worth mentioning that there is no noticeable discrepancy between both frequencies. Three coefficients of 5 minutes frequency are higher whereas the other five are lower with respect to 10 minutes frequency. Table 2 shows the results of the same specification for non-EA stock markets. There is a strong discrepancy between both groups: While the realized volatility is highly affected in EA countries with estimators at a 1% significance level for all but Finland, this effect only spills over to Switzerland. The other six markets are less affected – the estimator of the Danish index is even insignificant. As above, the choice between 5 versus 10 minutes frequency does not change the findings.

[Table 1 and Table 2 about here]

Consequently, the previously stated hypothesis  $\gamma > 0$  is confirmed. New information itself seems to increase asset's volatility. Traders are presumably nervous because they expect new information from the ECB, typically a change in monetary policy. They react accordingly – independent of the actual message of the respective press release. This reaction induces more trading activity which is reflected by an increased volatility during those days. Figure 3 plots the 95% confidence intervals of the dummy variable's estimator  $ECB_t$ . When comparing the countries, no particular pattern emerges such as core versus peripheral European countries or euro versus non-euro markets. The dummy variable's estimator all overlap closely. In sum, no striking differences among the countries can be claimed. Their stock market indices react similarly to monetary policy announcements. This seems to be reasonable because most ECB press releases concern the entire EA. Even stock markets which do not belong to the EA show significant responses highlighting the role of ECB's communication for global financial markets.

[Figure 3 about here]

To make the regression coefficients better comparable, they are normalized by dividing the coefficients by the corresponding mean value in Table A1 and plotted in Figure 4. For  $DE_5$  and  $FR_5$ , this translates to an increment of 39 and 46 per cent of average realized volatility for an announcement day, respectively. With the exception of Italy, all EA markets on the left side show values around 40 per cent. Interestingly, the increases in the non-EA market on the right side are only slightly lower than those of the EA markets on the left side. For example, an

announcement by the ECB has almost an identical impact on the Dutch and the Swiss stock market of around 31 per cent increment in terms of mean realized volatility.

[Figure 4 about here]

Table 3 depicts the result of the range specification defined in Eq. (3) for each asset under consideration. In line with the realized volatility measure, the estimators are very similar in size and significance indicating an equal impact across the EA countries. Except for Greece and Ireland – which are special cases in light of the European debt crisis – every country’s stock market index is influenced by ECB announcements. Greece and Ireland are deeply indebted so that national news determine asset volatility rather than information released by the ECB. A highly significant and positive estimator implies that a monetary policy announcement increases the asset volatility on that day for the respective stock market index. For instance, a press release by the ECB increases the daily price range of the German index by 0.3 basis points (bps), on average. This corresponds to an increment of 17 per cent of the average price range for an announcement day. The 4 volatility indices behave in the same manner implying that market participants’ expectations change significantly in response to ECB’s press releases. Take the volatility index of the CAC as an example. The increase in 13.4 bps reflects an increment of three quarters of the average daily price range of the VCAC.

[Table 3 about here]

In contrast to the realized volatility measure, the price range in all seven non-EA countries increases to a similar degree in response to ECB’s announcements. On the one hand, these spill-over effects stand to reason in light of highly intertwined global financial markets activity. My findings are consistent with Korus (2019) who find spill-over effects for Scandinavian financial assets. On the other hand, despite its particular role during the European debt crisis it is puzzling that the Irish and Greece stock markets do not seem to react to ECB’s releases whereas even non-European markets in Japan and the U.S. show an increased volatility. Communication by other central banks potentially biases the results hinting at spill-over effects that could originate from reactions to news from their domestic central bank. I evaluate this a minor risk as scheduled announcements by major central banks typically do not coincide (Brusa et al. (2019)).

In sum, enlarging the observation period and market sample, the price range measure confirms the above results. Except for Greece and Finland, the 95% confidence intervals of the

dummy variable's estimator overlap (Figure 5). Figure 6 illustrates the increments of the average price range triggered by an ECB announcement. Although the values are lower for the price range measure, the overall pattern corresponds to Figure 4. The non-EA markets on the right side show a slightly weaker reaction in terms of mean realized volatility. Apart from the (insignificant) stock market reactions of Ireland and Greece only Austria is prominent with a comparably low value. The other markets show a similar pattern that do not justify any grouping.

[Figure 5 and Figure 6 about here]

### 3.2 Comparison before and following the financial crisis

The significant effect since the financial crisis possibly outweighs the pre-crisis period. After the outbreak of the financial crisis in 2007 financial markets tend to be more responsive to central bank announcements. In particular, market participants are more accessible to new information, which increases the impact of monetary policy communication on volatility. To test this hypothesis, I estimate two distinct regressions and compare them to detect whether there is a different pattern/perception before and following the financial crisis. Therefore, the data are split up into two sub-samples. Since the financial crisis entails several events, it is hard to find a clear-cut date when the crisis actually starts, independent of the choice a certain degree of arbitrariness remains. Following Fausch and Sigonius (2018), August 22, 2007 is set as the beginning of the crisis period. Accordingly, the pre-crisis period goes from January 1998 (January 2000 in case of realized volatilities) to August 21, 2007 and the post-crisis period<sup>7</sup> starts on August 22, 2007 and ends in May 2019.

A structural break becomes evident looking at realized volatilities in Table 4.<sup>8</sup> Except for  $BE_5$ , all EA stock markets possess a lower significance level in the pre-crisis period compared to the post-crisis period. They become even non-significant for the indices of the Dutch, Finish, French ( $FR_{10}$  only), German and Spanish ( $ES_{10}$  only) stock market. These findings imply an increasing influence of ECB press releases over time. Chow tests confirm the structural break. The estimators before and after August 22, 2007 are significantly different from each other for every stock market index.

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<sup>7</sup>This term demarcates the period before and after the outbreak of the financial crisis. In this context post-crisis does not mean that the crisis has terminated during this period.

<sup>8</sup>In the following tables the estimators of the constant and control variables are omitted for the sake of readability. In fact, they remain stable in the subsequent specifications so that reporting them would not give additional insights. They are available upon request.

Due to data availability more observations exist in the post-crisis period. To control for the argument that the detected structural break originates from this fact, I apply a shortened post-crisis period using data only until March 2015 in Eq. (2) and until March 2017 in Eq. (3). Thereby the number of observations between both periods is roughly the same for most assets.<sup>9</sup> No noticeable differences emerge between the shortened and post-crisis period.

As above, comparing the realized volatility results of 5 and 10 minutes frequency with each other no noticeable discrepancy emerges. For that reason only the realized volatility of the 5 minutes window will be displayed in the following to conserve space. Instead of varying observation periods, in the last column I consider the full sample and add a crisis dummy  $crisis_t$  to Eq. (2) and Eq. (3). This variable takes the value of 1 starting from August 22, 2007, and 0 before that date. A mixed picture emerges for this dummy. While the volatility of Belgium, EU, Finland, and Spain is enhanced during the crisis period,  $crisis_t$  is insignificant for France and the Netherlands, and it is even significantly negative for Germany. For those stock markets that experience spill over effects there is not a stronger impact following the financial crisis, though. On the contrary, the volatility in the Japanese market is only significant before the crisis while in Switzerland both periods reveal a similar impact.<sup>10</sup>

[Table 4 about here]

Table 5 presents the results for the daily price range. Apart from the significance in the case of Ireland, the post-crisis period's results in the third column correspond qualitatively to the full sample displayed in the first column. The estimators have a similar magnitude and they are invariant to the chosen observation length. Hence, ECB announcements have a positive and time-invariant impact on the stock market indices' volatilities of its member countries for both periods.

[Table 5 about here]

However, the second column reveals a structural break. The Austrian market is not affected anymore. Furthermore, the significance level diminishes in France, Germany, Italy, Portugal, and Spain; and except for Finland the estimators become lower compared to the post-crisis period. The influence of an announcement is stronger following the financial crisis. For instance,

<sup>9</sup>It ranges between 2300 and 2400 observations for  $range_t$  and around 1900 observations for  $rv_{5,t}$  and  $rv_{10,t}$ . See Table A4 in the Appendix for the exact number of observations.

<sup>10</sup>The corresponding coefficients of  $ECB_t$  for this scenario are not reported in Table 4 but they are very similar to the long-term scenario without an additional crisis dummy variable.

the daily price range in the French and Italian market more than doubles in response to an announcement: 0.433 bps and 0.404 bps following the crisis compared to 0.140 bps and 0.134 bps before the crisis, respectively. In terms of the daily average price range, these figures better underline the break. They imply an increment of only 9 per cent before the crisis versus 28 per cent following the crisis for France. In the Italian market, the increment triples from 8 to 24 per cent following the crisis. This pattern can only be confirmed for the U.S. and Norway while the other non-EA markets are equally affected by ECB's announcements in both pre-crisis and post-crisis periods.

The fourth column demonstrates that the (shortened) post-crisis period estimators remain qualitatively unchanged. For instance, the Dutch and Belgian estimator are only marginally bigger in the shortened post-crisis period (increase of 0.3 bps for both assets). Hence, the number of observations does not cause the low significance level in the pre-crisis period. Even for the very short period of 500 to 700 observations in the case of the four volatility indices, they all reveal a significant impact following the crisis while the 2 indices with available data are not significant in the pre-crisis period.

The crisis dummy has highly significant and positive estimators in all countries except for the Dutch, Finnish and German ranges having a negative sign and Belgium, France and Spain being insignificant. This significance throughout the indices confirms the relevance of the respective period. Interestingly, the crisis period itself increases the price range in most markets while that in the Dutch, German and Finnish market reduces. One explanation for this discrepancy is that these markets are not hit by the crisis to the same degree as are other European markets. By contrast, these markets become calmer with respect to the pre-crisis period. All non-EA countries show a negative coefficient of  $crisis_t$  being significant only for the Japanese and Swiss market. In sum, the price range of the markets under consideration reacts similarly to ECB announcements but the extent attributable to the post-crisis period corresponds roughly to the core versus periphery countries scheme.

Figure 7 and Figure 8 showcase the increment in terms of realized volatility and average price range, respectively. They support the structural break. Figure 8 shows that the price range is less responsive to ECB announcements before the crisis in all EA markets except Finland and Greece. However, such a break is not valid for non-EA markets. Following the financial crisis realized volatility reactions are higher for each country and they more than double in most markets (Figure 7). In contrast to the range measure, this pattern also holds for all considered

non-EA markets meaning that the spill-over effects on realized volatility are more elaborated following the financial crisis.

It is imaginable that the asset volatility increases in general following the financial crisis. My results suggest that press releases by the ECB are one factor that contribute to this fact. However, Figure 1 and Figure 2 indicate the contrary having lower peaks since 2013. In addition, ECB (2017) emphasizes that favorable market developments across global economies have lead to low levels of equity market volatility and yields in advanced economies. With that said, the increasing sensitivity of the volatility to announcements is astonishing. A possible explanation could be that the volatility itself decreases but the stake of changes in volatility attributable to monetary policy announcements increases over time.

It is worth emphasizing that the non-significance in the pre-crisis period is not due to the number of events. The number of pre-crisis events ( $RV_t$ : 161,  $range_t$ : 200) lies in between the long-term period ( $RV_t$ : 299,  $range_t$ : 338) and the post-crisis period ( $RV_t$ ,  $range_t$ : 138), which exhibit both high significance levels. Although following the crisis fewer press releases occur during a longer period, these announcements affect the asset's volatility stronger than those before the crisis. Moreover, the application of randomly drawn events in Section 3.3 demonstrates that the timing and not the quantity of events matters.

### 3.3 Robustness Checks

Table 6 summarizes the results of robustness checks regarding the choice of events, that is the dummy variable  $ECB_t$  is modified. For the sake of brevity the tests refer to the post-crisis period only. This selection is appropriate for the following reasons. The announcement effects are strongest for this sample. If other factors play a role, they become most likely evident in this observation period. To guarantee comparability of the output to the scenario of asset purchase announcement events that follows, the post-crisis period is convenient. For this period, there is also a similar number of observations available for price range and realized volatility measures.<sup>11</sup>

[Table 6 about here]

First, the significant response could be pure coincidence. Therefore, I assign 129 randomly drawn dates to a dummy variable  $random_t$  instead of using the respective number of ECB press release dates. No range index is significant in the second column. Even after multiple

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<sup>11</sup>See Table A4 in the Appendix for the exact number of observations. The output of the other periods, however, is similar and available upon request.



iterations of any randomly chosen event set, merely one or two stock indices occasionally become significant. This result highlights the appropriateness of ECB announcements as a contributor to asset's volatility and underlines the non-negligible impact of ECB's press releases. The same holds for the realized volatilities measures.

Second, markets potentially need some time to digest new information or reversely even react in anticipation before an announcement is made. The former motivates studies to use two-day event windows (e.g. Altavilla et al. (2016), Brusa et al. (2019)). On the contrary, the content of an announcement sometimes becomes apparent even before its release. Cieslak et al. (2018) detect effects of informal communication of Fed officials with market participants prior to scheduled meetings. Lucca and Moench (2015) find large average excess returns in the U.S. equity market in anticipation of those meetings. For this purpose, the dummy  $ECB_t$  is adopted to  $ECB_{t-1}$  and  $ECB_{t+1}$  to account for a one day anticipated and delayed effect, respectively. Only a few anticipated effects appear in the third column (significantly negative coefficients for Switzerland and VAEX of  $range_t$  and Japan of  $RV_t$ ). Similarly, the next column gives significant delayed effects only for the price ranges of Italy, Portugal, VDAX, and VSTOXX and for the realized volatility of U.S. whereby the last three possess a positive sign. Investors seem to become calmer in the first and more nervous in the latter markets one day after an ECB's press release. However, these minor delayed effects are negligible. Hence, the hypothesis of market efficiency generally holds meaning prices and quantities immediately adjust after a policy announcement.

