IMES DISCUSSION PAPER SERIES

A Quest for Monetary Policy Shocks in Japan by High Frequency Identification

Fumitaka Nakamura, Nao Sudo, and Yu Sugisaki

Discussion Paper No. 2021-E-2

IMES

INSTITUTE FOR MONETARY AND ECONOMIC STUDIES

BANK OF JAPAN

2-1-1 NIHONBASHI-HONGOKUCHO
CHUO-KU, TOKYO 103-8660
JAPAN

IMES Discussion Paper Series 2021-E-2
April 2021

A Quest for Monetary Policy Shocks in Japan by High Frequency Identification

Fumitaka Nakamura*, Nao Sudo, and Yu Sugisaki*****

Abstract

The use of changes in short-term interest rates (STIRs) within a 30-minute window around monetary policy announcements has been increasingly adopted in empirical studies. However, variations of STIRs within such a narrow window may be too small under the effective lower bound (ELB). To address the issue, this paper constructs a measure of monetary policy shocks using STIR futures in Japan, where the policy interest rate has been close to the ELB for an exceptionally long period. We show that (i) variations within a 30-minute window are closely correlated with key financial variables while those outside the window are correlated less, suffering from noise, (ii) expansionary shocks with respect to unconventional measures have continued to lower the long-term yield, and (iii) the impulses of macroeconomic variables to the shocks agree with what conventional theory predicts overall.

Keywords: Monetary policy shocks; high frequency identification; effective lower bound

JEL classification: E32, E44, E52

***** Deputy Director and Economist, Institute for Monetary and Economic Studies, Bank of Japan (E-mail: fumitaka.nakamura@boj.or.jp)
****** Director and Senior Economist, Institute for Monetary and Economic Studies (currently, Financial System and Bank Examination Department), Bank of Japan (E-mail: nao.sudou@boj.or.jp)
******* Economist, Institute for Monetary and Economic Studies, Bank of Japan (E-mail: yuu.sugisaki@boj.or.jp)

We would like to thank Hiroyuki Kubota, Ko Munakata, Toshitaka Sekine, Mototsugu Shintani, Koji Takahashi, Yoichi Ueno, Shingo Watanabe, Toshiaki Watanabe, the seminar participants at the BOK/ERI–BOJ/IMES workshop, and the participants at the macroeconomics workshop at Osaka University for extremely valuable comments and suggestions. The views expressed in this paper are those of the authors and do not necessarily reflect the official views of the Bank of Japan.

1 Introduction

High frequency identification (HFI) is a way to extract monetary policy shocks from changes in short-term interest rate (STIR) futures (with expiration in one year or less), typically within a 30-minute window around monetary policy announcements.[1] Started by a pioneering paper by Gürkaynak, Sack, and Swanson (2005), this approach has been increasingly adopted in empirical studies, in particular those that focus on United States (U.S.) monetary policy shocks.[2]

In this paper, we follow the existing studies and construct monetary policy shocks in Japan using changes in STIR futures within a 30-minute window and study characteristics of these shocks. The sample period covers 2003 - 2017, which approximately coincides with the period during which STIRs in Japan were constrained by the effective lower bound (ELB). HFI based on STIRs in Japan poses an extra challenge in at least two opposing directions. On the one hand, variations in STIRs may be too small to extract relevant information, as pointed out, for example, by Nakashima, Shibamoto, and Takahashi (2019). On the other hand, variations in STIRs may not capture the intended effects of unconventional monetary policy measures. In the case of Japan, the Bank of Japan (BOJ) launched several unconventional measures during this period, including forward guidance, purchases of long-term government bonds, a negative interest rate policy, and yield curve control. The nature of monetary policy transmission may change depending on which of the measures is undertaken. Indeed, most existing studies that use STIRs focus on periods when the policy rate was well above the ELB, and studies on unconventional monetary policy employ longer-term yields (e.g., the two-year rate) or a wider window (e.g., 60 minutes) for their analysis.[3]

Figure 1 shows the time path of the uncollateralized overnight call rate together with government bond yields of different maturities since 1999. Overall, the overnight call rate was quite stable around zero during most of our sample period. Longer-yields, such as the ten-year interest rate, exceeded one percent earlier in the period, but has fallen below zero recently.

We address the following two questions — do changes in STIRs within a narrow window around monetary policy announcements under the ELB contain relevant information regarding monetary policy and how has that information changed over time? To this end, we first con-

[1] Another popular method to identify monetary policy shocks is the one proposed by Romer and Romer (2004). Studies such as Coibion, Gorodnichenko, Kueng, and Silvia (2017) and Nakamura (2019) employ this method using the sample period before the global financial crisis in the United States.

[2] A non-exhaustive list of works along this line includes Gertler and Karadi (2015), Gorodnichenko and Weber (2016), Nakamura and Steinsson (2018), Caldara and Herbst (2019), Paul (2019), and Jarociński and Karadi (2020).

[3] See Wright (2012), Gilchrist, López-Salido, and Zakrajšek (2015), and Gilchrist, Yue, and Zakrajšek (2019).

struct monetary policy shocks using Euroyen futures (Japanese three-month STIR futures) over a 30-minute window around each scheduled Monetary Policy Meeting (MPM) announcement. We then conduct three types of analyses. First, we focus on relationships between the identified shocks and key financial variables and study how the information contained in changes during a 30-minute window around MPMs differs from that outside the window, in terms of its relationships with key financial variables. Second, we examine the relationships between the identified shocks and the key financial variables closely and discuss how the transmission of these shocks to financial variables has changed over time. Third, we examine how identified monetary policy shocks affect key macroeconomic variables using the proxy structural vector autoregression (SVAR) approach à la Gertler and Karadi (2015). We use the identified monetary policy shocks as an instrument for the policy indicator (such as the one-year riskless interest rate) and formulate a vector autoregression (VAR), such as that employed in Stock and Watson (2012) or Mertens and Ravn (2013).

Our findings are three-fold. First, the relationships between changes in STIRs and key financial variables are significant and the signs of the relationships are consistent with the standard macroeconomic theory for changes in STIRs during the 30-minute window around MPMs. By contrast, the relationships weaken or even disappear when the changes are measured using a wider window. We also find that there is some degree of background noise outside the 30-minute window using the heteroskedasticity-based estimator developed by Rigobon and Sack (2004).

Second, we find that these changes in STIRs affect key financial variables, especially short- and long-term yields differently. Specifically, expansionary shocks with respect to unconventional measures affect long-term more than short-term yields on a policy announcement day. Our results indicate that these shocks have flattened the yield curve up to the ten-year rate in Japan, as discussed in Gilchrist, López-Salido, and Zakrajšek (2015). Furthermore, the impacts of the innovations in STIRs on financial variables have, on the whole, changed over time, which is possibly due to changes in the economic environment, such as hitting the ELB, as pointed out by recent studies, including Swanson and Williams (2014a, b) and Fatum, Hara, and Yamamoto (2019). Distinct from the existing literature, we moreover find that the effect of our shocks persists beyond the announcement day: expansionary shocks had continued to flatten the Japanese yield curve up to the ten-year rate up until the next monetary policy announcement.

Third, we find that monetary policy shocks instrumented by these changes in STIRs deliver dynamics of key macroeconomic variables, such as the consumer price index (CPI), the capacity utilization rate, and corporate bond yields significantly and in a manner consistent with the standard macroeconomic theory.

Related literature.— Most of the existing HFI studies focus on the non-ELB period.[4] These studies include Gürkaynak, Sack, and Swanson (2005), Gertler and Karadi (2015), Gorodnichenko and Weber (2016), Nakamura and Steinsson (2018), Caldara and Herbst (2019), Paul (2019) and Jarociński and Karadi (2020), and typically extract monetary policy shocks from changes in STIR futures over a 30-minute window around FOMC announcements using U.S. data. Among them, our work is closest to Nakamura and Steinsson (2018) and Gertler and Karadi (2015) in terms of the econometric specification.

There are also works that focus on monetary policy shocks in the ELB period. These studies typically use changes in long-term interest rates within a window wider than 30 minutes to identify monetary policy shocks. For example, Wright (2012) uses longer-term yields, such as ten-year or thirty-year interest rates, with a two-hour window around policy announcements. Gilchrist, López-Salido, and Zakrajšek (2015), and Gilchrist, Yue, and, Zakrajšek (2019) exploit the two-year Treasury yield with a 60-minute window around policy announcements.[5] Regarding Japan's ELB period, Arai (2017) uses daily changes in Japanese Government Bond (JGB) yields with maturities longer than two years. Nakashima, Shibamoto, and Takahashi (2019) construct their measure of monetary policy shocks from daily changes in various financial variables, including long-term interest rates, such as ten-year or thirty-year interest rates. One exception is Kubota and Shintani (2020), who construct monetary policy shocks from changes in STIR futures prices over a 30-minute window and argue that the shocks they extract are characterized by two factors — the "target" and "path" factors — as in Gürkaynak, Sack, and Swanson (2005).[6] Another exception is Munakata, Oi, and Ueno (2019), who exploit high frequency innovations in STIR futures, as well as those in longer-term interest rate futures and stock market futures, to identify information effects and term-premium shocks. Our paper differs from these works by studying in detail how the information contained in changes in STIRs within a 30-minute window differs from that outside the window and how relationships between these changes in

[4]To give an example, the high frequency data that Gertler and Karadi (2015) use cover about 21 years (1991:1 – 2012:6), during which the federal funds rate remained zero for less than 4 years (2008:12 – 2012:6).

[5]Swanson (2020) exploits STIR futures as well as long-term bond yields, stock prices, and exchange rates within a 30-minute window.

[6]The important differences between Kubota and Shintani (2020) and this paper are two-fold. First, they extract two principal components from changes in the four Euroyen futures prices to characterize monetary policy shocks, while our measure of monetary policy shocks is the first principal component of the four Euroyen futures prices, following Nakamura and Steinsson (2018). Second, this paper focuses on how the transmission of the identified shocks to financial variables has changed over time (see section 4).

STIRs and financial variables change over time.

Layout.— The remainder of this paper is organized as follows. Section 2 presents some illustrative examples of intraday financial data that qualitatively justify the choice of Euroyen futures prices, the 30-minute window, and not including unscheduled MPMs in our sample. Section 3 describes how we construct our measure of monetary policy shocks and compares it with other measures. Section 4 provides properties of the monetary policy shocks in terms of how differently the short-end and long-end of the yield curve are affected. Section 5 estimates responses of the key macroeconomic variables to these shocks. Section 6 concludes.

2 Market Movements on MPM days

Before the quantitative analysis, we explore what asset prices and what window length we should exploit in extracting monetary policy shocks using a case study on some illustrative dates. Qualitatively, we see that the use of STIR futures and a 30-minute window is reasonable. By contrast, it seems difficult to extract the shocks from changes in long-term yields or price movements on unscheduled MPM days because their movements are volatile and it is difficult to decide the appropriate size of the window for capturing the shocks while excluding noise.

2.1 STIR Futures, Long-Term Yields, and Stock Prices

Within several tens of minutes after an MPM announcement, responses to the announcement vary by financial variable. The choice of Euroyen futures prices seems reasonable, at least qualitatively, in order to clearly extract exogenous monetary policy shocks. Figure 2 shows the intraday data of STIRs (extracted from the one-quarter ahead Euroyen futures price), the Japanese government bond (JGB) ten-year interest rate, and the Nikkei 225 stock price index on January 29th, 2016, when the BOJ introduced the negative interest rate policy.[7] On this day, the MPM ended at 12:31 (indicated as a vertical line in each panel) and immediately after that the policy statement was published on the BOJ website. After this announcement, the STIR clearly dropped, hit the bottom within 20-30 minutes, and then remained at almost the same level toward the end of the day. In this case, it is likely that news about the monetary policy decision was clearly reflected in the change over the 20-30 minute window around the MPM announcement and there is little noise unrelated to the MPM decision within the narrow window. By contrast, the JGB ten-year rate and the Nikkei 225 stock price index were very volatile: the

[7]See the data appendix for details on the source of the data.

JGB ten-year rate gradually decreased for about an hour, but then increased slightly, and finally decreased again after that. The Nikkei 225 stock price index spiked immediately after the announcement, then dropped sharply until about 13:15, and increased after that toward the end of the day. From such volatile innovations, it seems difficult to extract changes in market expectations about monetary policy.[8]

2.2 The 30-minute Window

The next issue is how wide the window should be or whether the 30-minute window is too narrow or not. For the definition of the 30-minute window, following preceding studies such as Gürkaynak, Sack, and Swanson (2005), we set the beginning at 10 minutes prior to the monetary policy announcement and the ending at 20 minutes after the policy announcement. If market participants do not completely digest news regarding an MPM announcement in this 30-minute window, the window is not wide enough to capture monetary policy shocks. However, some examples of movements around the MPM announcement imply that the 30-minute window is reasonable in that we do not need a wider window to extract monetary policy shocks. If we use a wider window, it is more likely that the asset price changes incorporate noise unrelated to the monetary policy decision and, what is worse, the constructed measure causes an endogeneity problem. Figure 3 makes this point. The start and the end of the window are indicated by the vertical lines. The first panel again describes the intraday movement of the STIR (extracted from the one-quarter ahead Euroyen futures price) on January 29th, 2016, when the BOJ introduced the negative interest rate policy, and the second panel on July 29th, 2016, when the BOJ increased the purchase of ETFs (Exchange-Traded Funds). Both of the examples show that the change within the 30-minute window dominates the entire movement of the day: the STIR changed much in the narrow window, but remained almost unchanged during the rest of the day. This indicates that the 30-minute window is presumably wide enough to completely capture the shocks.

We also show the case where a wider window (e.g., one-day) induces the problem that asset price changes would contain movements driven by factors other than monetary policy. The third panel of Figure 3 shows the intraday movement of the STIR on December 19th, 2008, when the BOJ decreased the uncollateralized overnight call rate (policy target interest rate then). In the morning, the government announced that it would launch a fiscal policy package named "The Immediate Policy Package to Safeguard People's Daily Lives" in response to the recession caused

[8] Indeed, as we show in the appendix, the JGB futures price is affected by a relatively large amount of noise unrelated to the monetary policy decision.

by the global financial crisis. We see that the STIR responded to the fiscal announcement.

2.3 Unscheduled MPMs

Our final issue in constructing the measure of monetary policy shocks is whether we should exclude unscheduled MPMs. We define an MPM as "unscheduled" if it is specified so in the MPMs minutes.[9] The list of unscheduled MPMs is presented in Table 1. During our sample period (from 2003:04 to 2017:10) we have nine unscheduled MPMs. The presence of the unscheduled MPMs might make it difficult to identify exogenous monetary policy shocks, since innovations of financial variables are dominated by noise unrelated to monetary policy. Consider the following example of the MPM held on March 14th, 2011, when the BOJ responded to the Tohoku-Pacific Ocean earthquake and expanded the asset purchase program. Figure 4 shows the intraday data of the STIR extracted from the four-quarter ahead Euroyen futures price, with the 30-minute window denoted by two vertical lines. On this day, news about the Fukushima Daiichi Nuclear Power Station accident caused by the Tohoku-Pacific Ocean earthquake was frequently updated. The movements of asset prices are considered to have been affected by such news frequently and are thus volatile, as we can see in Figure 4. In such a situation, non-monetary noise is likely to be contained in the movement within the narrow window (which would contaminate our identification, as is implied in the result of subsection 3.2.3). As in this case, an unscheduled MPM tends to be held in response to an unexpected event (e.g., the Lehman Brothers bankruptcy[10]), and in such situations responses of financial markets as well as the formation of expectations regarding unscheduled MPMs are qualitatively different from those regarding scheduled MPMs. Thus, we exclude them from our sample.