Third, further disentangling the events according to its type of announcements, for example focusing only on asset purchase program announcements, gives additional insights. I follow Fendel and Neugebauer (2018) and choose 23 crucial asset purchase announcements  $APA_t$ .<sup>12</sup> One the one hand, the bottom part of the fifth column representing realized volatilities has weaker significance levels than  $ECB_t$ . This result underlines that every announcement by the ECB concerns asset volatility – independent of its specific content. One the other hand, in the upper part Austria and Belgium are unaffected while the other countries' coefficients are higher compared to the baseline specification. If events are restricted to asset purchase announcements, they affect some volatilities stronger whereas they affect two countries and the realized volatilities weaker than in  $ECB_t$ .

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<sup>12</sup>Refer to Table A1 in Fendel and Neugebauer (2018) for an overview of all relevant events. Note that for this specification the observation period ends in August 2017.

Forth, regular monetary policy meetings usually take place on Thursdays. Many but not all events included in  $ECB_t$  coincide with this day of the week. For this purpose an additional dummy  $Thursday_t$  is added to control for a general effect of this day, taking the value of 1 on each Thursday, and 0 otherwise. Testing for the Thursday effect in general, that is replacing  $ECB_t$  by  $Thursday_t$ , the sixth column gives coefficients that are lower compared to  $ECB_t$  and Austria gets insignificant. Regarding realized volatilities, the coefficients of the Dutch, French, German and European market have a lower significance level. Hence, only considering Thursdays slightly reduces the impact on volatility. The last column tests for both effects, ECB announcements and Thursdays. To prevent double accounting, the dummy is adjusted to  $adj\_Thursday_t$ , which only takes the value of 1 on Thursdays when there is not an ECB announcement at the same day. Despite the inclusion of  $adj\_Thursday_t$  the coefficients of  $ECB_t$  (not reported in Table 6) are still highly significant at a similar magnitude. Only six coefficients of  $adj\_Thursday_t$  imply a Thursday effect on its own. Neither of the range or realized volatility measures react in the EA except for the Italian  $RV_t$  which requires a cautious interpretation due to limited data availability. In sum, ECB announcements cause volatility increases while a Thursday effect is negligible.

The country-specific control variable  $MSCI_t$  is replaced by several global alternative measures.<sup>13</sup> They impose that national indices are insufficient as financial developments across Europe and the world matter. The MSCI Europe Index and the MSCI World Index are broad global equity indices comprising 15 and 23 developed countries, respectively. Following Georgiadis and Gräb (2016) the Citigroup Economic Surprise Index for the Eurozone (CESI) covers weighted historical standard deviations of macroeconomic data surprises. The surprises are constructed as the difference between consensus expectations and economic releases. The V2TX index is based on Eurostoxx 50 realtime option prices and reflects market uncertainty in Europe. Applying those measures and multiple combinations of them the results persist. The coefficients' magnitude and significance level remain stable. The same holds for the application of the daily surprise and uncertainty indices by Scotti (2016). The country-specific MSCI indices are preferred because they are available for a longer period compared to the other control variables (cf. Table A1). There is no double accounting problem when using national instead of global measures as control variables because the results are invariant to the implementation

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<sup>13</sup>Since the global indices are available for a shorter period the following robustness checks refer to a shortened period starting in 2003. The output tables for each robustness check are available upon request.

of CESI and MSCI World excluding Europe.

## 4 Forward Looking

The instant effect is not surprising. Investors might be interested in the persistence of stock market volatility following ECB announcements. To test for this, I replace the present realized volatility by the cumulative future volatility the next 1, 3, 5 and 10 days, respectively. If there are still significant effects one can claim that ECB communication triggers uncertainty in stock markets.

Eq. (3) changes accordingly to

$$\sum_{i=0}^m RV_{t+i} = \alpha + \beta_1 RV_{t-1} + \beta_2 \Delta \ln(MSCI_t) + \gamma ECB_t + \varepsilon_t, \quad (4)$$

with  $m = 1, 3, 5,$  and  $10$  giving the horizon of the aggregated future volatility.

## 5 Identification of monetary policy shocks

There is a vast literature that uses high-frequency data to deduce the monetary policy shocks. For instance, Rogers et al. (2014) compare the reaction to announcements by four major central banks using tight windows of 15 minutes before and after the event. Cieslak and Schrimpf (2019) rely on equity and interest futures to construct shocks around a comprehensive set of communication events appertaining to those banks. Unfortunately, this type of data is not available for all assets under consideration for the chosen time span. Nevertheless, I adopt this idea to the daily data set. Other events taken place during that day could confound the measure. Since government bond yields are particularly responsive to central bank communication and less susceptible to non-monetary news this is considered as an acceptable risk. First, I calculate the change in yields:

$$shock_t = 100 \times \ln \left( \frac{y_t}{y_{t-1}} \right) \quad (5)$$

where  $y_t$  is the 10-year government bond benchmark yield obtained from Datastream (cf. Table A1 in the Appendix). These changes are then regressed on realized volatility. The (equally-weighted) dummy  $ECB_t$  is refined by letting it interact with the particular shock on the re-

spective announcement day:

$$RV_t = \alpha + \beta_1 RV_{t-1} + \beta_2 \Delta \ln(MSCI_t) + \gamma |shock_t| \times ECB_t + \varepsilon_t. \quad (6)$$

Similarly Eq. (3) changes to

$$range_t = \alpha + \beta_1 range_{t-1} + \beta_2 \Delta \ln(MSCI_t) + \gamma |shock_t| \times ECB_t + \varepsilon_t. \quad (7)$$

I take the absolute value of  $shock_t$  because for the volatility the direction of the surprise does not matter. A restrictive and an expansive policy announcement should similarly affect stock market volatility. Hence, the extent the announcement shifted the respective government bond yield enters in Eq. (6) and Eq. (7). This approach to assess the sensitivity rather than the sign of yield changes is consistent with current work (e.g. Cieslak and Schrimpf (2019)).

Table 7 shows the results for EA stock markets as defined in Eq. (6) and Eq. (7) and confronts them to the use of  $ECB_t$ . The first two columns represent the full-time period. In the upper part, the range measures of the Austrian, Finish and German stock market as well as the VCAC get unaffected after the weighting of events. At the same time, the coefficients of Ireland and Greece become significant. These changes hint at the core/periphery pattern, that is markets of periphery countries are more prone to ECB's announcements than core countries. The Eurostoxx 50 as a mixture of both core and peripheral markets supports this view by showing a weak significance for  $shock_t$ . The realized volatility measures in the lower part further confirm this argument. The Dutch, Finish and German markets become insignificant and the significance levels of the Belgian and French market decline. Analogous reasoning applies for the post-crisis period in the last two columns. In contrast, the results of the pre-crisis period (forth and fifth column) are qualitatively unchanged when comparing  $ECB_t$  to  $shock_t$ . In sum, replacing  $ECB_t$  by  $shock_t$  leaves the pre-crisis period unaltered but supports a core/periphery pattern for the period following the financial crisis.

[Table 7 about here]

To quantify the shock for non-EA markets, a simple average of the eleven EA yields is taken

into account.<sup>14</sup> In general, the seven non-EA markets are less affected by ECB's announcements when using  $shock_t$  as Table 8 reveals. While minor spill-over effects persist for the stock markets of Great Britain, Sweden and Switzerland for the range measure, any influence disappears for the realized volatility measures for the full time period. As for the EA markets, the non-EA markets in the pre-crisis period react similarly after the exchange of the dummy variable. For the post-crisis period, no reaction is found for realized volatilities so that the spill-over effects of Great Britain, Norway, Switzerland and the U.S. disappear. Significant effects for the Swedish and Danish market still persists and the Swiss stock market becomes weakly significant for the range measure. However, the amount and level of significance reduces in general when using  $shock_t$ . Consequently, the weighting of the announcements seems to cancel out the previously detected spill-over effects for most indices of  $range_t$  and for all indices of  $RV_t$  under consideration.

[Table 8 about here]

Note that the value of  $shock_t$  in Eq. (6) and (7) is zero on non-announcement days assuming that the government bond yield change is only relevant on announcement days. This assumption requires that significant changes in the yield are unlikely on non-announcement days. An alternative specification controls for this concern by adding the shock as an additional control variable.

$$RV_t = \alpha + \beta_1 RV_{t-1} + \beta_2 \Delta \ln(MSCI_t) + \gamma |shock_t| \times ECB_t + \delta |shock_t| + \varepsilon_t. \quad (8)$$

$$range_t = \alpha + \beta_1 range_{t-1} + \beta_2 \Delta \ln(MSCI_t) + \gamma |shock_t| \times ECB_t + \delta |shock_t| + \varepsilon_t. \quad (9)$$

The interaction term should show a higher impact than the general effect of the yield change, which translates to the hypothesis  $\gamma > \delta$ . Table 9 juxtaposes the specifications with and without the government bond yield change as control. I reject my hypothesis taking into account that there is no distinct pattern, in some markets  $\gamma$  is higher while in others  $\delta$  is higher. These differences are tiny, though. Most importantly, both size and significance levels do not vary considerably between Eq. (6) and Eq. (8) and Eq. (7) and Eq. (9), respectively. Summing up  $\gamma$  and  $\delta$  in Eq. (8) and Eq. (9) roughly corresponds to the value of  $\delta$  of the respective specification

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<sup>14</sup>I refrain from constructing a weighted average (e.g. according to GDP, market size) for the following reason. Due to the long observation period one would have to adjust the weights over time. The frequency of this adjustment is arbitrary especially in light of daily data and weights deduced from lower frequency data. In case of  $range_t$  the yield of Greece is excluded in the calculation of the yield before April 1, 1999 due to data unavailability. As a robustness check, I also assigned the average yield change to the shock of EA markets. The results (available upon request) are almost identical.

without the explicit control for government bond yield change for most countries. While the main findings for the interaction term are robust to this inclusion, the control itself is arguable being significant in only half of the range measures and 9 out of 15 realized volatility measures. The change affects both measures differently. It predominately decreases realized volatility (8 out of 9 significant coefficients). In contrast, the majority of range measures (6 versus 5 coefficients) reacts positively to yield changes. In particular periphery markets experience an increase in the price range in response to yield changes whereas the German and Dutch market show the reverse effect.

[Table 9 about here]

## 6 The persistence of announcement effects

This section tests whether the announcements cause a lasting increase in volatility or whether the effects only appear in the short-term. Therefore, I incorporate the previous analysis in a standard local projections framework.

## 7 Conclusion

This study evaluates the influence of ECB announcements on asset price volatility in the EA between January 1998 and May 2019. I consider two volatility measures. First, a realized volatility measure is based on intraday data for 7 national EA stock market indices, 7 national non-EA markets, and the aggregate Eurostoxx 50 index. Second, a price range measures approximates volatility using daily prices from key national stock market indices of 11 EA and 7 non-EA economies as well as 4 European volatility indices. Both specifications highlight that announcements increase the volatility level on the same day. Anticipated, delayed and Thursday effects are negligible. Since every asset seems similarly affected no national peculiarities arise. The effects also spill over to non-EA markets underlining the role of ECB's communication for global financial markets. Previous studies classify European countries when investigating volatility on sovereign bond markets. In contrast, my findings do not allow a classification of national stock markets.

This study extends existing literature by also including the pre-crisis period which results in a comprehensive observation period of up to twenty years. A structural break is detected

claiming that ECB announcements have a stronger impact following the global financial crisis. A general positive effect on asset volatility emerges. This effect reinforces over time. While it is weak and only partially existing in the EA before 2007 it gets more significant following the financial crisis. The mere number of announcements does not seem to matter. Although following the crisis fewer press releases occur during a longer period, these announcements affect the asset's volatility stronger than those before the crisis. Consequently, fewer announcement do not lead to less financial volatility. To reduce volatility, policy makers should focus on the quality of their announcements and they can possibly neglect the announcement frequency. My findings are in line with Kurov and Stan (2018) who state that 'when monetary policy uncertainty is high, policy expectations become more sensitive to economic news, which affects the response of a variety of markets to such fundamental news' (p. 128). The present study confirms this assertion for the European stock markets. Overall, both daily and intraday data suggest a significantly positive impact of ECB's press announcements on asset volatility in EA countries.

Due to various data availabilities among the assets under consideration I refrain from pooling them in a panel. The proportion of missing data is yet too diverse in order to reasonably apply imputation methods. For future research, it will be interesting to use a panel and to account for interaction effects within the EA. One could disaggregate the analysis to different sectors examining whether the assets of financial institutions are more concerned than other sectors to ECB's information releases. Financial markets are subject to political factors as well. ECB (2018) relates higher volatility levels in US and European equity and credit markets after the spike in February 2018 to tax reforms and global trade war rhetoric from the USA. Future research might have a closer look at those factors in order to explain volatility on financial markets more accurately.

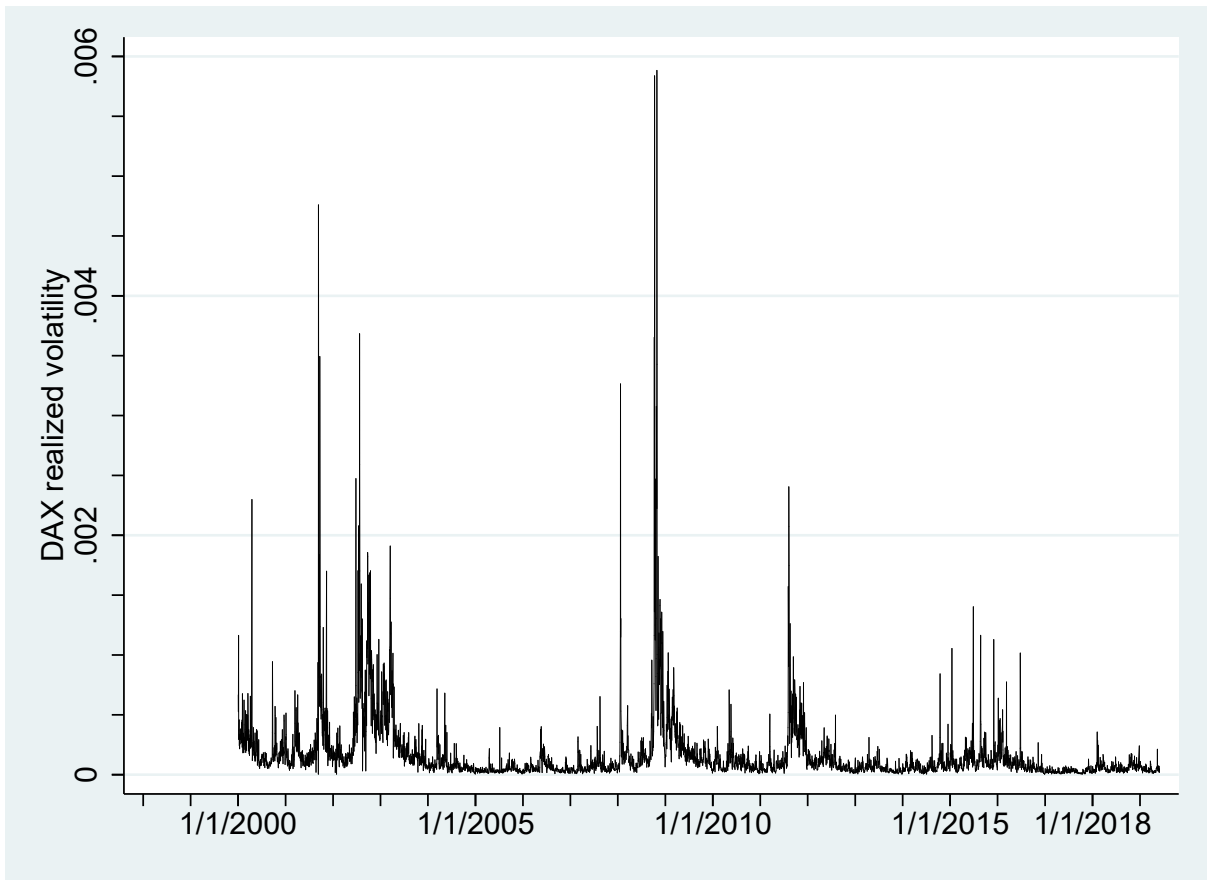
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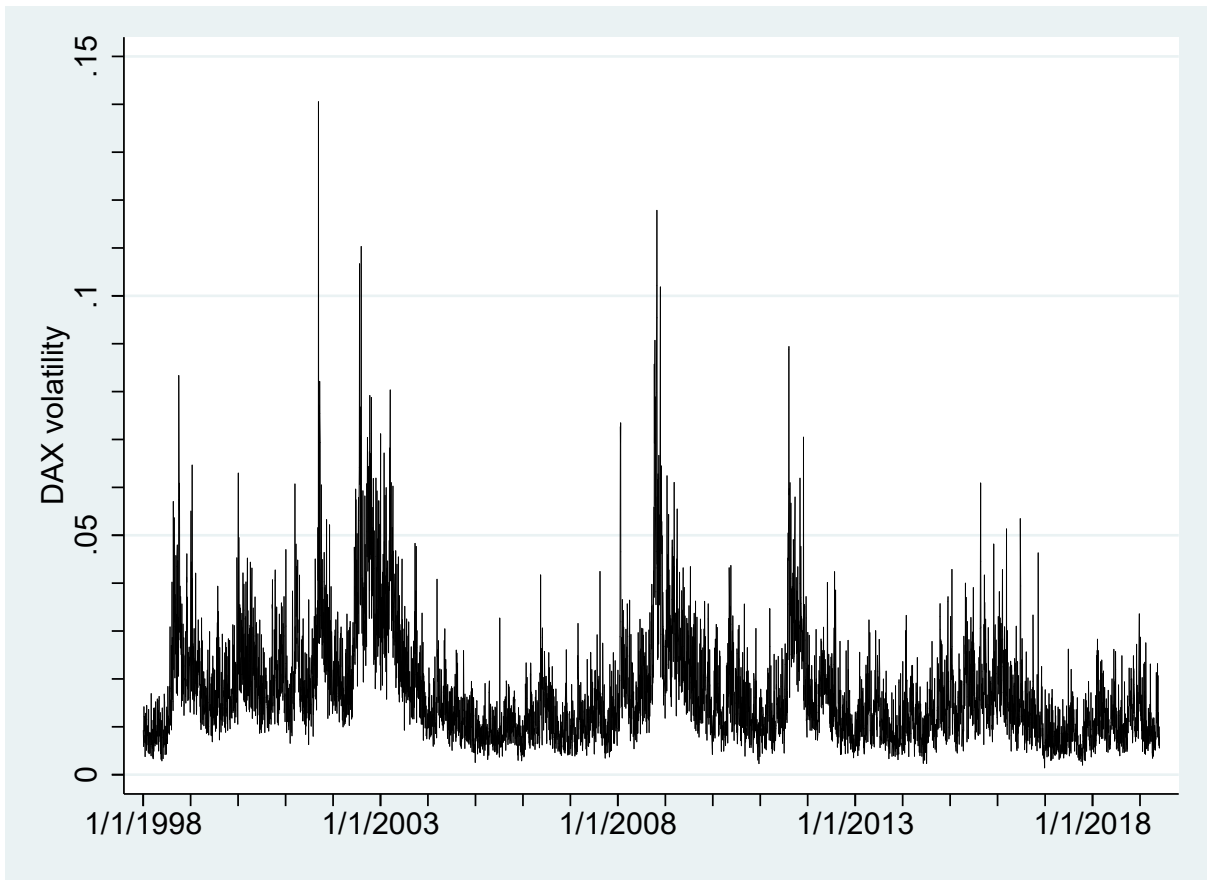
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Figure 1: Daily Realized Volatility of DAX index



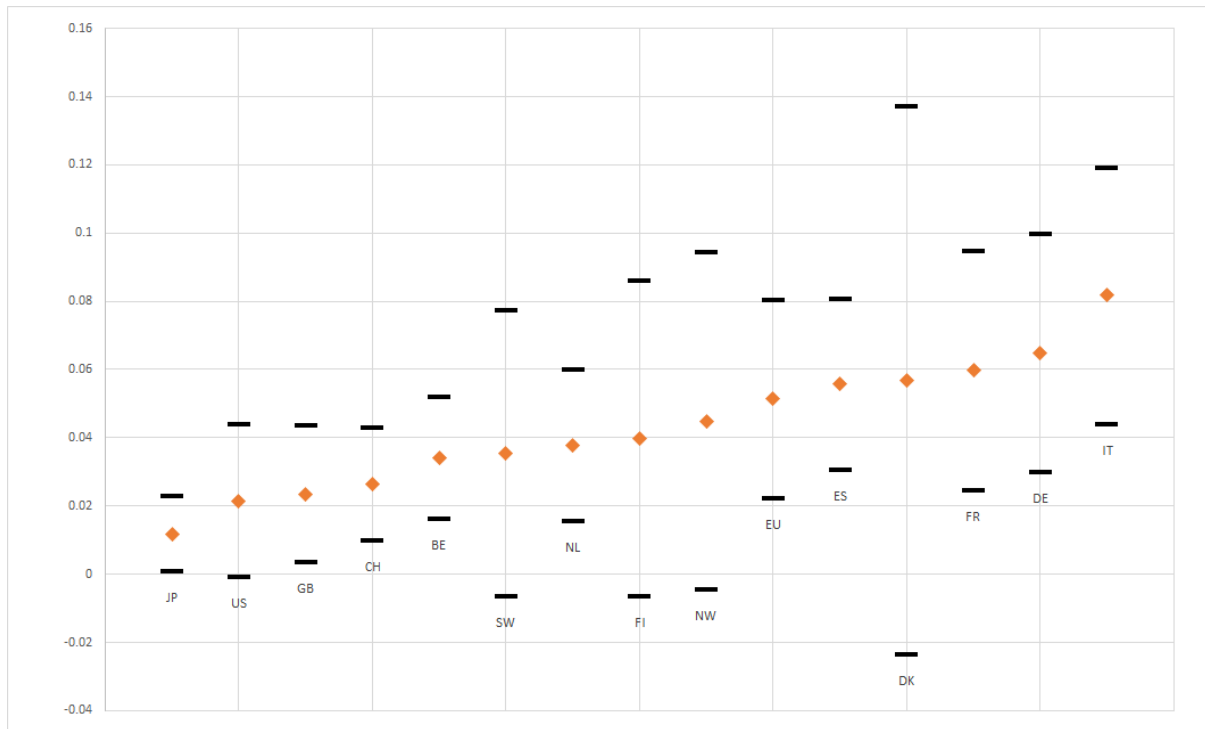
Source: Heber et al. (2009), using 5 minutes frequency data. Using a 10 minutes frequency yields a similar pattern. Time span: January 3, 2000 to May 31, 2019.

Figure 2: Daily Price Range of DAX index



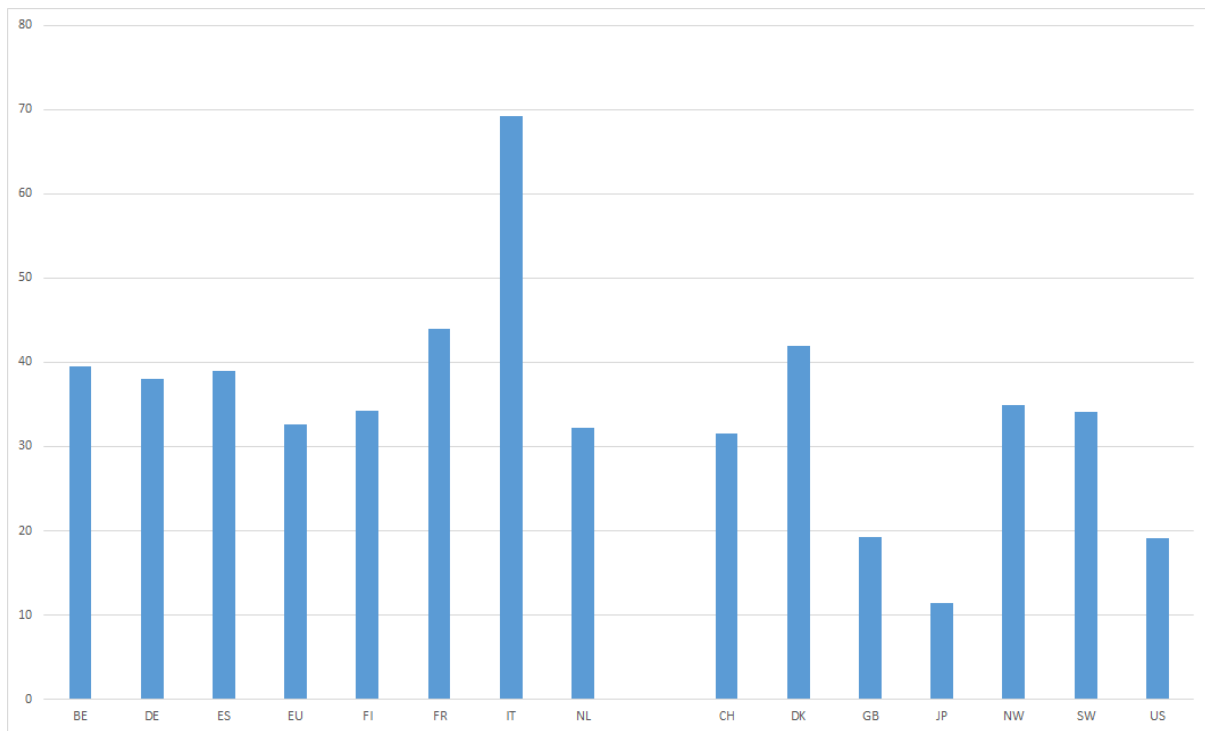
Source: Datastream. Time span: January 2, 1998 to May 31, 2019.

Figure 3: 95% confidence intervals of announcement impact: realized stock market volatility



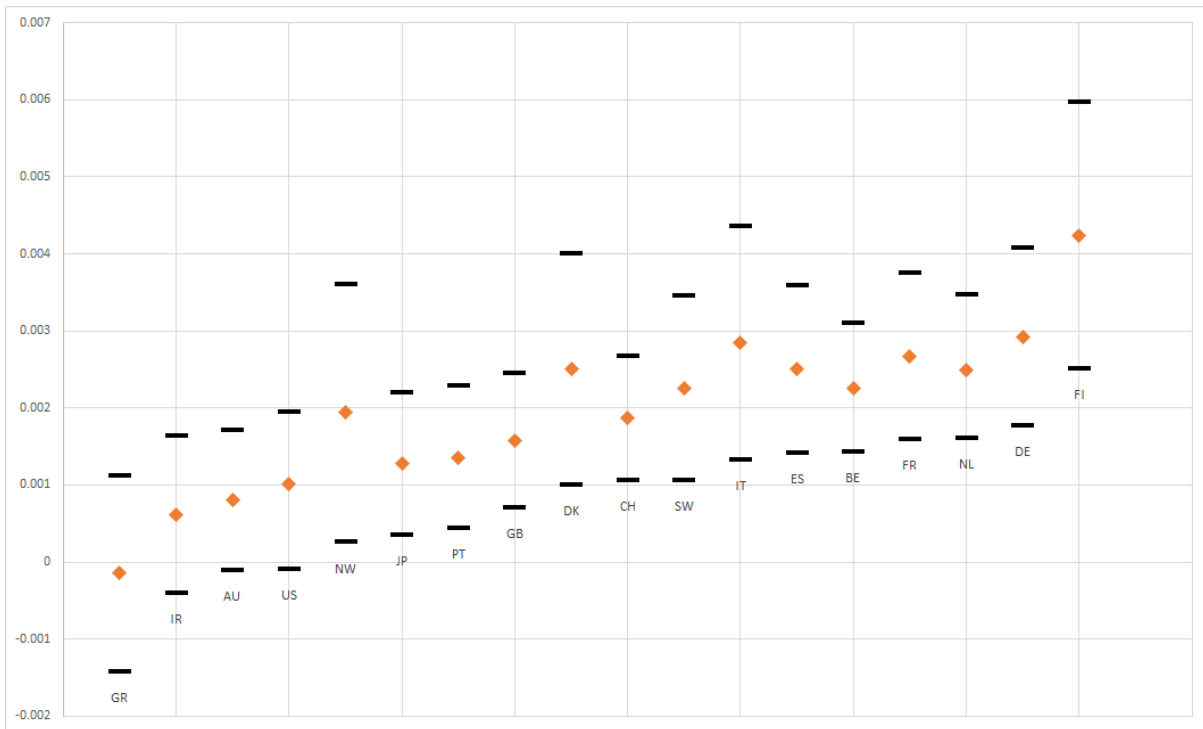
The ordinate denotes the range of coefficients and the abscissa defines the country's stock index. The rhombus gives the estimated coefficient for  $\gamma$  while the lines indicate the lower and upper bound of the 95% confidence interval. 5 minutes frequency intraday data apply. To enhance comparability, the markets are ordered by the magnitude of their coefficient.