3 Constructing a Measure of Monetary Policy Shocks

3.1 Methodology

The Euroyen futures.— We employ three-month Euroyen futures rates. The price of Euroyen futures indicates the expected interest rate at a future point defined by the contract month.[11] We use one-, two-, three, and four-quarter-ahead Euroyen futures rates, which we denote as

[9] For the definition of an unscheduled MPM, we follow Munakata, Oi, and Ueno (2019), who identify monetary policy shocks using the same data in the same sample period.

[10] Lehman Brothers went bankrupt on September 15, 2008. The BOJ held an unscheduled MPM on September 18, 2008 in response to the bankruptcy.

[11] A detailed description of Euroyen futures is provided on the following website of the Tokyo Financial Exchange Inc.: `https://www.tfx.co.jp/en/wholesale/products/ey.html`

YE1, YE2, YE3, and YE4, respectively. The choice of these particular contracts is motivated by liquidity considerations: we do not use futures prices whose contract dates are further than one year away because they do not have enough trading volume.[12] The sample period ranges from April 30, 2003 to October 31, 2017, during which, except for a short period, the STIR in Japan hit the ELB.

We choose as our baseline measure for monetary policy shocks the first principal component of the changes in these four futures prices over a 30-minute window around each scheduled MPM. We take the principal component only in order to minimize the effect of noise in a specific contract. We obtain similar results if we use one of the Euroyen futures prices instead.

The start and the end of the window.— The 30-minute window starts 10 minutes before the announcement and ends 20 minutes after it.[13] In many cases, a meeting ends during lunch time (when the financial markets are not open). We adjust the definition of the window in such cases by following Munakata, Oi, and Ueno (2019): if a meeting ends before 12:30, we always set the end of the 30-minute window at 12:50, or specifically, 20 minutes after 12:30.

Similarly, when analyzing a window larger than 30 minutes (for example, 60 minutes), we assume that a $10x$-minute window, for $x = 1, 2, ..., 6$, starts 10 minutes before the announcement and ends $10(x-1)$ minutes after it. For meetings that end during lunch time, we apply a similar rule to that applied when constructing the 30-minute window. Specifically, we set the end of the window at $10(x-1)$ minutes after 12:30. For example, for the case of a 60-minute window, the end of the window is set at 13:20.

Exclusion of unscheduled meetings from the sample.— Given the discussion in section 2.3, we use scheduled meetings exclusively in order for the window not to include noise unrelated to monetary policy.

3.2 Importance of Window Size and Choice of Meetings

3.2.1 Setting the Criteria

Before analyzing how our monetary policy shocks affect key financial and macroeconomic variables, we study how these shocks are altered depending on the construction methodology by

[12] Gürkaynak, Sack, and Swanson (2005) and Nakamura and Steinsson (2018) also do not use futures prices whose contract dates are further than one year away for the same reason as we do not use them.

[13] We regard the time at which each MPM ends as identical to the announcement time.

choosing a different window size or by including unscheduled meetings. To this end, we first estimate impacts of these shocks on financial variables following Nakamura and Steinsson (2018) using the OLS procedure described below and see how the estimated impacts change when alternative construction methodologies are employed:

$$\Delta R_t = \alpha + \beta Z_t^{\mathrm{HF}} + e_t. \tag{1}$$

Here, ΔR_t is the change in a financial variable on an MPM day, measured by the one-day window, as in Nakamura and Steinsson (2018), Z_t^{HF} is the measure of monetary policy shocks, and e_t is an error term. The coefficient β stands for the explanatory power of our baseline monetary policy shocks, i.e., the first principal component of changes in STIRs over the 30-minute window around scheduled MPM announcements, denoted as Z_t^{HF}, for the variable ΔR_t.[14]

Table 2 presents the estimation results. The dependent variables include the daily change in the U.S. Dollar/Japanese Yen (USD/JPY) exchange rate, Nikkei 225 stock price index, ten-year JGB futures price, one-, two-, five-, and ten-year JGB yields, and ten-year real interest rate. The coefficient in each column represents the impact of our baseline measure on the corresponding variable. In all cases, the coefficients are statistically significantly different from zero and their signs are consistent with what the standard theory predicts, i.e., expansionary shocks depreciate the exchange rate, raise stock prices, and lower both nominal and real government bond yields.

We also estimate the following equation by two-stage least squares (hereafter TSLS), using again our baseline measure of monetary policy shocks Z^{HF} as an instrument:

$$\Delta R_t = \alpha + \beta \Delta i_t + e_t, \tag{2}$$

where Δi_t is the daily change of the JGB one-, two-, or five-year rate. Table 3 shows the results. For each combination of a dependent variable and independent variable set, the estimated coefficient is again statistically significant. Our measure identifies the pass-through from medium- and long-term yields to Japanese financial variables.

3.2.2 Role of 30-minute window around MPM

The size of the window is important to identify exogenous monetary policy shocks. On the one hand, a narrower window is better because it excludes non-monetary policy shocks. On

[14] By using a sufficiently narrow window in constructing Z_t^{HF}, the endogeneity problem is presumably avoided as described in section 2. The same approach is employed in Gürkaynak, Sack, and Swanson (2005), for example.

the other hand, market participants may need more time to understand news about the policy decision. In this subsection, we assess the relevance of using a 30-minute window in two ways: examining the sensitivity of R^2 to a change in the length of the window and using the Rigobon estimator.

Assessment using $\mathbf{R^2}$

The local optimality of the 30 minute window.— One straightforward way to pin down the optimal length of the window is to seek a window, say τ, that best explains the daily change in a financial variable on a day when an MPM takes place. We compute the change in the Euroyen futures prices over different window lengths, say 30 minutes or 40 minutes, denoting them as $Z_t^{\text{HF}}(\tau)$. We then regress daily changes of the Euroyen futures prices, which we denote as Z_t^{Daily}, on $Z_t^{\text{HF}}(\tau)$ for different τ's.

$$Z_t^{\text{Daily}} = \alpha + \beta Z_t^{\text{HF}}(\tau) + \xi_t. \tag{3}$$

Figure 5 shows the R^2 of the equation above for the four different Euroyen futures and our baseline measure with different window sizes τ. Indeed, R^2 peaks when τ is around 30 minutes for most of our measures, including the baseline measure, and no gain is obtained when τ is set longer than 30 minutes. This observation indicates setting the window at 30 minutes is fairly reasonable from the perspective of R^2. Figure 6 shows the case when the dependent variable Z_t^{Daily} is replaced with the daily change in the two-year government bond yield and the exchange rate, respectively. A similar observation holds, though the size of R^2 varies across dependent variables.

The dominance of monetary policy shocks.— Next we discuss that it is not any 30-minute window but the 30-minute window around an MPM announcement that is important. To address this issue, we execute what we refer to as a "randomized R-squared method." We define T as the sample of Z_t around the actual MPM announcements ("treatment sample"), and C as a sample of equally narrow windows that do not contain MPM announcements ("control sample"). Let R_T^2 represent the R^2 for T, and R_C^2 represent the R^2 for C in equation (3). If the 30-minute window around the MPM has a specific importance to variations in financial variables, then we expect that $R_T^2 > R_C^2$. To verify this expectation statistically, we test the "null-hypothesis" that $R_T^2 = R_C^2$ using the following bootstrap-like "randomized R-square method" :

1. For each MPM day ($j = 1, 2, ..., 196$), let w_j be the 30-minute window around the MPM.

2. Compute changes in the Euroyen futures prices, and let the change be Z_j^T (this corresponds to constructing a sample for T).