Figure 4: Average reaction to ECB announcements in terms of mean realized volatility



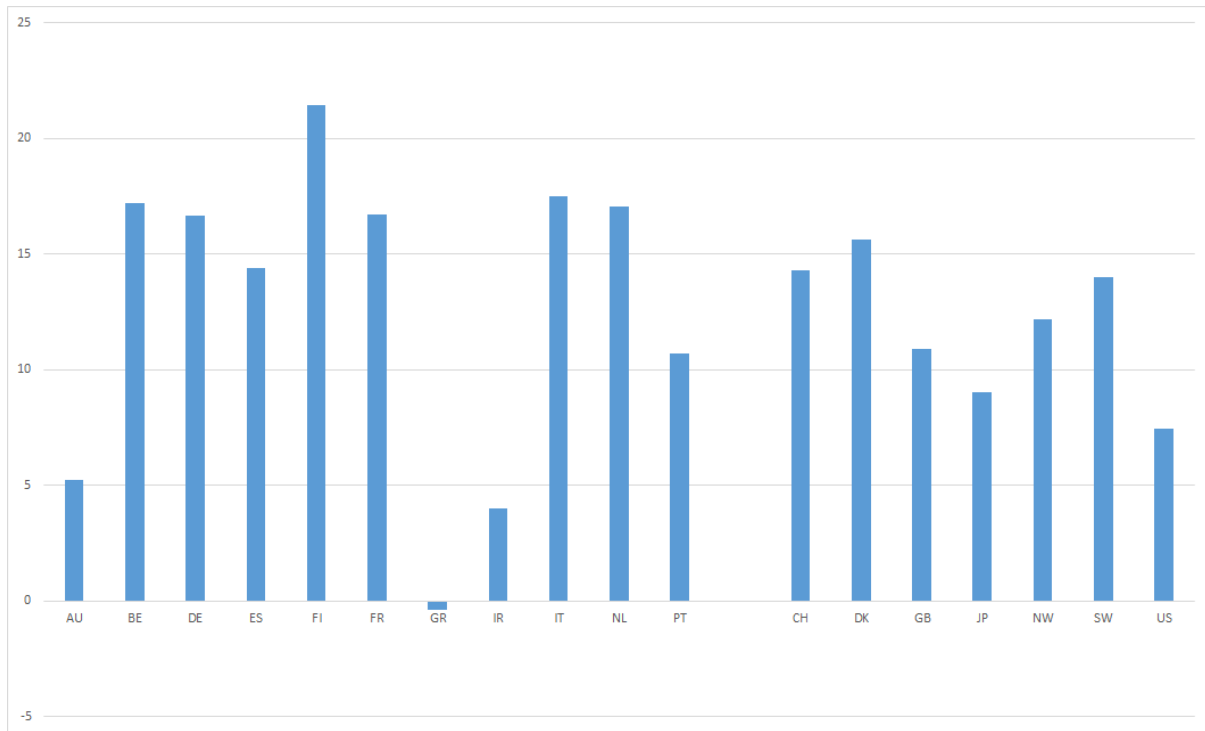
The ordinate gives the change of realized volatility as a percentage of the mean price range. The left side covers 8 EA markets while the right side shows the reactions of 7 non-EA markets. Realized volatility is calculated using 5 minutes frequency.

Figure 5: 95% confidence intervals of announcement impact: stock market price range



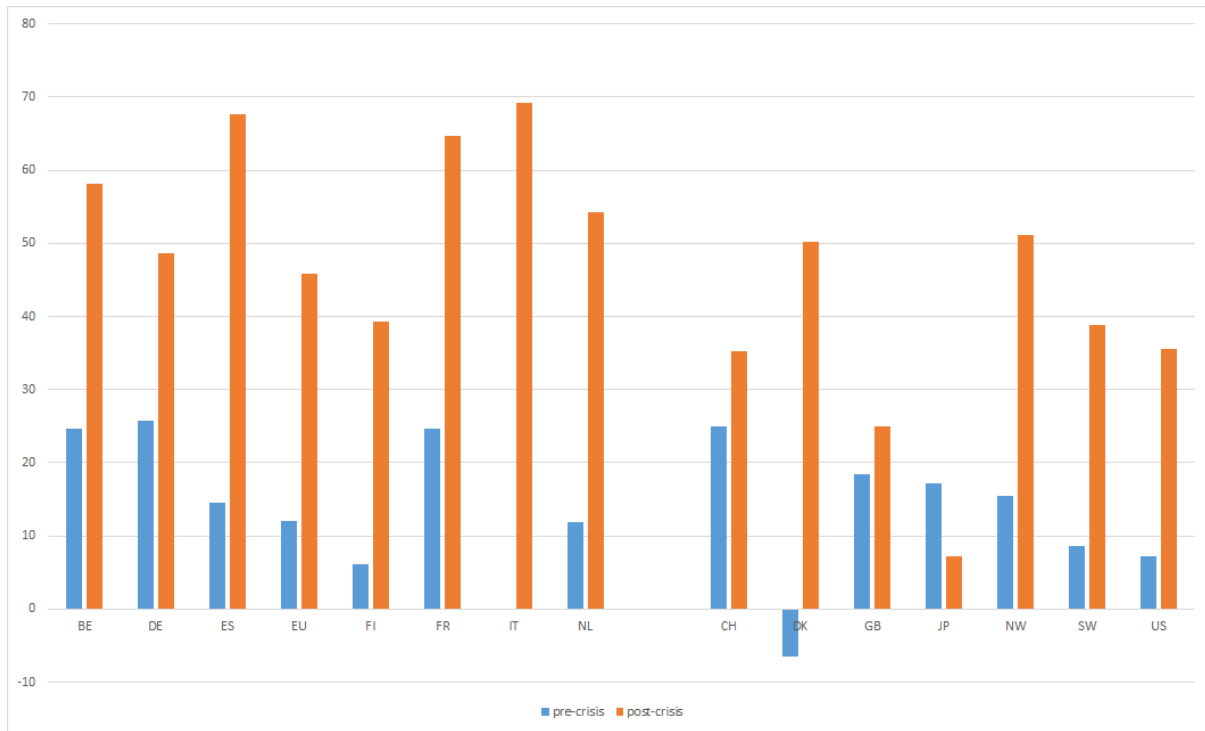
The ordinate denotes the range of coefficients and the abscissa defines the country's stock index. The rhombus gives the estimated coefficient for  $\gamma$  while the lines indicate the lower and upper bound of the 95% confidence interval. To enhance comparability, the markets are ordered by the magnitude of their coefficient.

Figure 6: Average reaction to ECB announcements in terms of mean price range



The ordinate gives the change of price range as a percentage of the mean price range. The left side covers 11 EA markets while the right side shows the reactions of 7 non-EA markets.

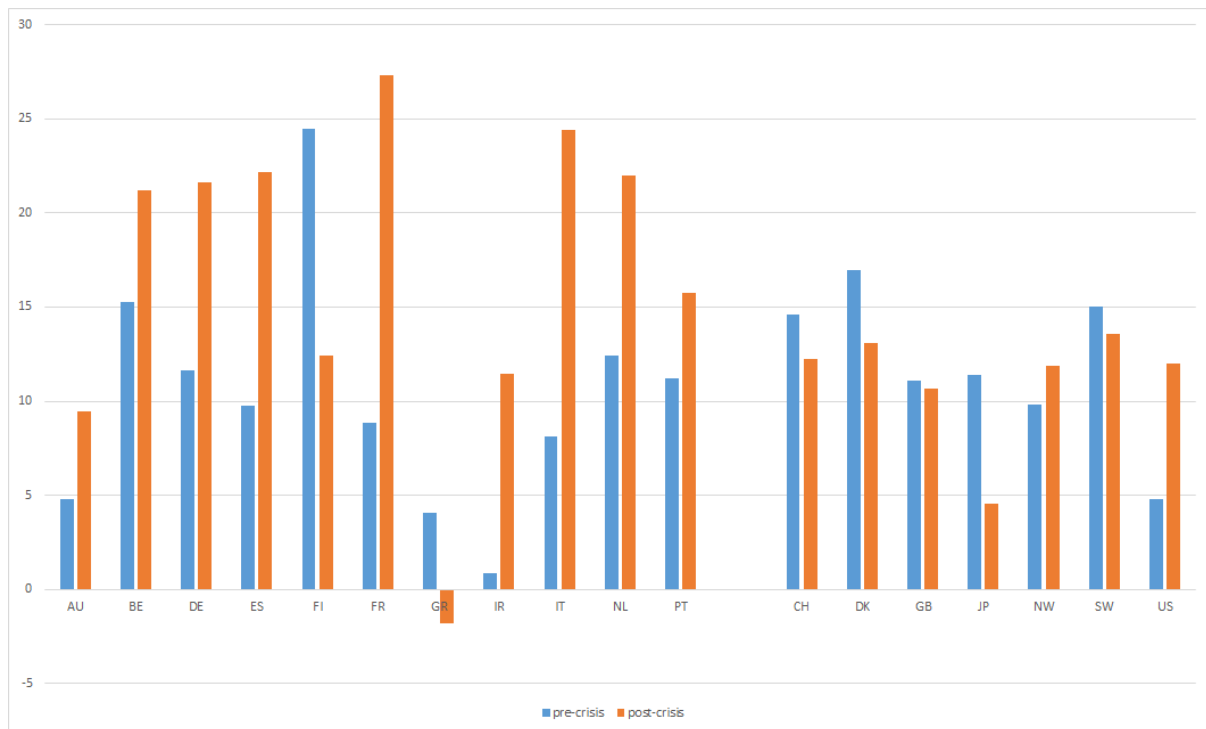
Figure 7: Average reaction to ECB announcements in terms of mean realized volatility: pre-crisis vs. post-crisis



The ordinate gives the change of realized volatility as a percentage of the mean price range. The left side covers 8 EA markets while the right side shows the reactions of 7 non-EA markets. Realized volatility is calculated using 5 minutes frequency.



Figure 8: Average reaction to ECB announcements in terms of mean price range: pre-crisis vs. post-crisis



The ordinate gives the change of price range as a percentage of the mean price range. The left side covers 11 EA markets while the right side shows the reactions of 7 non-EA markets.

Table 1: Effect of ECB announcements on realized asset volatility: EA

|           | constant  | $RV_{t-1}$ | $\Delta MSCI_t$ | $ECB_t$   | observations |
|-----------|-----------|------------|-----------------|-----------|--------------|
| $BE_5$    | 0.0297*** | 632.6***   | -2.118***       | 0.0343*** | 4,945        |
| $BE_{10}$ | 0.0273*** | 667.6***   | -2.010***       | 0.0340*** |              |
| $DE_5$    | 0.0442*** | 708.7***   | -2.988***       | 0.0628*** | 4,923        |
| $DE_{10}$ | 0.0439*** | 706.4***   | -2.505***       | 0.0606*** |              |
| $ES_5$    | 0.0497*** | 625.5***   | -2.681***       | 0.0553*** | 4,915        |
| $ES_{10}$ | 0.0620*** | 546.9***   | -1.928*         | 0.0562*** |              |
| $EU_5$    | 0.0631*** | 530.4***   | -4.648**        | 0.0512*** | 4,188        |
| $EU_{10}$ | 0.0715*** | 463.8***   | -4.781*         | 0.0558*** |              |
| $FI_5$    | 0.0916*** | 210.2      | -1.295          | 0.0404*   | 3,427        |
| $FI_{10}$ | 0.0567*** | 521.3***   | -1.602          | 0.0624**  |              |
| $FR_5$    | 0.0391*** | 679.6***   | -3.469***       | 0.0585*** | 4,947        |
| $FR_{10}$ | 0.0443*** | 640.5***   | -3.150***       | 0.0631*** |              |
| $IT_5$    | 0.0392*** | 634.5***   | -2.108***       | 0.0814*** | 2,538        |
| $IT_{10}$ | 0.0416*** | 617.5***   | -1.812***       | 0.0746*** |              |
| $NL_5$    | 0.0274*** | 742.2***   | -3.155***       | 0.0369*** | 4,948        |
| $NL_{10}$ | 0.0273*** | 746.0***   | -2.885***       | 0.0376*** |              |

Note: \*\*\*, \*\*, and \* denote 1%, 5%, and 10% significance levels, respectively. Newey-West-adjusted standard errors. 300 relevant events included in  $ECB_t$ . Sample period: January 2000 to May 2019. The country's subindices 5 and 10 indicate a 5 or 10 minutes frequency, respectively. To enhance legibility, all coefficients are multiplied by the factor 1000.

Table 2: Effect of ECB announcements on realized asset volatility: non-EA

|           | constant  | $RV_{t-1}$ | $\Delta MSCI_t$ | $ECB_t$   | observations |
|-----------|-----------|------------|-----------------|-----------|--------------|
| $CH_5$    | 0.0275*** | 650.5***   | -2.570***       | 0.0261*** | 4,863        |
| $CH_{10}$ | 0.0301*** | 616.8***   | -2.587***       | 0.0252*** |              |
| $DK_5$    | 0.0799*** | 364.6**    | -3.321**        | 0.0536    | 3,396        |
| $DK_{10}$ | 0.0779*** | 402.5***   | -3.821**        | 0.0661    |              |
| $GB_5$    | 0.0588*** | 484.6***   | -3.731*         | 0.0224**  | 4,893        |
| $GB_{10}$ | 0.0681*** | 438.6***   | -4.012          | 0.0284**  |              |
| $JP_5$    | 0.0335*** | 669.1***   | -2.871***       | 0.0119**  | 4,723        |
| $JP_{10}$ | 0.0411*** | 621.2***   | -3.442***       | 0.0180**  |              |
| $NW_5$    | 0.0477*** | 609.8***   | -2.188**        | 0.0444*   | 4,422        |
| $NW_{10}$ | 0.0542*** | 562.1***   | -2.761**        | 0.0552*   |              |
| $SW_5$    | 0.0637*** | 362.2**    | -0.975          | 0.0348*   | 3,428        |
| $SW_{10}$ | 0.0693*** | 397.4***   | -1.412          | 0.0480*   |              |
| $US_5$    | 0.0334*** | 679.9***   | -2.133***       | 0.0206*   | 4,871        |
| $US_{10}$ | 0.0340*** | -1.904**   | 679.3***        | 0.0213*   |              |

Note: \*\*\*, \*\*, and \* denote 1%, 5%, and 10% significance levels, respectively. Newey-West-adjusted standard errors. 300 relevant events included in  $ECB_t$ . Sample period: January 2000 to May 2019. The country's subindices 5 and 10 indicate a 5 or 10 minutes frequency, respectively. To enhance legibility, all coefficients are multiplied by the factor 1000.

Table 3: Effect of ECB announcements on daily price range

|        | constant   | $range_{t-1}$ | $\Delta MSCI_t$ | $ECB_t$    | observations |
|--------|------------|---------------|-----------------|------------|--------------|
| AU     | 0.00603*** | 0.624***      | -0.0884***      | 0.000843*  | 5,309        |
| BE     | 0.00483*** | 0.624***      | -0.107***       | 0.00227*** | 5,450        |
| DE     | 0.00553*** | 0.670***      | -0.0948***      | 0.00288*** | 5,433        |
| ES     | 0.00673*** | 0.604***      | -0.0891***      | 0.00250*** | 5,424        |
| FI     | 0.00478*** | 0.744***      | -0.0761***      | 0.00422*** | 5,370        |
| FR     | 0.00558*** | 0.638***      | -0.101***       | 0.00265*** | 5,464        |
| GR     | 0.00945*** | 0.553***      | -0.0515**       | -8.16e-05  | 5,285        |
| IR     | 0.00758*** | 0.526***      | -0.0577**       | 0.000641   | 4,885        |
| IT     | 0.00569*** | 0.646***      | -0.123***       | 0.00290*** | 4,022        |
| NL     | 0.00467*** | 0.675***      | -0.105***       | 0.00253*** | 5,468        |
| PT     | 0.00494*** | 0.614***      | -0.135***       | 0.00140*** | 4,897        |
| CH     | 0.00427*** | 0.661***      | -0.128***       | 0.00185*** | 5,380        |
| DK     | 0.00959*** | 0.383***      | -0.0972***      | 0.00246*** | 4,916        |
| GB     | 0.00511*** | 0.637***      | -0.0871***      | 0.00156*** | 5,408        |
| JP     | 0.00657*** | 0.532***      | -0.103***       | 0.00128*** | 5,253        |
| NW     | 0.00495*** | 0.683***      | -0.102***       | 0.00193**  | 3,270        |
| SW     | 0.00576*** | 0.632***      | -0.0602***      | 0.00224*** | 4,495        |
| US     | 0.00468*** | 0.646***      | -0.0779***      | 0.000996** | 5,386        |
| VAEX   | 0.0888***  | 0.0891**      | -1.236**        | 0.0845*    | 2,776        |
| VCAC   | 0.144***   | 0.169***      | -2.601***       | 0.134**    | 2,776        |
| VDAX   | 0.0471***  | 0.271***      | -0.746***       | 0.00931*** | 3,561        |
| VSTOXX | 0.0594***  | 0.171**       | -0.968***       | 0.00893**  | 3,563        |

Note: \*\*\*, \*\*, and \* denote 1%, 5%, and 10% significance levels, respectively. The dashed horizontal lines separate the volatility measures. The upper part considers 11 EA national stock market volatility measures, the middle part 7 non-EA stock markets, while the lower part covers 4 volatility measures of volatility indices. Newey-West-adjusted standard errors. 338 relevant events included in  $ECB_t$ . Sample period: January 1998 to May 2019.

Table 4: Distinguishing observation periods for realized volatility: Coefficients of  $ECB_t$ 

|             | long-term       | pre-crisis      | post-crisis     | shortened post-crisis | $crisis_t$      |
|-------------|-----------------|-----------------|-----------------|-----------------------|-----------------|
| $BE_5$      | 0.0343***       | 0.0214***       | 0.0505***       | 0.0590**              | 0.00251         |
| $BE_{10}$   | 0.0340***       | 0.0223**        | 0.0499***       | 0.0558**              | 0.00408         |
| $DE_5$      | 0.0628***       | 0.0425          | 0.0802***       | 0.0842***             | -0.0200***      |
| $DE_{10}$   | 0.0606***       | 0.0407          | 0.0807***       | 0.0875***             | -0.0194**       |
| $ES_5$      | 0.0553***       | 0.0206*         | 0.0961***       | 0.109***              | 0.0193***       |
| $ES_{10}$   | 0.0562***       | 0.0269          | 0.0912***       | 0.100***              | 0.0229***       |
| $EU_5$      | 0.0512***       | 0.0189*         | 0.0719***       | 0.0816***             | 0.0224**        |
| $EU_{10}$   | 0.0558***       | 0.0190*         | 0.0795***       | 0.0931**              | 0.0247**        |
| $FI_5$      | 0.0404*         | 0.00718         | 0.0465*         | 0.0462                | 0.0444**        |
| $FI_{10}$   | 0.0624**        | 0.0203          | 0.0691**        | 0.0807                | 0.0192*         |
| $FR_5$      | 0.0585***       | 0.0328*         | 0.0861***       | 0.0975**              | -0.000697       |
| $FR_{10}$   | 0.0631***       | 0.0307          | 0.0993**        | 0.115**               | -0.00171        |
| $IT_5$      | 0.0814***       |                 | 0.0814***       | 0.0871***             |                 |
| $IT_{10}$   | 0.0746***       |                 | 0.0746***       | 0.0769***             |                 |
| $NL_5$      | 0.0369***       | 0.0137          | 0.0621***       | 0.0690**              | -0.00425        |
| $NL_{10}$   | 0.0376***       | 0.0173          | 0.0593***       | 0.0647**              | -0.00496        |
| $CH_5$      | 0.0261***       | 0.0207**        | 0.0291**        | 0.0327*               | -0.000128       |
| $CH_{10}$   | 0.0252***       | 0.0213*         | 0.0257**        | 0.0280**              | -0.000479       |
| $DK_5$      | 0.0536          | -0.00831        | 0.0643          | 0.0905                | 0.0343***       |
| $DK_{10}$   | 0.0661          | -0.00437        | 0.0784          | 0.107                 | 0.0348***       |
| $GB_5$      | 0.0224**        | 0.0216*         | 0.0292*         | 0.0405*               | 0.0131          |
| $GB_{10}$   | 0.0284**        | 0.0226*         | 0.0346          | 0.0483*               | 0.0161          |
| $JP_5$      | 0.0119**        | 0.0178**        | 0.00748         | 0.0156                | -0.00296        |
| $JP_{10}$   | 0.0180**        | 0.0218**        | 0.0166          | 0.0279                | -0.00243        |
| $NW_5$      | 0.0444*         | 0.0198          | 0.0651          | 0.0849                | 0.0138**        |
| $NW_{10}$   | 0.0552*         | 0.0213          | 0.0834          | 0.111                 | 0.0170**        |
| $SW_5$      | 0.0348*         | 0.00878         | 0.0396*         | 0.0460                | 0.0242**        |
| $SW_{10}$   | 0.0480*         | 0.0161          | 0.0536*         | 0.0640                | 0.0200          |
| $US_5$      | 0.0206*         | 0.00779         | 0.0382*         | 0.0549*               | 0.00845         |
| $US_{10}$   | 0.0213*         | 0.0133          | 0.0360          | 0.0540*               | 0.00613         |
| period      | 01/2000-05/2019 | 01/2000-08/2007 | 08/2007-05/2019 | 08/2007-03/2015       | 08/2017-05/2019 |
| # of events | 299             | 161             | 138             | 98                    | 138             |

Note: \*\*\*, \*\*, and \* denote 1%, 5%, and 10% significance levels, respectively. Newey-West-adjusted standard errors. The dashed horizontal line separates the volatility measures. The upper part considers 7 EA stock markets and the Eurostoxx while the lower part covers 7 realized volatility measures of markets that do not belong to the EA. To enhance legibility, the latter are multiplied by the factor 1000. Constants and control variables omitted. Number of observations vary (see Table A3 in the Appendix). The observations of the Italian stock index start in June 2009 so that there are no results for the pre-crisis period in these cases. When adding the crisis dummy variable in the full period specification the estimators of  $ECB_t$  (not reported here) remain similar to the case without its implementation.

Table 5: Distinguishing observation periods for daily price range: Coefficients of  $ECB_t$ 

|             | long-term       | pre-crisis      | post-crisis     | shortened post-crisis | $crisis_t$      |
|-------------|-----------------|-----------------|-----------------|-----------------------|-----------------|
| AU          | 0.000843*       | 0.000773        | 0.00153*        | 0.00176*              | 0.00196***      |
| BE          | 0.00227***      | 0.00202***      | 0.00280***      | 0.00310***            | 0.000272        |
| DE          | 0.00288***      | 0.00201**       | 0.00373***      | 0.00395***            | -0.00108***     |
| ES          | 0.00250***      | 0.00169**       | 0.00385***      | 0.00424***            | 0.000555*       |
| FI          | 0.00422***      | 0.00482***      | 0.00245***      | 0.00229***            | -0.00309***     |
| FR          | 0.00265***      | 0.00140**       | 0.00433***      | 0.00463***            | -0.000266       |
| GR          | -8.16e-05       | 0.000860        | -0.000382       | -0.000468             | 0.00325***      |
| IR          | 0.000641        | 0.000141        | 0.00184**       | 0.00157*              | 0.00168***      |
| IT          | 0.00290***      | 0.00134*        | 0.00404***      | 0.00454***            | 0.00418***      |
| NL          | 0.00253***      | 0.00184***      | 0.00326***      | 0.00356***            | -0.000594**     |
| PT          | 0.00140***      | 0.00147**       | 0.00206***      | 0.00199***            | 0.00160***      |
| VAEX        | 0.0845*         |                 | 0.0845*         | 0.104*                |                 |
| VCAC        | 0.134**         |                 | 0.134**         | 0.102***              |                 |
| VDAX        | 0.00931***      | 0.0152          | 0.00799***      | 0.00956***            | 0.00141         |
| VSTOXX      | 0.00893**       | 0.0105          | 0.00892***      | 0.0108***             | -0.000110       |
| CH          | 0.00185***      | 0.00189***      | 0.00158***      | 0.00160***            | -0.000567**     |
| DK          | 0.00246***      | 0.00267**       | 0.00206**       | 0.00214**             | -0.000681       |
| GB          | 0.00156***      | 0.00159***      | 0.00153**       | 0.00163**             | -0.000132       |
| JP          | 0.00128***      | 0.00162**       | 0.000646        | 0.000951              | -0.00118***     |
| NW          | 0.00193**       | 0.00156         | 0.00189**       | 0.00187*              | -0.000284       |
| SW          | 0.00224***      | 0.00240**       | 0.00217***      | 0.00235***            | -0.000264       |
| US          | 0.000996**      | 0.000642        | 0.00160**       | 0.00220***            | -0.000374       |
| period      | 01/1998-05/2019 | 01/1998-08/2007 | 08/2007-05/2019 | 08/2007-03/2017       | 08/2017-05/2019 |
| # of events | 338             | 200             | 138             | 117                   | 138             |

Note: \*\*\*, \*\*, and \* denote 1%, 5%, and 10% significance levels, respectively. Newey-West-adjusted standard errors. The dashed horizontal lines separate the volatility measures. The upper part considers 11 EA national stock market volatility measures, the middle part 7 non-EA stock markets, while the lower part covers 4 volatility measures of volatility indices. Constants and control variables omitted. Number of observations vary (see Table A3 in the Appendix). The observations of VAEX and VCAC start in June 2008 so that there are no results for the pre-crisis period in these cases. When adding the crisis dummy variable in the full period specification the estimators of  $ECB_t$  (not reported here) remain similar to the case without its implementation.