3. Regress $\Delta Z_j^{\text{Daily}}$ on Z_j^T. Let the R-squared value of this regression be R^* (which is regarded as R_T^2 in this case).

4. To construct a sample for C, for each j, draw a 30-minute window from the set $\{w_1, w_2, ..., w_{196}\}$ randomly with replacement, and assign it to meeting j. Let the assigned window be x_j. In most cases,[15] x_j does not overlap with w_j so that it can be regarded as part of C.

5. For each j, compute the change in the Euroyen futures prices over the window x_j of the same day as j is held, and let the change be Z_j^C.

6. Regress $\Delta Z_j^{\text{Daily}}$ on Z_j^C and compute R^2 (which is an analogue of R_C^2).

7. Repeat step 4 - step 6 5,000 times and compute the percentile of R^2 values, to estimate the distribution of R^2 when C is arbitrarily selected. Then compare the percentile to R^* calculated in step 3.

Figure 7 presents the median of the values of R^2 and the 2.5th and 97.5th percentiles. Overall, R^* is larger than R^2 when a 30-minute window does not sandwich the time announcements are made (R_C^2). From this result, we reject the null-hypothesis that $R_T^2 = R_C^2$ and conclude that monetary policy shocks dominate Z_t^{HF}.

Assessment using the Rigobon Estimator

Another way to check whether the 30-minute window around the MPM has a particular importance to financial variables is to study possible changes in the variance of a financial variable around the MPMs. To this end, we compare the estimates of equation (1) by OLS (described in Table 2) with estimates based on the estimation method of Rigobon (2003) and Rigobon and Sack (2004).[16] Here, we consider a model where changes in a financial variable are expressed as the sum of monetary policy shocks and background noise. If the OLS estimation yields similar results to the Rigobon estimator, it is likely that the impact of background noise is not very important. In order to filter out the background noise, the Rigobon estimator looks at the differences in the co-movements of financial variables and Euroyen futures prices between

[15] Given the window length of 30 minutes, the probability that x_j does not include the actual MPM announcement time is about 65 percent.

[16] A discussion regarding the use of these estimators in High Frequency identification is described in Nakamura and Steinsson (2018).

T and C. The identifying assumption is that the variance of monetary policy shocks increases around MPM announcements, while the variance of noise is unchanged. Here, we construct the control sample from the data of immediately preceding days during the same time as the treatment sample, following Shibamoto (2016).

Table 4 compares the OLS estimator and the Rigobon estimator for some of the financial variables considered in the preceding subsection. We see that when a 30-minute window is used, the difference between the estimators (and, more importantly, the difference between the 95 percent confidence intervals[17]) is so small that we expect little noise in the changes in Euroyen futures prices over a 30-minute window.

By contrast, we see that the amount of background noise is increasing as we consider wider windows. The similarity between the OLS estimates and the Rigobon estimates still holds for a 60-minute window for such financial variables as the JGB two-year rate and the JGB five-year rate. However, the Rigobon estimate for the JGB one-year rate is not statistically significant while the OLS estimate is, and in the case of estimates for the JGB futures prices, the point estimate of the Rigobon estimator is different from the OLS point estimate by more than two robust standard errors for the OLS estimate, implying that the point estimate based on the Rigobon estimator is outside of the 95 percent confidence interval of the OLS estimate (see Figure 8). The differences between the estimates are more striking when we use a one-day window. These results indicate that the presence of background noise in a one-day window contaminates the estimation of the effect of monetary policy shocks on financial variables.

3.2.3 Role of distinction between scheduled and unscheduled meeting

Whether or not to include unscheduled meetings in the sample is mixed among existing studies. Arai (2017) includes, for example, the meeting held on December 1st, 2009, arguing that the meeting is associated with an "important" BOJ official policy change. On the other hand, Munakata, Oi, and Ueno (2019) drop these cases from their sample, stressing that the expectation formation of market participants on the day unscheduled MPMs are held may be qualitatively different from those on scheduled MPM days.

There are nine unscheduled meetings during our sample period. To see how inclusion of these meetings affects our results, we first estimate equation (1) by OLS based on the sample that includes these meetings and compare the result to the OLS estimates presented above. Table 5 shows that the estimated impact of our shocks on financial variables is significantly weakened if

[17]We construct the confidence intervals for the Rigobon estimator using weak instruments robust bootstrap method proposed in Nakamura and Steinsson (2018).

the unscheduled meetings are included in the sample. Scatter plots in Figure 9 show the reason. Here, the vertical axis denotes the daily change in the five-year JGB yield on MPM days and the horizontal axis denotes our measure of monetary policy shocks. It can be seen that the observations that correspond to the unscheduled MPM days are mostly outliers in the sense that the magnitude of changes within the 30-minute window of these observations is far larger than most of the rest of the sample and that changes in the STIR and the five-year yield move in the opposite direction for these observations whereas they move in the same direction in the rest of the sample.

4 Response of Financial Variables to the Identified Monetary Policy Shocks

Existing studies that extract monetary policy shocks using HFI, such as Nakamura and Steinsson (2018) and Gilchrist, López-Salido, and Zakrajšek (2015), document that impacts of these shocks on financial variables are different across variables, for example across yields with different maturities. Along this line, in this section we study in detail how the monetary policy shocks constructed above affect key financial variables.

4.1 Response of bond yields

4.1.1 Impacts on yields with different maturities

As discussed in the introduction, during our sample period, the STIR was close to zero and the BOJ had introduced various unconventional monetary policy measures. Theoretically speaking, the type of monetary policy measure implemented can matter to how identified monetary policy shocks are translated to changes in financial variables. For example, long-term yields may be less affected by monetary policy shocks when conventional monetary policy is implemented compared with when unconventional monetary policy is implemented. Indeed, Gilchrist, López-Salido, and Zakrajšek (2015), who study the impacts of unconventional monetary policy shocks on yields with different maturities, stress the difference between conventional and unconventional monetary policy in terms of how monetary policy shocks affect bond yields with different maturities.

To see the relationship between the type of monetary policy measure in place and the transmission of our monetary policy shocks to financial variables, we extend regression model (1) and estimate the following equation:

$$\Delta R_t = \alpha + \beta Z_t^{\text{HF}} + \gamma_1 Z_t^{\text{HF}} \delta_t^1 + \gamma_2 Z_t^{\text{HF}} \delta_t^2 + \gamma_3 Z_t^{\text{HF}} \delta_t^3 + e_t. \tag{4}$$

The dummy variable δ_t^1 is unity if the announcement was made during the period running from the start of QQE in April 2013 to the period just before the introduction of the negative interest rate policy (NIRP) in January 2016, and takes a value of zero otherwise. Similarly, the dummy variable δ_t^2 is unity if the announcement was made during the period running from the introduction of the NIRP to the period just before the introduction of yield curve control (YCC) in September 2016 and the dummy variable δ_t^3 is unity if the announcement was made during the period after the introduction of YCC.

Table 6 presents the results together with the results for the U.S. reported by Nakamura and Steinsson (2018) and Gilchrist, López-Salido, and Zakrajšek (2015). We scale the coefficients so that the coefficient on the one-year rate is 100 basis points (and the coefficient on the five-year rate is 100 basis points for Gilchrist, López-Salido, and Zakrajšek 2015). Note that, in our estimation with the dummy variables specified in equation (4), the coefficient β, shown in the first row of the table, is the slope coefficient of our shocks on bond yields during the period before 2013. The estimated coefficient β peaks for the two-year yield and then declines monotonically as the maturity increases. For the ten-year yield, the coefficient is not statistically significant, indicating that monetary policy shocks affected yields only of the maturities up to five years before the introduction of QQE. A similar tendency is observed for the U.S. monetary policy shocks identified by Nakamura and Steinsson (2018).