Table 6: Robustness checks: choice of events

|        | $ECB_t$    | $random_t$ | $ECB_{t-1}$ | $ECB_{t+1}$ | $APA_t$    | $Thursday_t$ | $adj\_Thursday_t$ |
|--------|------------|------------|-------------|-------------|------------|--------------|-------------------|
| AU     | 0.00153*   | 0.00102    | -0.000176   | 0.000260    | 0.00372    | 0.000386     | 0.000116          |
| BE     | 0.00280*** | 0.000523   | -0.000344   | -7.13e-05   | 0.00370    | 0.000880***  | 0.000393          |
| DE     | 0.00373*** | 0.000938   | -0.000173   | -0.000584   | 0.00719*** | 0.00121***   | 0.000543          |
| ES     | 0.00385*** | -0.000373  | 0.000597    | -0.000200   | 0.0108**   | 0.00123***   | 0.000450          |
| FI     | 0.00245*** | -0.000244  | 6.77e-05    | -0.000125   | 0.00413**  | 0.00103**    | 0.000713          |
| FR     | 0.00433*** | -0.000863  | -0.000435   | -0.000351   | 0.00911*** | 0.00138***   | 0.000587          |
| GR     | -0.000382  | -0.00176   | 0.000872    | 0.000219    | 0.00481    | -0.000683    | -0.000759         |
| IR     | 0.00184**  | 0.000754   | -0.00106    | 0.000157    | 0.00828*** | 0.000740*    | 0.000386          |
| IT     | 0.00404*** | 0.000675   | 0.000134    | -0.00134*   | 0.0107***  | 0.00137***   | 0.000534          |
| NL     | 0.00326*** | -0.000222  | -0.000682   | -0.000451   | 0.00606*** | 0.000647*    | 1.87e-05          |
| PT     | 0.00206*** | 0.000898   | 0.000456    | -0.00102**  | 0.00460*** | 0.000715**   | 0.000421          |
| VAEX   | 0.0845*    | 0.0305     | -0.0246***  | 0.0244      | 0.0330*    | 0.0347*      | 0.0190            |
| VCAC   | 0.134**    | -0.00870   | -0.0192     | -0.00743    | 0.270*     | 0.0552***    | 0.0287            |
| VDAX   | 0.00799*** | -0.00355   | -0.00141    | 0.00675**   | 0.0135*    | 0.00678***   | 0.00646***        |
| VSTOXX | 0.00892*** | -0.00457   | -0.00263    | 0.00708**   | 0.0240***  | 0.00990***   | 0.00986***        |
| CH     | 0.00158*** | 0.000251   | -0.000959*  | 0.000251    | 0.00257*   | 0.00124***   | 0.00116***        |
| DK     | 0.00206**  | 0.000187   | -0.000337   | -0.000577   | 0.00300*   | 0.000697*    | 0.000487          |
| GB     | 0.00153**  | 7.76e-05   | -0.000402   | -0.000111   | 0.00402**  | 0.000310     | 0.000118          |
| JP     | 0.000646   | 0.000608   | -5.24e-05   | 0.000300    | -0.00163   | 0.000797**   | 0.000885**        |
| NW     | 0.00189**  | 0.00115    | -0.000691   | 0.000223    | 0.00479**  | 0.000420     | 9.60e-05          |
| SW     | 0.00217*** | -0.000194  | -0.000562   | -0.000159   | 0.00124    | 0.000349     | -4.89e-05         |
| US     | 0.00160**  | -0.000187  | 0.000189    | 0.000209    | 0.00383**  | 0.000791**   | 0.000480          |
| $BE_5$ | 0.0505***  | -0.00571   | 0.00322     | -0.00409    | 0.00226    | 0.0115***    | 0.00465           |
| $DE_5$ | 0.0802***  | -0.000744  | -0.000175   | -0.00568    | 0.0854     | 0.0141**     | 0.00105           |
| $ES_5$ | 0.0961***  | 0.00468    | 0.00442     | -0.0136     | 0.235*     | 0.0261***    | 0.00828           |
| $EU_5$ | 0.0719***  | 0.0831     | -0.0114     | 0.00942     | 0.108*     | 0.0128       | 0.00185           |
| $FI_5$ | 0.0465*    | 0.224      | -0.0130     | 0.0330      | 0.0264     | 0.0106       | 0.00670           |
| $FR_5$ | 0.0861***  | -0.0123    | 0.000422    | -0.00642    | 0.107**    | 0.0182**     | 0.00732           |
| $IT_5$ | 0.0814***  | 0.00424    | -0.000109   | -0.0148     | 0.150**    | 0.0285***    | 0.0122**          |
| $NL_5$ | 0.0621***  | 0.0109     | 0.000910    | -0.00393    | 0.0491     | 0.0109*      | 0.00142           |
| $CH_5$ | 0.0291**   | -0.000574  | -0.00278    | 0.00686     | -0.00660   | 0.0169**     | 0.0157*           |
| $DK_5$ | 0.0643     | -0.00651   | -0.0183*    | -0.00107    | 0.00432    | -0.00907     | -0.0129           |
| $GB_5$ | 0.0292*    | 0.0719     | -0.00552    | 0.0147      | -0.0296    | 0.00257      | -8.78e-06         |
| $JP_5$ | 0.00748    | -0.000108  | -0.00540    | 0.0166      | -0.0234    | 0.00662      | 0.00516           |
| $NW_5$ | 0.0651     | -0.0148*   | -0.00843    | -0.00327    | -0.0304    | 0.0104       | 0.00742           |
| $SW_5$ | 0.0396*    | 0.0788     | -0.0115     | 0.0220      | -0.0310    | -0.00478     | -0.0100           |
| $US_5$ | 0.0382*    | 0.00745    | -0.0129     | 0.0235*     | -0.00976   | 0.0135       | 0.00963           |

Note: \*\*\*, \*\*, and \* denote 1%, 5%, and 10% significance levels, respectively. Newey-West-adjusted standard errors. The solid horizontal line separates the volatility measures. The upper part considers 22 basic volatility measures while the lower part covers 15 realized volatility measures. To enhance legibility, the latter are multiplied by the factor 1000. The dashed lines separate euro against non-euro markets. 138 relevant events included. Only coefficients of dummy variables are displayed. Sample period: August 2007 to May 2019. Observation period is shorter for  $APA_t$  because asset purchase announcements event set ends earlier than May 2019 (see Table A3 in the Appendix for details). To enhance legibility, all coefficients of the lower part are multiplied by the factor 1000. When adding the dummy variable  $adj\_Thursday_t$  the estimators of  $ECB_t$  (not reported here) remain similar to the case without its implementation.

Table 7: Comparison of  $ECB_t$  versus  $shock_t$ : EA markets

|                   | full-time  |             | pre-crisis |            | post-crisis |             |
|-------------------|------------|-------------|------------|------------|-------------|-------------|
|                   | $ECB_t$    | $shock_t$   | $ECB_t$    | $shock_t$  | $ECB_t$     | $shock_t$   |
| AU                | 0.000843*  | 0.000108    | 0.000773   | 0.000551   | 0.00153*    | 6.22e-05    |
| BE                | 0.00227*** | 0.000366**  | 0.00202*** | 0.00213*** | 0.00280***  | 0.000302**  |
| DE                | 0.00288*** | 5.36e-05    | 0.00201**  | 0.00260**  | 0.00373***  | 5.26e-05    |
| ES                | 0.00250*** | 0.00144***  | 0.00169**  | 0.00195**  | 0.00385***  | 0.00134***  |
| FI                | 0.00422*** | 7.08e-05    | 0.00482*** | 0.00421*** | 0.00245***  | 6.05e-05    |
| FR                | 0.00265*** | 0.000609*** | 0.00140**  | 0.00183**  | 0.00433***  | 0.000569*** |
| GR                | -8.16e-05  | 0.00148**   | 0.000860   | 0.00125    | -0.000382   | 0.00162*    |
| IR                | 0.000641   | 0.000335*** | 0.000141   | 0.00105    | 0.00184**   | 0.000295*** |
| IT                | 0.00290*** | 0.00212***  | 0.00134*   | 0.00185**  | 0.00404***  | 0.00202***  |
| NL                | 0.00253*** | 0.000240**  | 0.00184*** | 0.00241*** | 0.00326***  | 0.000223**  |
| PT                | 0.00140*** | 0.00109***  | 0.00147**  | 0.00148*   | 0.00206***  | 0.00103***  |
| VAEX              | 0.0845*    | 0.00190**   |            |            | 0.0845*     | 0.00190**   |
| VCAC              | 0.134**    | 0.0358      |            |            | 0.134**     | 0.0358      |
| VDAX              | 0.00931*** | 7.38e-05    | 0.0152     | 0.0267     | 0.00799***  | 5.58e-05    |
| VSTOXX            | 0.00893**  | 0.00115*    | 0.0105     | 0.0235     | 0.00892***  | 0.00115**   |
| $\overline{BE}_5$ | 0.0343***  | 0.00387*    | 0.0214***  | 0.0233***  | 0.0505***   | 0.00327*    |
| $\overline{DE}_5$ | 0.0628***  | 0.00109     | 0.0425     | 0.0615     | 0.0802***   | 0.00106     |
| $\overline{ES}_5$ | 0.0553***  | 0.0279***   | 0.0206*    | 0.0177     | 0.0961***   | 0.0280***   |
| $\overline{EU}_5$ | 0.0512***  | 0.00613*    | 0.0189*    | 0.0241*    | 0.0719***   | 0.00535     |
| $\overline{FI}_5$ | 0.0404*    | -0.000183   | 0.00718    | 0.0241     | 0.0465*     | -0.000302   |
| $\overline{FR}_5$ | 0.0585***  | 0.00825**   | 0.0328*    | 0.0373**   | 0.0861***   | 0.00736**   |
| $\overline{IT}_5$ | 0.0814***  | 0.0362***   |            |            | 0.0814***   | 0.0362***   |
| $\overline{NL}_5$ | 0.0369***  | 0.00207     | 0.0137     | 0.0175*    | 0.0621***   | 0.00192     |

Note: \*\*\*, \*\*, and \* denote 1%, 5%, and 10% significance levels, respectively. Newey-West-adjusted standard errors. 338 (300 in case of  $RV_t$ ) relevant events included in  $ECB_t$  and  $shock_t$ . Sample period: January 1998 (2000 in case of  $RV_t$ ) to May 2019. The dashed horizontal line separates the volatility measures. The upper part considers 15 basic volatility measures while the lower part covers 8 realized volatility measures. To enhance legibility, the latter are multiplied by the factor 1000. Number of observations vary (see Table A3 in the Appendix).

Table 8: Comparison of  $ECB_t$  versus  $shock_t$ : non-EA markets

|              | full-time  |            | pre-crisis |            | post-crisis |            |
|--------------|------------|------------|------------|------------|-------------|------------|
|              | $ECB_t$    | $shock_t$  | $ECB_t$    | $shock_t$  | $ECB_t$     | $shock_t$  |
| CH           | 0.00185*** | 0.000213** | 0.00189*** | 0.00245*** | 0.00158***  | 0.000155*  |
| DK           | 0.00246*** | 0.000146   | 0.00267**  | 0.00162*   | 0.00206**   | 0.000187** |
| GB           | 0.00156*** | 0.000160*  | 0.00159*** | 0.00180**  | 0.00153**   | 0.000117   |
| JP           | 0.00128*** | -7.97e-05  | 0.00162**  | 0.00139**  | 0.000646    | -8.48e-05  |
| NW           | 0.00193**  | 8.87e-05   | 0.00156    | 0.00360    | 0.00189**   | 8.87e-05   |
| SW           | 0.00224*** | 0.000250** | 0.00240**  | 0.00262**  | 0.00217***  | 0.000216** |
| US           | 0.000996** | 3.85e-05   | 0.000642   | 0.000902   | 0.00160**   | 3.60e-05   |
| $\bar{C}H_5$ | 0.0261***  | 0.00144    | 0.0207**   | 0.0248**   | 0.0291**    | 0.000698   |
| $DK_5$       | 0.0536     | 0.000435   | -0.00831   | 0.00201    | 0.0643      | 8.93e-05   |
| $GB_5$       | 0.0224**   | 2.01e-05   | 0.0216*    | 0.0245**   | 0.0292*     | -0.000932  |
| $JP_5$       | 0.0119**   | -0.000474  | 0.0178**   | 0.0189**   | 0.00748     | -0.000799  |
| $NW_5$       | 0.0444*    | 0.00145    | 0.0198     | 0.0162     | 0.0651      | 0.000935   |
| $SW_5$       | 0.0348*    | 0.000190   | 0.00878    | 0.0342     | 0.0396*     | -0.000152  |
| $US_5$       | 0.0206*    | 0.000362   | 0.00779    | 0.00724    | 0.0382*     | -5.20e-05  |

Note: \*\*\*, \*\*, and \* denote 1%, 5%, and 10% significance levels, respectively. Newey-West-adjusted standard errors. 338 (300 in case of  $RV_t$ ) relevant events included in  $ECB_t$  and  $shock_t$ . Sample period: January 1998 (2000 in case of  $RV_t$ ) to May 2019. The dashed horizontal line separates the volatility measures. The upper part considers 7 basic volatility measures while the lower part covers 7 realized volatility measures. To enhance legibility, the latter are multiplied by the factor 1000. Number of observations vary (see Table A3 in the Appendix).