The estimate for β based on equation (4) differs starkly from the estimate for β based on equation (1). For the latter, β is smallest for the one-year yield, gradually increasing as maturity increases. The coefficients, including that for the ten-year yield, are all statistically significant. This tendency contrasts with the results of Nakamura and Steinsson (2018), which studies a sample period that largely coincides with the period when conventional monetary policy was in place. However, our results agree with those of Gilchrist, López-Salido, and Zakrajšek (2015), which studies the period when unconventional monetary policy was in place.

Indeed, the coefficients for the dummy variables γ_1, γ_2, and γ_3 are informative regarding which part of our sample period is responsible for the gap between the two βs, based on equations (1) and (4). First, the coefficient γ_1 is negative for the shorter-yields, i.e., the one-year and two-year yields, and positive for the longer-yields, i.e., the five-year and ten-year yields.[18] Second,

[18]The only coefficient that is statistically significant is that of the ten-year yield. The result implies that under

the coefficient γ_2 is positive for all of the yields but not significant for shorter-term yields and significant for longer-term yields. Lastly, the coefficient γ_3 is positive and significant for all of the yields except for the one-year yield whose coefficient is positive but not significant. It is also noticeable that the absolute value of coefficient γ_3 is substantially larger than the coefficient γ_2 for all of the yields.

To see these observations from a different angle, we estimate OLS regression (1) using a rolling window over four years and explore how coefficient β changes over time. Figure 10 shows the results. Consistent with what is shown in Table 6, there is an important difference between how monetary policy shocks have affected shorter-term yields and longer-term yields. For the former yields, the impacts have changed markedly over time. They were above zero until around 2010 before falling to zero and remaining at that level for a few years, then climbed to a value above zero again toward the latest period of our sample. By contrast, for the latter two yields, such ups and downs were moderate and the impacts were above zero throughout the sample period. The difference in impacts on shorter-term yields and longer-term yields is greatest around 2010.

To summarize, there are three takeaways from the results. First, our monetary policy shocks affect not only the short-term yields but also the long-term yields despite the fact that they are extracted from changes in STIRs. Second, our shocks actually affect the long-term yields more than the short-term yields. This observation accords well with the studies that focus on the effects of unconventional monetary policy shocks, such as Gilchrist, López-Salido, and Zakrajšek (2015) and contrasts with those that focus on conventional monetary policy shocks, such as Nakamura and Steinsson (2018). Third, the impact of our shocks is different across time periods, depending on which monetary policy measures were in place.

4.2 Persistence of the Shocks

We investigate the transmission across yields with different maturities in terms of the persistence of the impacts of the shocks. In the second row of Table 7, we show the results of the regressions where the dependent variables are changes in yields within a two-day window (from a day before the announcement to a day after the announcement) instead of a one-day window. Note that the independent variables remain the same. Each estimated coefficient is statistically different from

QQE, the impact of our shocks on the shorter-term yields has been unchanged or may have been attenuated and the impact on the longer-term yields, at least on the ten-year yield, has been more pronounced, compared with the period before QQE was implemented. This result is consistent with the view that expansionary shocks to conventional monetary policy measures steepen the yield curve while those to unconventional measures flatten the yield curve, as pointed out in Gilchrist, López-Salido, and Zakrajšek (2015).

zero and the sign of each coefficient is unchanged from the case of the one-day window. Note that the ordering of the relative sizes of the coefficients across yields with different maturities is unchanged as well. We also execute the same estimation using inter-MPM changes in financial variables (i.e., changes from a day before the MPM announcement to a day before the next MPM announcement) as the dependent variables. As shown in the third row of the Table 7, the coefficients of long-term yields remains statistically significant while that of the short-term yield (one-year) loses its statistical significance.

From this result, it is clear that the effect of the shocks persists beyond the announcement day and lasts until the next MPM, especially for the longer-end of the yield curve. Also, note that as we use the wider window for the dependent variable, the estimated coefficients overall get larger for longer-term yields, while that of the short-term yield (one-year) remains almost the same. This observation indicates that expansionary shocks continued to flatten the yield curve up to the ten-year rate until the next announcement.[19]

5 Response of Macroeconomic Variables to the Identified Monetary Policy Shocks

This section studies dynamic responses of financial and macroeconomic variables to our baseline measure for monetary policy shocks. To estimate impulse responses, we use monetary policy shocks identified by high frequency Euroyen futures prices as an external instrument for a structural VAR model. The obtained impulse responses to our monetary policy shocks are overall in accord with what traditional theory predicts.

5.1 Estimation method

To study dynamic impulse responses of financial and macroeconomic variables, we exploit the proxy SVAR approach developed by Mertens and Ravn (2013) and Gertler and Karadi (2015).

[19]Regarding the results for the regressions when the inter-MPM window is used, the same conclusion is reached even if we slightly alter the specification by using, for example, the five-one year JGB yield spread as a dependent variable instead of an individual yield:

$$\Delta(y_t^5 - y_t^1) = \alpha + \beta Z_t^{\mathrm{H}F} + e_t,$$

where $\Delta(y_t^5 - y_t^1)$ is the five-one year JGB yield spread measured by the inter-MPM window. The point estimate for β is 1.46, which is statistically significant at the 10 percent level. Furthermore, when we use the ten-one year JGB spread as a dependent variable, the point estimate for β is 1.76, which is again significantly distinct from zero at the 10 percent level and larger than that of the five-one year JGB spread, also comporting with the view that expansionary shocks continued to flatten the yield curve up to the 10-year rate.

We describe the outline of the estimation process in this subsection.

Consider the VAR model as follows:

$$\mathbf{A}\mathbf{Y}_t = \sum_{p=1}^{P} \mathbf{C}_p \mathbf{Y}_{t-p} + \boldsymbol{\epsilon}_t,$$

where $\mathbf{Y}_t$ is a vector of economic and financial variables, P is the lag length, $\mathbf{A}$ and $\mathbf{C}_p$ (for any $p = 1, ..., P$) are conformable coefficient matrices, and $\boldsymbol{\epsilon}_t$ is a vector of structural shocks. The reduced form expression of the VAR is

$$\mathbf{Y}_t = \sum_{p=1}^{P} \mathbf{B}_p \mathbf{Y}_p + \mathbf{u}_t, \tag{5}$$

where $\mathbf{B}_p = \mathbf{A}^{-1}\mathbf{C}_p$, and $\mathbf{u}_t$ is the reduced form of the shock and is represented as

$$\mathbf{u}_t = \mathbf{S}\boldsymbol{\epsilon}_t, \tag{6}$$

with $\mathbf{S} = \mathbf{A}^{-1}$. Let i_t be the monetary policy indicator (the one-year or two-year JGB rate in our analysis) and $\mathbf{y}_t$ be a vector of other macroeconomic and financial variables in the VAR. We consider the partition $\mathbf{Y}_t = [i_t, \mathbf{y}_t']'$ and $\mathbf{u}_t = [u_t^i, \mathbf{u}_t^{y\prime}]'$ to rewrite equation (5) as

$$\begin{pmatrix} i_t \\ \mathbf{y}_t \end{pmatrix} = \sum_{p=1}^{P} \mathbf{B}_p \begin{pmatrix} i_{t-p} \\ \mathbf{y}_{t-p} \end{pmatrix} + \begin{pmatrix} u_t^i \\ \mathbf{u}_t^y \end{pmatrix}.$$

One can simply use least squares estimation of the reduced form VAR to obtain estimates of the coefficients in $\mathbf{B}_p$.

Moreover, consider the partition $\boldsymbol{\epsilon}_t = [\epsilon_t^i, \boldsymbol{\epsilon}_t^{y\prime}]'$ and the corresponding matrix of structural coefficients

$$\mathbf{S} = [\mathbf{S}_1 \, \mathbf{S}_2] = \begin{pmatrix} s^i & \mathbf{S}^{iy} \\ \mathbf{S}^{yi} & \mathbf{S}^{yy} \end{pmatrix},$$

to rewrite equation (6) as

$$\begin{pmatrix} u_t^i \\ \mathbf{u}_t^y \end{pmatrix} = \begin{pmatrix} s^i & \mathbf{S}^{iy} \\ \mathbf{S}^{yi} & \mathbf{S}^{yy} \end{pmatrix} \begin{pmatrix} \epsilon_t^i \\ \boldsymbol{\epsilon}_t^y \end{pmatrix}.$$

In the conventional VAR approach to identifying monetary policy shocks, one imposes the timing restriction (as in Christiano, Eichenbaum, and Evans 1999) to suppose that the impact of the policy indicator on the other variables occurs with a lag of at least one period. However, the proxy SVAR approach does not utilize this restriction. Instead it exploits the external instrument, Z_t, which correlates exogenous shocks to the policy indicator ϵ_t, and is orthogonal to within period movements in the other variables in the VAR. Namely, we need

$$\mathrm{E}[Z_t \epsilon_t^i] = \phi,$$

for some $\phi \in \mathbb{R}$ and

$$\mathrm{E}[Z_t \boldsymbol{\epsilon}_t^y] = \mathbf{0}.$$

In our case, Z_t is the monetary policy shocks constructed from changes in the Euroyen futures prices over a 30-minute window around MPM announcements.

To obtain contemporaneous effects of exogenous shocks to the policy indicator, we only have to estimate the coefficients in $\mathbf{S}_1$. Let $s^y \in \mathbf{S}^{yi}$ and $u_t^y \in \mathbf{u}_t^y$. Using the TSLS estimation of u_t^y on u_t^i with Z_t as an instrument, we can estimate s^y/s^i to identify the contemporaneous innovation of each VAR variable given a unit increase of the policy indicator.[20] Given the estimates of $\mathbf{S}_1$ and $\mathbf{B}_p$, we can compute impulse responses.

One advantage of the proxy SVAR approach over other methods (e.g., the local projection delineated by Jordà 2005) is that one can estimate the impulse responses even if the measure of shocks does not fully cover the period that is used to estimate the coefficient matrix $\mathbf{B}_p$. In our case, since we wish to focus on the ELB period in Japan, it is desirable that we construct a measure of monetary policy shocks whose sample period starts in 1999, when the BOJ lowered the overnight call rate (then the policy target rate) to virtually zero. However, due to the limited availability of data, we can only access data since 2003. Even in such a situation, we can compute the impulses: we estimate $\mathbf{B}_p$ using macroeconomic variables with a sample period spanning from 1999 to 2019, while obtaining the estimates of $\mathbf{S}_1$ by implementing the TSLS procedure by exploiting only the VAR residuals for which the instrument is available for the corresponding sample period.

For the proxy SVAR approach, we run a monthly[21] VAR with the log of CPI, log of IIP

[20] See Mertens and Ravn (2013) and Gertler and Karadi (2015) for more detailed estimation procedures.

[21] To use our baseline measure for monetary policy shocks in a monthly VAR scheme, we have to take into account that the day of the MPMs vary over the month: effects of a shock on monthly data are different depending

(Index of Industrial Production, the capacity utilization rate), Nikkei 225 stock price index, corporate bond index, and JGB one-year rate or two-year rate as the policy indicator, using 12 lags.[22] We use our measure of monetary policy shocks constructed from Euroyen futures price changes as an external instrument for the indicator.

The setup we use for the VAR of equation (5) is designed to estimate impacts of monetary policy shocks under unconventional monetary policy: first, the sample period of the monthly VAR is 1999:1 to 2019:12, during which the policy target rate was constrained by the ELB and the BOJ launched several unconventional measures. Second, we choose the JGB one- or two-year rate as the policy indicator since it incorporates the shocks to forward guidance (see Gertler and Karadi 2015; Gerko and Rey 2017; Jarociński and Karadi 2020). Third, we can study dynamic impulses of variables on the real side of the economy through financial variables such as stock prices and corporate bond yields, whose movements unconventional monetary policy is intended to manage through asset purchase programs, for instance. Note that, unlike the standard timing restriction, we assume that monetary policy shocks will affect all variables in the VAR contemporaneously. In particular, the VAR specified above has three financial variables (JGB one/two- year rate, stock prices, and corporate bond yields) where traditional Cholesky ordering is difficult to carry out. In such a situation, we can estimate the contemporaneous innovations of financial and macroeconomic variables by using instruments.

5.2 The Weak Instruments Problem and Impulse Responses

When we identify contemporaneous effects of monetary policy shocks on economic variables in the proxy SVAR approach, we need to avoid the weak instruments problem in the TSLS estimation of u_t^y on u_t^i with the external instrument Z_t. In other words, u_t^i must be strongly correlated with Z_t. According to Stock, Wright, and Yogo (2002), a first-stage F statistic below 10 could indicate that a weak instruments problem is present.[23]

We examine whether the weak instruments problem is present when we use the JGB one-

on the day on which an announcement is made. In order not to lose information by disregarding this point, following Gertler and Karadi (2015), we convert our measure into a monthly series as follows: (1) For each day, we cumulate the changes in Euroyen futures price changes on any unscheduled MPM days during the last 31 days and (2) average these changes across each day of the month. Similar manipulation is done by Romer and Romer (2004) and Barakchian and Crowe (2013).

[22] The results presented below are robust to other VAR specifications, such as excluding the corporate bond index, adding the JGB five-year rate, and using the core CPI instead of the CPI.

[23] Stock and Yogo (2005), Montiel Olea and Pflueger (2013), and Andrews, Imbens, and Sun (2019) among others propose a different standard to detect weak instruments. We confirm that our instrument satisfies their standards to conclude that a weak instruments problem is not present when using the JGB one-year rate as a policy indicator.

year rate and JGB two-year rate as the policy indicator. Table 8 summarizes the results. When our baseline measure (with a 30-minute window, the left column of the table) is used as an instrument for the JGB one-year rate innovation, the robust F statistic is 28.56, which is above 10, and the robust F statistic is still over 10 if we use the JGB two-year rate as a policy indicator. By contrast, the middle and right columns of Table 8 shows that a weak instruments problem is present when we use a 60-minute window or a one-day window. Again, these results support the use of a 30-minute window in identifying monetary policy shocks during the ELB period.

The strong correlation between the VAR residuals and our measure with a 30-minute window corroborates the finding that our measure contains shocks regarding unconventional monetary policy (e.g., forward guidance): since the policy rate was zero for most of our sample period, the VAR residual of the policy indicator (such as the JGB one-year rate and two-year rate) reflects shocks to unconventional monetary policy. Thus, the strong correlation with the VAR residuals is evidence that our measure contains such shocks. On the other hand, the result that the correlation becomes weaker as we use a wider window may reflect the fact that the instrument is more affected by background noise, as is argued in section 3.2.2.

Figure 11 shows the impulse responses of the macroeconomic and financial variables. We focus on the impulse responses when we use the JGB one-year rate as the policy indicator, due to the better performance as an instrument of our policy shock measure.[24] The monetary policy shock is standardized so that it decreases the JGB one-year rate by one basis point. Each panel reports the estimated impulse response along with the 90 percent confidence interval, computed using bootstrapping methods.[25] We see that the impulses in Figure 11 are in line with what conventional theory predicts: there is an increase in industrial production and stock prices.[26] A small increase is observed in the consumer price index. Gertler and Karadi (2015) argues that the "price puzzle" disappears if the federal funds futures rate is used as an instrument, which is in line with our result. Corporate bond yields decline significantly. The evidence from these impulses suggests that our baseline measure of monetary policy shocks captures news related to a monetary policy change well: monetary policy shocks captured by our measure have a

[24]Even if we use the two-year rate as the policy indicator, we obtain almost same results.