Table 9: Robustness Check to inclusion of  $shock_t$  as a control

|        | Eq. (6)     | Eq. (8)     |              |
|--------|-------------|-------------|--------------|
|        | $\gamma$    | $\gamma$    | $\delta$     |
| $BE_5$ | 0.00387*    | 0.00457**   | -0.000850**  |
| $DE_5$ | 0.00109     | 0.00135     | -0.000282*** |
| $ES_5$ | 0.0279***   | 0.0214***   | 0.00987**    |
| $EU_5$ | 0.00613*    | 0.00606*    | 0.000100     |
| $FI_5$ | -0.000183   | 0.000375    | -0.000599*   |
| $FR_5$ | 0.00825**   | 0.00921**   | -0.00120**   |
| $IT_5$ | 0.0362***   | 0.0350***   | 0.00191      |
| $NL_5$ | 0.00207     | 0.00218     | -0.000136**  |
| $CH_5$ | 0.00144     | 0.00205**   | -0.000773*** |
| $DK_5$ | 0.000435    | 0.000615    | -0.000232    |
| $GB_5$ | 2.01e-05    | 7.17e-06    | 1.63e-05     |
| $JP_5$ | -0.000474   | -0.000435   | -4.83e-05    |
| $NW_5$ | 0.00145     | 0.00187     | -0.000534    |
| $SW_5$ | 0.000190    | 0.00184*    | -0.00213***  |
| $US_5$ | 0.000362    | 0.00112     | -0.000953**  |
|        | Eq. (7)     | Eq. (9)     |              |
|        | $\gamma$    | $\gamma$    | $\delta$     |
| AU     | 0.000108    | 5.72e-05    | 6.05e-05*    |
| BE     | 0.000366**  | 0.000364**  | 2.67e-06     |
| DE     | 5.36e-05    | 6.22e-05    | -9.31e-06**  |
| ES     | 0.00144***  | 0.00110***  | 0.000516***  |
| FI     | 7.08e-05    | 9.13e-05    | -2.19e-05    |
| FR     | 0.000609*** | 0.000609*** | 4.52e-07     |
| GR     | 0.00148**   | 0.000875    | 0.00131**    |
| IR     | 0.000335*** | 0.000300*** | 4.55e-05     |
| IT     | 0.00212***  | 0.00148***  | 0.000975***  |
| NL     | 0.000240**  | 0.000246*** | -7.23e-06**  |
| PT     | 0.00109***  | 0.000760*** | 0.000558***  |
| CH     | 0.000213**  | 0.000240**  | -3.45e-05**  |
| DK     | 0.000146    | 0.000177**  | -3.96e-05    |
| GB     | 0.000160*   | 0.000146    | 1.75e-05     |
| JP     | -7.97e-05   | -4.16e-05   | -4.64e-05*   |
| NW     | 8.87e-05    | 0.000112    | -3.06e-05    |
| SW     | 0.000250**  | 0.000246**  | 5.42e-06     |
| US     | 3.85e-05    | 9.58e-05    | -7.24e-05*** |
| VAEX   | 0.00190**   | 0.00188**   | 2.21e-05     |
| VCAC   | 0.0358      | 0.0333      | 0.00333      |
| VDAX   | 7.38e-05    | 4.14e-05    | 3.59e-05     |
| VSTOXX | 0.00115*    | 0.000849    | 0.000392**   |

Note: \*\*\*, \*\*, and \* denote 1%, 5%, and 10% significance levels, respectively. Newey-West-adjusted standard errors. 338 (300 in case of  $RV_t$ ) relevant events included in  $shock_t$ . Sample period: January 1998 (2000 in case of  $RV_t$ ) to May 2019. The dashed horizontal line separates the volatility measures. The upper part considers 22 daily price range measures while the lower part covers 15 realized volatility measures (5 minutes frequency). To enhance legibility, the latter are multiplied by the factor 1000. Number of observations vary (see Table A3 in the Appendix).

## Appendix

Table A1: Descriptive statistics

| Variable                       | Observations | Mean       | Std. Dev. | Min.      | Max.      | Source             |
|--------------------------------|--------------|------------|-----------|-----------|-----------|--------------------|
| <i>range</i> <sub>AU</sub>     | 5,310        | 0.0161839  | 0.0114041 | 0.0033403 | 0.1347715 | ATXINDX            |
| <i>range</i> <sub>BE</sub>     | 5,452        | 0.0132106  | 0.0087162 | 0.0021763 | 0.1125419 | BGBEL20            |
| <i>range</i> <sub>CH</sub>     | 5,382        | 0.0129169  | 0.0091523 | 0.0021526 | 0.1452622 | SWISSMI            |
| <i>range</i> <sub>DE</sub>     | 5,434        | 0.0172689  | 0.0119663 | 0.0014377 | 0.1405444 | DAXINDX            |
| <i>range</i> <sub>DK</sub>     | 4,917        | 0.0157371  | 0.012476  | 0.0029396 | 0.1946582 | DKKFXIN            |
| <i>range</i> <sub>ES</sub>     | 5,426        | 0.0173563  | 0.0107278 | 0.0028445 | 0.1427609 | IBEX35I            |
| <i>range</i> <sub>FI</sub>     | 5,371        | 0.0196928  | 0.020261  | 0.0025717 | 0.2706402 | HEXINDX            |
| <i>range</i> <sub>FR</sub>     | 5,465        | 0.0158351  | 0.0102148 | 0.0023462 | 0.0953724 | FRCAC40            |
| <i>range</i> <sub>GB</sub>     | 5,409        | 0.0143303  | 0.0095158 | 0.002325  | 0.1019542 | FTSE100            |
| <i>range</i> <sub>GR</sub>     | 5,287        | 0.0211716  | 0.0145026 | 0.0031493 | 0.2287592 | GRAGENL            |
| <i>range</i> <sub>IR</sub>     | 4,889        | 0.0160998  | 0.011985  | 0.0026408 | 0.2713273 | ISEQUIT            |
| <i>range</i> <sub>IT</sub>     | 4,023        | 0.0165504  | 0.0109204 | 0.0022998 | 0.1238377 | FTSEMIB            |
| <i>range</i> <sub>JP</sub>     | 5,254        | 0.0142022  | 0.0093158 | 0.0019318 | 0.1285823 | JAPDOWA            |
| <i>range</i> <sub>NL</sub>     | 5,470        | 0.0148196  | 0.0105661 | 0.0020459 | 0.1226604 | AMSTEOE            |
| <i>range</i> <sub>NW</sub>     | 3,272        | 0.0158788  | 0.0118428 | 0.0029061 | 0.1161843 | OSLOASH            |
| <i>range</i> <sub>PT</sub>     | 4,902        | 0.0130761  | 0.0082219 | 0.0000961 | 0.0887101 | POPS120            |
| <i>range</i> <sub>SW</sub>     | 4,496        | 0.015993   | 0.0109335 | 0.0027936 | 0.1179102 | SWEDOMX            |
| <i>range</i> <sub>US</sub>     | 5,387        | 0.0133396  | 0.0098623 | 0.0014575 | 0.1121896 | S&PCOMP            |
| <i>range</i> <sub>AEX</sub>    | 2,785        | 0.1014521  | 0.2948062 | 0.0067103 | 8.483335  | AEXVOLI            |
| <i>range</i> <sub>CAC</sub>    | 2,785        | 0.180897   | 0.4031877 | 0.0165319 | 7.599474  | CACVOLI            |
| <i>range</i> <sub>VDAX</sub>   | 3,564        | 0.0650114  | 0.0408645 | 0.0120075 | 1.06916   | VDAXNEW            |
| <i>range</i> <sub>VSTOXX</sub> | 3,569        | 0.0720488  | 0.068008  | 0.0136986 | 2.670115  | VSTOXXI            |
| <i>CEST</i>                    | 4,283        | 4.226313   | 55.8822   | -188.6    | 162.5     | EKCESIR            |
| <i>MSCI</i> <sub>AU</sub>      | 5,587        | 585.3575   | 259.0667  | 298.043   | 1437.188  | MSASTRL            |
| <i>MSCI</i> <sub>BE</sub>      | 5,587        | 954.9202   | 255.8319  | 351.33    | 1481.435  | MSBELGL            |
| <i>MSCI</i> <sub>CH</sub>      | 5,587        | 942.4166   | 179.6968  | 481.432   | 1311.771  | MSSWITL            |
| <i>MSCI</i> <sub>DE</sub>      | 5,587        | 721.3651   | 180.4338  | 282.724   | 1106.945  | MSGERML            |
| <i>MSCI</i> <sub>DK</sub>      | 5,587        | 4052.6     | 2302.012  | 1245.81   | 8850.109  | MSDNMKL            |
| <i>MSCI</i> <sub>ES</sub>      | 5,587        | 897.63     | 179.5173  | 498.199   | 1471.388  | MSSPANL            |
| <i>MSCI</i> <sub>FI</sub>      | 5,587        | 668.8985   | 290.2286  | 261.946   | 1210.131  | MSFINDL            |
| <i>MSCI</i> <sub>FR</sub>      | 5,587        | 1481.293   | 305.3106  | 793.03    | 2234.516  | MSFRNCL            |
| <i>MSCI</i> <sub>GB</sub>      | 5,587        | 1728.827   | 267.3022  | 986.384   | 2276.19   | MSUTDKL            |
| <i>MSCI</i> <sub>GR</sub>      | 5,587        | 768.7642   | 613.2336  | 35.621    | 2435.018  | MSGREEL            |
| <i>MSCI</i> <sub>IR</sub>      | 5,587        | 287.5274   | 138.4866  | 85.838    | 592.674   | MSEIREL            |
| <i>MSCI</i> <sub>IT</sub>      | 5,587        | 946.2183   | 300.7245  | 464.289   | 1625.89   | MSITALL            |
| <i>MSCI</i> <sub>JP</sub>      | 5,587        | 767.0906   | 187.34    | 426.666   | 1146.638  | MSJPANL            |
| <i>MSCI</i> <sub>NL</sub>      | 5,587        | 1101.846   | 291.1657  | 507.284   | 1763.055  | MSNETHL            |
| <i>MSCI</i> <sub>NW</sub>      | 5,587        | 2075.221   | 683.1648  | 762.244   | 3501.445  | MSNWAYL            |
| <i>MSCI</i> <sub>PT</sub>      | 5,587        | 146.4121   | 51.56283  | 70.369    | 271.562   | MSPORDL            |
| <i>MSCI</i> <sub>SW</sub>      | 5,587        | 8137.167   | 2697.456  | 2914.851  | 13613.9   | MSSWDNL            |
| <i>MSCI</i> <sub>US</sub>      | 5,587        | 1430.027   | 500.3852  | 645.347   | 2807.299  | MSUSAML            |
| <i>MSCI Europe</i>             | 4,283        | 1500.628   | 287.4312  | 726.164   | 2235.356  | MSEROP\$           |
| <i>MSCI World</i>              | 5,325        | 1371.926   | 351.4951  | 688.638   | 2248.93   | MSWRLD\$           |
| <i>MSCI World exEu</i>         | 4,283        | 123.6737   | 44.07675  | 56.193    | 230.262   | MSWXEUE            |
| <i>V2TX</i>                    | 5,325        | 23.96001   | 9.470102  | 10.68     | 87.51     | VSTOXXI            |
| <i>surprise</i>                | 5,580        | -0.0595907 | 0.3773679 | -1.653775 | 1.059795  |                    |
| <i>uncertainty</i>             | 5,580        | 0.9892397  | 0.3564789 | 0.2795983 | 2.461624  | from Scotti (2016) |
| <i>y</i> <sub>AU</sub>         | 5587         | 3.151606   | 1.662252  | 0.0517    | 5.8683    | OEBRYLD            |
| <i>y</i> <sub>BE</sub>         | 5587         | 3.321037   | 1.619746  | 0.1027    | 5.8813    | BGBRYLD            |
| <i>y</i> <sub>DE</sub>         | 5587         | 2.894359   | 1.706933  | -0.2158   | 5.6463    | BDBRYLD            |
| <i>y</i> <sub>ES</sub>         | 5587         | 3.86056    | 1.42882   | 0.7162    | 7.59      | ESBRYLD            |
| <i>y</i> <sub>FI</sub>         | 5587         | 3.064202   | 1.681723  | -0.0149   | 5.8401    | FNBRYLD            |
| <i>y</i> <sub>FR</sub>         | 5587         | 3.162477   | 1.572892  | 0.0967    | 5.8334    | FRBRYLD            |
| <i>y</i> <sub>GR</sub>         | 5262         | 7.561544   | 5.824416  | 3.2056    | 48.602    | GRBRYLD            |
| <i>y</i> <sub>IR</sub>         | 5587         | 3.934724   | 2.155079  | 0.0395    | 13.895    | IRBRYLD            |
| <i>y</i> <sub>IT</sub>         | 5587         | 4.001273   | 1.24979   | 1.0488    | 7.288     | ITBRYLD            |
| <i>y</i> <sub>NL</sub>         | 5587         | 3.062988   | 1.66948   | -0.028    | 5.7808    | NLBRYLD            |
| <i>y</i> <sub>PT</sub>         | 5587         | 4.717218   | 2.240749  | 0.8134    | 16.211    | PTBRYLD            |
| <i>rv</i> <sub>5, BE</sub>     | 4,946        | 0.0000869  | 0.0001386 | 4.04E-06  | 0.003343  |                    |
| <i>rv</i> <sub>10, BE</sub>    | 4,946        | 0.0000886  | 0.0001433 | 3.81E-06  | 0.003261  | Bel 20             |
| <i>rv</i> <sub>5, CH</sub>     | 4,864        | 0.0000827  | 0.0001569 | 6.06E-06  | 0.0042179 |                    |
| <i>rv</i> <sub>10, CH</sub>    | 4,864        | 0.0000821  | 0.0001637 | 4.82E-06  | 0.0051775 | Swiss Stock Market |
| <i>rv</i> <sub>5, DE</sub>     | 4,924        | 0.000165   | 0.0002911 | 4.14E-06  | 0.0058835 |                    |
| <i>rv</i> <sub>10, DE</sub>    | 4,924        | 0.0001628  | 0.0002916 | 3.12E-06  | 0.0068955 | DAX 30             |
| <i>rv</i> <sub>5, DK</sub>     | 3,397        | 0.000128   | 0.0003742 | 6.87E-06  | 0.0121591 |                    |
| <i>rv</i> <sub>10, DK</sub>    | 3,397        | 0.0001334  | 0.000398  | 5.44E-06  | 0.0120936 | OMX Copenhagen     |
| <i>rv</i> <sub>5, ES</sub>     | 4,916        | 0.000142   | 0.0002079 | 4.10E-06  | 0.00551   |                    |
| <i>rv</i> <sub>10, ES</sub>    | 4,916        | 0.0001447  | 0.0002314 | 2.86E-06  | 0.0071279 | IBEX 35            |
| <i>rv</i> <sub>5, EU</sub>     | 4,948        | 0.0001571  | 0.0003134 | 9.29E-09  | 0.0108267 |                    |
| <i>rv</i> <sub>10, EU</sub>    | 4,948        | 0.0001572  | 0.0003238 | 1.14E-08  | 0.0125019 | Eurostoxx 50       |
| <i>rv</i> <sub>5, FI</sub>     | 3,428        | 0.0001182  | 0.0004731 | 4.05E-06  | 0.0224565 |                    |
| <i>rv</i> <sub>10, FI</sub>    | 3,428        | 0.0001244  | 0.000337  | 3.60E-06  | 0.0099407 | OMX Helsinki       |
| <i>rv</i> <sub>5, FR</sub>     | 4,948        | 0.0001332  | 0.0002248 | 2.74E-06  | 0.0051221 |                    |
| <i>rv</i> <sub>10, FR</sub>    | 4,948        | 0.0001339  | 0.000235  | 3.06E-06  | 0.0065747 | CAC 40             |
| <i>rv</i> <sub>5, GB</sub>     | 4,894        | 0.0001167  | 0.000273  | 1.33E-06  | 0.0106001 |                    |
| <i>rv</i> <sub>10, GB</sub>    | 4,894        | 0.0001244  | 0.0003311 | 9.51E-07  | 0.0126161 | FTSE 100           |
| <i>rv</i> <sub>5, IT</sub>     | 2,539        | 0.0001176  | 0.0001495 | 7.65E-07  | 0.0022156 |                    |
| <i>rv</i> <sub>10, IT</sub>    | 2,539        | 0.0001178  | 0.0001537 | 7.97E-07  | 0.0023993 | FTSE MIB           |
| <i>rv</i> <sub>5, JP</sub>     | 4,724        | 0.0001038  | 0.0001669 | 3.95E-06  | 0.0032289 |                    |
| <i>rv</i> <sub>10, JP</sub>    | 4,724        | 0.0001117  | 0.000211  | 3.12E-06  | 0.0049586 | Nikkei 225         |
| <i>rv</i> <sub>5, NL</sub>     | 4,949        | 0.0001146  | 0.0001982 | 1.58E-06  | 0.003624  |                    |
| <i>rv</i> <sub>10, NL</sub>    | 4,949        | 0.0001163  | 0.0002073 | 2.85E-06  | 0.0036022 | AEX                |
| <i>rv</i> <sub>5, NW</sub>     | 4,423        | 0.0001274  | 0.0002647 | 6.65E-06  | 0.0072923 |                    |
| <i>rv</i> <sub>10, NW</sub>    | 4,423        | 0.0001295  | 0.0002858 | 6.26E-06  | 0.0090507 | Oslo All Share     |
| <i>rv</i> <sub>5, SW</sub>     | 3,429        | 0.0001021  | 0.0002975 | 2.40E-06  | 0.0105349 |                    |
| <i>rv</i> <sub>10, SW</sub>    | 3,429        | 0.0001183  | 0.0003604 | 2.14E-06  | 0.0107064 | OMX Stockholm      |
| <i>rv</i> <sub>5, US</sub>     | 4,872        | 0.0001074  | 0.0002432 | 1.22E-06  | 0.0077477 |                    |
| <i>rv</i> <sub>10, US</sub>    | 4,872        | 0.0001094  | 0.0002469 | 1.30E-06  | 0.0077841 | S&P 500            |