[25]Following Mertens and Ravn (2013) and Gertler and Karadi (2015), we use the wild-bootstrap method where the estimation errors related to the instrumental variable regression are incorporated into the confidence interval.

[26]Note that, according to Gertler and Karadi (2015), the impulse of industrial production peaks around 24 months after an expansionary shock, which is almost in accord with our result. Note also that, while the daily response of the stock price is statistically significant as in Table 2, the response is very weak in the impact period in Figure 11, which may be due to noise contained in the data other than MPM days, leading to a larger confidence interval. Nevertheless, in the impulse of the monthly VAR, stock prices increase and reach their peak around 24 months after the impact period, possibly reflecting better performance of firms accompanied by an increase in production.

significant impact on macroeconomic variables in the long run.

6 Conclusion

HFI of monetary policy shocks has been increasingly used in empirical studies, particularly in those that focus on U.S. monetary policy shocks. These studies typically extract changes in STIRs within a 30-minute window around the FOMC meetings and regard them as monetary policy shocks. In this paper, we follow these studies and apply HFI to Japanese data for the period when the policy rate was almost always bounded by the ELB. By looking closely at the relationships between these changes in STIRs and other financial and macroeconomic variables, we find the following three points. First, we find that changes in STIRs within a 30-minute window around the MPM contain important information regarding variations in key financial variables, such as short- and long-term yields, the exchange rate, and stock prices. By contrast, changes in STIRs outside the window do not hold much information, possibly due to the fact that background noise is large. Second, we find that the transmission of these changes is different across variables and that its nature has varied over time. For example, the impacts of these monetary policy shocks was larger for long-term yields than short-term yields throughout our sample period. Third, we find that these changes can be used as an instrument to help estimate the effects of monetary policy shocks on macroeconomic variables during the ELB period. Moreover, the estimated responses are consistent with what the standard macroeconomic theory predicts.

References

Andrade, Philippe, and Filippo Ferroni. 2020. "Delphic and Odyssean Monetary Policy Shocks: Evidence from the Euro Area." *Journal of Monetary Economics*, forthcoming.

Andrews, Isaiah, James H. Stock, and Liyang Sun. 2019. "Weak Instruments in Instrumental Variables Regression: Theory and Practice." *Annual Review of Economics*, **11**, 727-753.

Arai, Natsuki. 2017. "The Effects of Monetary Policy Announcements at the Zero Lower Bound." *International Journal of Central Banking*, **13(2)**, 159-196.

Barakchian, S. Mahdi, and Christopher Crowe. 2013. "Monetary Policy Matters: Evidence from New Shocks Data." *Journal of Monetary Economics*, **60(8)**, 950-966.

Caldara, Dario, and Edward Herbst. 2019. "Monetary Policy, Real Activity, and Credit Spreads: Evidence from Bayesian Proxy SVARs." *American Economic Journal: Macroeconomics*, **11(1)**, 157-192.

Christiano, Lawrence J., Martin Eichenbaum, and Charles L. Evans. 1999, "Monetary Policy Shocks: What Have We Learned and to What End?" In *Handbook of Macroeconomics*, Elsevier, **1**, 65-148.

Cieslak, Anna, and Andreas Schrimpf. 2019. "Non-Monetary News in Central Bank Communication." *Journal of International Economics*, **118**, 293-315.

Cœuré, Benoît. 2017. "Monetary Policy, Exchange Rates and Capital Flows." Speech at the 18th Jacques Polak Annual Research Conference hosted by the International Monetary Fund, Washington D.C., November 2017.

Coibion, Olivier, Yuriy Gorodnichenko, Lorenz Kueng, and John Silvia. 2017. Innocent Bystanders? Monetary Policy and Inequality." *Journal of Monetary Economics*, **88**, 70-89.

Fatum, Rasmus, Naoko Hara, and Yohei Yamamoto. 2019. "Negative Interest Rate Policy and the Influence of Macroeconomic News on Yields." *IMES Discussion Paper Series*, No.2019-E-2, Bank of Japan.

Gerko, Elena, and Hélène Rey. 2017. "Monetary Policy in the Capitals of Capital." *Journal of the European Economic Association*, **15(4)**, 721-745.

Gertler, Mark, and Peter Karadi. 2015. "Monetary Policy Surprises, Credit Costs, and Economic Activity." *American Economic Journal: Macroeconomics*, **7(1)**, 44-76.

Gilchrist, Simon, David López-Salido, and Egon Zakrajšek. 2015. "Monetary Policy and Real Borrowing Costs at the Zero Lower Bound." *American Economic Journal: Macroeconomics*, **7(1)**, 77-109.

Gilchrist, Simon, Vivian Yue, and Egon Zakrajšek. 2019. "U.S. Monetary Policy and International Bond Markets." *Journal of Money, Credit and Banking*, **51(S1)**, 127-161.

Gorodnichenko, Yuriy, and Michael Weber. 2016. "Are Sticky Price Costly? Evidence from the Stock Market. " *American Economic Review*, **106(1)**, 165-199.

Gürkaynak, Refet S., Brian Sack, and Eric T. Swanson. 2005. "Do Actions Speak Louder than Words? The Response of Asset Prices to Monetary Policy Actions and Statements." *International Journal of Central Banking*, **1(1)**, 55-93.

Jarociński, Marek, and Peter Karadi. 2020. "Deconstructing Monetary Policy Surprises – The Role of Information Shocks." *American Economic Journal: Macroeconomics*, **12(2)**, 1-43.

Jordà, Òscar. 2005. "Estimation and Inference of Impulse Responses by Local Projections." *American Economic Review*, **95(1)**, 161-182.

Kubota, Hiroyuki, and Mototsugu Shintani. 2020. "High-frequency Identification of Unconventional Monetary Policy Shocks in Japan." *CARF working paper*, CARF-F-502, The University of Tokyo.

Mertens, Karel, and Morten O. Ravn. 2013. "The Dynamic Effects of Personal and Corporate Income Tax Changes in the United States." *American Economic Review*, **103(4)**, 1212-1247.

Montiel Olea, José Luis, and Carolin Pflueger. 2013. "A Robust Test for Weak Instruments." *Journal of Business & Economic statistics*, **31(3)**, 358-369.

Munakata, Ko, Hiroyuki Oi, and Yoichi Ueno. 2019. "Monetary Policy Framework and Information Effect: Evidence from Japanese Data." Mimeo.

Nakamura, Fumitaka. 2019. "Household Income, Portfolio Choice and Heterogeneous Consumption Responses to Monetary Policy Shocks." *IMES Discussion Paper Series*, No. 2019-E-19, Bank of Japan.

Nakamura, Emi and Jón Steinsson. 2018. "High-Frequency Identification of Monetary Non-Neutrality: The Information Effect." *Quarterly Journal of Economics*, **133(3)**, 1283-1330.

Nakashima, Kiyotaka, Masahiko Shibamoto, and Koji Takahashi. 2019. "Identifying Quantitative and Qualitative Monetary Policy Shocks." Mimeo.

Paul, Pascal. 2019. "The Time-Varying Effect of Monetary Policy on Asset Prices." Federal Reserve Bank of San Francisco Working Paper, 2017-09.

Rigobon, Roberto. 2003. "Identification through Heteroskedasticity." *Review of Economics and Statistics*, **85(4)**, 777-792.

Rigobon, Roberto, and Brian Sack. 2004. "The Impact of Monetary Policy on Asset Prices." *Journal of Monetary Economics*, **51**, 1553-1575.

Romer, Christina D., and David H. Romer. 2004. "A New Measure of Monetary Shocks: Derivation and Implications." *American Economic Review*, **94(4)**, 1055-1084.

Shibamoto, Masahiko. 2016. "Empirical Assessment of the Impact of Monetary Policy Communication on the Financial Market."*RIEB Discussion Paper Series*, DP 2016-19, Kobe University.