Note: The upper part represent 22 volatility indices *range*<sub>t</sub> and are calculated from the raw minimum, maximum and opening prices of the data source. The middle part covers the applied control variables. The last column gives the Datastream mnemonics up to and including MSNWAYL. Both surprise and uncertainty index are obtained from Scotti (2016) while the 30 realized volatility indices in the lower part are obtained from Heber et al. (2009).

Table A2: Correlation coefficients of country-specific  $RV_t$

|    | BE     | DE     | ES     | EU     | FI     | FR     | IT     | NL     | CH     | DK     | GB     | JP     | NW     | SW     | US |
|----|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|----|
| BE | 1      |        |        |        |        |        |        |        |        |        |        |        |        |        |    |
| DE | 0.8856 | 1      |        |        |        |        |        |        |        |        |        |        |        |        |    |
| ES | 0.7322 | 0.6241 | 1      |        |        |        |        |        |        |        |        |        |        |        |    |
| EU | 0.9273 | 0.8885 | 0.7759 | 1      |        |        |        |        |        |        |        |        |        |        |    |
| FI | 0.181  | 0.1578 | 0.1559 | 0.1882 | 1      |        |        |        |        |        |        |        |        |        |    |
| FR | 0.961  | 0.8966 | 0.7599 | 0.9544 | 0.1791 | 1      |        |        |        |        |        |        |        |        |    |
| IT | 0.8332 | 0.7521 | 0.8019 | 0.8492 | 0.1696 | 0.8355 | 1      |        |        |        |        |        |        |        |    |
| NL | 0.9462 | 0.8651 | 0.6651 | 0.9045 | 0.1862 | 0.9505 | 0.7615 | 1      |        |        |        |        |        |        |    |
| CH | 0.5851 | 0.6341 | 0.3982 | 0.5611 | 0.0978 | 0.577  | 0.4699 | 0.581  | 1      |        |        |        |        |        |    |
| DK | 0.215  | 0.1896 | 0.1532 | 0.2075 | 0.0497 | 0.2011 | 0.1796 | 0.216  | 0.1394 | 1      |        |        |        |        |    |
| GB | 0.7993 | 0.7582 | 0.5822 | 0.8567 | 0.15   | 0.8016 | 0.6408 | 0.7997 | 0.5079 | 0.2084 | 1      |        |        |        |    |
| JP | 0.2338 | 0.1978 | 0.1718 | 0.2516 | 0.039  | 0.2146 | 0.172  | 0.2361 | 0.1708 | 0.0845 | 0.2808 | 1      |        |        |    |
| NW | 0.6885 | 0.6469 | 0.5475 | 0.7343 | 0.136  | 0.6861 | 0.5591 | 0.6809 | 0.4208 | 0.2103 | 0.8413 | 0.2722 | 1      |        |    |
| SW | 0.3344 | 0.3166 | 0.2554 | 0.3412 | 0.92   | 0.3336 | 0.2949 | 0.335  | 0.2027 | 0.0736 | 0.317  | 0.0687 | 0.279  | 1      |    |
| US | 0.7464 | 0.6586 | 0.5457 | 0.7407 | 0.1149 | 0.7586 | 0.5747 | 0.7917 | 0.4331 | 0.1733 | 0.7576 | 0.2217 | 0.6912 | 0.2429 | 1  |

Note: The dashed lines separate EA and non-EA markets. Only 5 minutes frequency. Values of 10 minutes frequency very similar.

Table A3: Correlation coefficients of country-specific  $range_t$

|    | AU     | BE     | DE     | ES     | FI     | FR     | GR     | IR     | IT     | NL     | PT     | CH     | DK     | GB     | JP     | NW     | SW     | US |
|----|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|----|
| AU | 1      |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |    |
| BE | 0.7794 | 1      |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |    |
| DE | 0.7613 | 0.8341 | 1      |        |        |        |        |        |        |        |        |        |        |        |        |        |        |    |
| ES | 0.6675 | 0.7695 | 0.7597 | 1      |        |        |        |        |        |        |        |        |        |        |        |        |        |    |
| FI | 0.777  | 0.7729 | 0.7728 | 0.6642 | 1      |        |        |        |        |        |        |        |        |        |        |        |        |    |
| FR | 0.7724 | 0.8882 | 0.9195 | 0.8423 | 0.791  | 1      |        |        |        |        |        |        |        |        |        |        |        |    |
| GR | 0.4089 | 0.3794 | 0.4093 | 0.441  | 0.3656 | 0.4122 | 1      |        |        |        |        |        |        |        |        |        |        |    |
| IR | 0.7146 | 0.6787 | 0.6121 | 0.5528 | 0.69   | 0.6528 | 0.3295 | 1      |        |        |        |        |        |        |        |        |        |    |
| IT | 0.6742 | 0.7642 | 0.7937 | 0.8544 | 0.6629 | 0.8472 | 0.4488 | 0.5282 | 1      |        |        |        |        |        |        |        |        |    |
| NL | 0.7891 | 0.899  | 0.8952 | 0.7651 | 0.7938 | 0.935  | 0.3899 | 0.6771 | 0.7779 | 1      |        |        |        |        |        |        |        |    |
| PT | 0.6263 | 0.6973 | 0.6468 | 0.7136 | 0.5999 | 0.7028 | 0.4753 | 0.5406 | 0.7097 | 0.6756 | 1      |        |        |        |        |        |        |    |
| CH | 0.6997 | 0.8001 | 0.7987 | 0.6567 | 0.7191 | 0.8234 | 0.3174 | 0.6251 | 0.6697 | 0.8349 | 0.6047 | 1      |        |        |        |        |        |    |
| DK | 0.6997 | 0.6904 | 0.6811 | 0.5469 | 0.7113 | 0.68   | 0.349  | 0.6364 | 0.5558 | 0.7222 | 0.558  | 0.671  | 1      |        |        |        |        |    |
| GB | 0.8245 | 0.8074 | 0.8152 | 0.6817 | 0.7967 | 0.8393 | 0.3835 | 0.762  | 0.6814 | 0.8594 | 0.6313 | 0.7817 | 0.7314 | 1      |        |        |        |    |
| JP | 0.5074 | 0.4746 | 0.4802 | 0.3552 | 0.4669 | 0.4635 | 0.2333 | 0.4313 | 0.3535 | 0.498  | 0.363  | 0.4875 | 0.4954 | 0.5456 | 1      |        |        |    |
| NW | 0.8106 | 0.7368 | 0.7153 | 0.5763 | 0.7676 | 0.7372 | 0.3509 | 0.6976 | 0.5809 | 0.7888 | 0.5572 | 0.7001 | 0.7149 | 0.8308 | 0.5295 | 1      |        |    |
| SW | 0.8043 | 0.7903 | 0.8106 | 0.6572 | 0.8353 | 0.8123 | 0.3268 | 0.7229 | 0.6663 | 0.8313 | 0.5855 | 0.7606 | 0.7319 | 0.8483 | 0.4986 | 0.8021 | 1      |    |
| US | 0.7239 | 0.7269 | 0.7364 | 0.6086 | 0.6989 | 0.7444 | 0.3048 | 0.6438 | 0.6099 | 0.7693 | 0.5595 | 0.7084 | 0.6362 | 0.7811 | 0.5213 | 0.7367 | 0.7308 | 1  |

Note: The dashed lines separate EA and non-EA markets.

Table A4: Number of observations for different specifications

|                  | long term | pre-crisis | post-crisis | shortened post-crisis | $APA_t$ |
|------------------|-----------|------------|-------------|-----------------------|---------|
| AU               | 5,309     | 2,387      | 2,922       | 2,387                 | 2,737   |
| BE               | 5,447     | 2,435      | 3,012       | 2,462                 | 2,823   |
| CH               | 5,380     | 2,424      | 2,956       | 2,417                 | 2,771   |
| DE               | 5,433     | 2,447      | 2,986       | 2,443                 | 2,800   |
| DK               | 4,916     | 1,977      | 2,939       | 2,403                 | 2,755   |
| ES               | 5,424     | 2,419      | 3,005       | 2,455                 | 2,816   |
| FI               | 5,369     | 2,413      | 2,956       | 2,415                 | 2,771   |
| FR               | 5,464     | 2,451      | 3,013       | 2,463                 | 2,824   |
| GB               | 5,408     | 2,433      | 2,975       | 2,430                 | 2,787   |
| GR               | 5,285     | 2,358      | 2,906       | 2,368                 | 2,722   |
| IR               | 4,885     | 1,897      | 2,988       | 2,440                 | 2,799   |
| IT               | 4,022     | 1,037      | 2,985       | 2,439                 | 2,798   |
| JP               | 5,253     | 2,372      | 2,881       | 2,353                 | 2,704   |
| NL               | 5,468     | 2,455      | 3,013       | 2,463                 | 2,824   |
| NW               | 3,269     | 331        | 2,938       | 2,401                 | 2,754   |
| PT               | 4,896     | 1,883      | 3,013       | 2,463                 | 2,824   |
| SW               | 4,495     | 1,539      | 2,956       | 2,415                 | 2,770   |
| US               | 5,386     | 2,422      | 2,964       | 2,420                 | 2,778   |
| VAEX             | 2,776     |            | 2,776       | 2,228                 | 2,587   |
| VCAC             | 2,776     |            | 2,776       | 2,228                 | 2,587   |
| VDAX             | 3,561     | 585        | 2,976       | 2,433                 | 2,790   |
| VSTOXX           | 3,563     | 585        | 2,978       | 2,435                 | 2,792   |
| $BE_5 / BE_{10}$ | 4,945     | 1,935      | 3,010       | 1,948                 | 2,822   |
| $CH_5 / CH_{10}$ | 4,863     | 1,912      | 2,951       | 1,910                 | 2,767   |
| $DE_5 / DE_{10}$ | 4,923     | 1,938      | 2,985       | 1,933                 | 2,800   |
| $DK_5 / DK_{10}$ | 3,396     | 474        | 2,922       | 1,885                 | 2,739   |
| $ES_5 / ES_{10}$ | 4,915     | 1,913      | 3,002       | 1,940                 | 2,813   |
| $EU_5 / EU_{10}$ | 4,188     | 1,180      | 3,008       | 1,943                 | 2,820   |
| $FI_5 / FI_{10}$ | 3,427     | 474        | 2,953       | 1,909                 | 2,768   |
| $FR_5 / FR_{10}$ | 4,947     | 1,936      | 3,011       | 1,948                 | 2,823   |
| $GB_5 / GB_{10}$ | 4,893     | 1,918      | 2,975       | 1,923                 | 2,787   |
| $IT_5 / IT_{10}$ | 2,538     |            | 2,538       | 1,482                 | 2,351   |
| $JP_5 / JP_{10}$ | 4,723     | 1,843      | 2,880       | 1,863                 | 2,703   |
| $NL_5 / NL_{10}$ | 4948      | 1,937      | 3,011       | 1,948                 | 2,823   |
| $NW_5 / NW_{10}$ | 4,422     | 1,483      | 2,939       | 1,911                 | 2,755   |
| $SW_5 / SW_{10}$ | 3,428     | 473        | 2,955       | 1,909                 | 2,769   |
| $US_5 / US_{10}$ | 4,871     | 1,908      | 2,963       | 1,915                 | 2,777   |

Note: The horizontal line separates the volatility measures. The upper part considers 22 basic volatility measures while the lower part covers 15 realized volatility measures. The number of events varies in the pre-crisis and full-time period because the observations of volatility starts in 1998 while those of realized volatility start in 2000. The observations of VAEX and VCAC start in June 2008 and the realized volatility measures of Italy start in June 2009 so that there are no entries for the pre-crisis period in these cases.