Stock, James H., and Mark W. Watson. 2012. "Disentangling the Channels of the 2007-09 Recession." *Brooking Papers on Economic Activity*, **42(1)**, 81-135.

Stock, James H., Jonathan H. Wright, and Motohiro Yogo. 2002. "A Survey of Weak Instruments and Weak Identification in Generalized Method of Moments." *Journal of Business & Economic statistics*, **20(4)**, 518-529.

Stock, James H., and Motohiro Yogo. 2005. "Testing for Weak Instruments in Linear IV Regression." In *Andrews DWK Identification and Inference for Econometric Models*, Cambridge University Press, 80-108.

Swanson, Eric T. 2020. "Measuring the Effects of Federal Reserve Forward Guidance and Asset Purchases on Financial Markets." *Journal of Monetary Economics*, forthcoming.

Swanson, Eric T. and John C. Williams. 2014a. "Measuring the Effect of the Zero Lower Bound on Medium- and Longer-Term Interest Rates." *American Economic Review*, **104(10)**, 3154-3185.

Swanson, Eric T. and John C. Williams. 2014b. "Measuring the Effect of the Zero Lower Bound on Yields and Exchange Rates in the U.K. and Germany." *Journal of International Economics*, **92(Supplement 1)**, S2-S21 .

Wright, Jonathan H. 2012, "What Does Monetary Policy Do to Long-Term Interest Rates at the Zero lower Bound?" *Economic Journal*, **122**, F447-F466.

Data Appendix

- Euroyen futures prices (YE1, YE2, YE3, YE4): obtained from Tokyo Financial Exchange Inc.
- Japanese Government Bond (JGB) one-, two-, five-, and ten-year rates: retrieved from Bloomberg.
- Japanese Breakeven inflation rate (BEI): retrieved from Bloomberg.
- United States Dollar/Japanese Yen (USD/JPY) exchange rate: retrieved from Bloomberg.
- Nikkei 225 stock price index: retrieved from Bloomberg.
- CPI (Consumer Price Index): Excluding fresh foods, consumption tax adjusted, obtained from the website of the Ministry of Internal Affairs and Communications. We get seasonally adjusted series by using Census X-12.
- IIP (Index of Industrial Production): operation rate, seasonally adjusted, obtained from the website of the Ministry of Economy, Trade and Industry.
- Corporate bond index: rating A by R&I, one-year rate, retrieved from Bloomberg.
- Ten-year JGB futures: obtained from Bloomberg and Nikkei NEEDS.

Appendix: Identification with High Frequency Data for Long-Term Rates

In order to identify monetary policy shocks under the ELB, some studies exploit high frequency data for long-term interest rates (e.g., Wright 2012; Gilchrist, López-Salido, and Zakrajšek 2015; Gilchrist, Yue, and Zakrajšek 2019). This section is devoted to studying whether such high frequency movements in long-term interest rates are useful to capture different aspects of monetary policy shocks from those captured by the STIR futures. We extract changes in long-term interest rates from the ten-year JGB futures,[27] which we obtained from Nikkei NEEDS. The changes are measured by a 50-minute window, since the R^2 value for regression (3) peaks at the 50-minute window and there seems to be no advantage to using a wider window (see Figure 12).[28]

Decomposition into Short Shocks and Long Shocks

We decompose the ten-year JGB futures changes into the following two components: (i) the component that is explained by movements in Euroyen futures (referred to as "short" shocks), and (ii) the component that is orthogonal to changes in Euroyen futures (referred to as "long" shocks), following the econometric framework proposed by Gilchrist, López-Salido, and Zakrajšek (2015).

Model specification.— Consider the following equation:

$$\Delta y_t^L = \lambda_S \Delta y_t^S + \Delta m_t^L, \tag{7}$$

where Δy_t^L denotes the change in the ten-year JGB futures over a 50-minute window around an MPM announcement, and Δy_t^S is our baseline measure (denoted by Z_t^{HF} in section 3). Δm_t^L represents the monetary policy shock that is orthogonal to changes in Euroyen futures. The

[27]The ten-year JGB futures contract represents the face value of a standardized 6 percent ten-year JGB. Deliverable grade bonds are interest-bearing ten-year JGBs with 7 years or more but less than 11 years. We use the futures whose contract date is from one day to 3 months ahead, and our sample period ranges from January 19, 2005 to March 16, 2017. The start and end of the window are same as in the case of the Euroyen futures. A more detailed description is given on the following website of the Japan Exchange Group: `https://www.jpx.co.jp/english/derivatives/products/jgb/jgb-futures/01.html`

[28]Unlike in the case of Table 2, for the ten-year JGB futures, the 30-minute window is not appropriate to capture monetary policy shocks. If we regress the daily changes of key financial variables on the shocks measured by a 30-minute window, the coefficients are not statistically significant. We also evaluate the noise contained in the JGB futures: we compare the OLS estimates to the Rigobon estimates, as described in Figure 13.

impacts of Δy_t^S and Δm_t^L on financial variables, ΔR_t, are represented as

$$\begin{aligned} \Delta R_t &= \beta_S \Delta y_t^S + \beta_L \Delta m_t^L \\ &= (\beta_S - \lambda_S \beta_L) \Delta y_t^S + \beta_L \Delta y_t^L + u_t, \end{aligned} \tag{8}$$

where u_t absorbs all non-monetary shocks. β_S and β_L determine the impact of "short" and "long" monetary policy shocks. Equations (7) and (8) are jointly estimated by system nonlinear least squares (NLLS).

Results of the regression.— Table 9 presents the result of the system NLLS estimation.[29] When the USD/JPY exchange rate is the dependent variable, we find that while the short shocks have a statistically significant effect on the exchange rate, long shocks do not. In other words, shifts in the short end of the yield curve have a significant effect on exchange rates, while the exchange rate is less affected by shifts in the long end of the yield curve, as pointed out by Cœurè (2017). In addition, when JGB yields are used as the dependent variable, the estimated coefficients for both short and long shocks are statistically significant: the reactions of these safe interest rates are affected by both types of shocks.

Presence of information effect.— On the other hand, when the Nikkei 225 stock price index is the dependent variable, the sign of the estimated coefficients for short and long shocks are different: "short" monetary policy easing shocks increase stock prices, though "long" monetary policy easing shocks decrease stock prices.[30] This implies that the long shocks include an information effect — an effect caused by the revision of private economic agents' expectations, such that monetary policy easing is regarded as a signal of a central bank's view of weak economic conditions so that private agents' view is revised downward.

When the information effect is dominant on an announcement day, interest rates and stock prices should positively co-move. Regarding this point, the simple scatter plots indicate that the changes in ten-year JGB futures are more affected by information effects than changes in Euroyen futures. The left panel of Figure 14 shows the scatter plot for the daily change in the Nikkei 225 stock price index (the vertical axis) and the short shocks/long shocks (the horizontal axis). Each dot represents a scheduled MPM announcement. In quadrants I and III we observe

[29] The estimates of coefficients for short shocks are not identical to those in the OLS regression in section 4 since the sample period is different. We do not use the sample of 2003:05 - 2004:12 and 2017:03 - 2017:10 because we do not have access to the high frequency data of the ten-year JGB futures.

[30] In Kubota and Shintani (2020), the impacts of path factor on stock prices are not significant.

a positive co-movement, and 38.4 percent of the interior data points are in quadrants I and III. By contrast, for the case of changes in the long shocks (see the right panel of Figure 14), 59.8 percent of the interior data points are in quadrants I and III.

As is discussed in the recent HFI literature (e.g., Cieslak and Schrimpf 2019; Andrade and Ferroni 2020; Jarociński and Karadi 2020), the information effect is a distinguished concept from pure monetary policy shocks and they are often separately identified, using the sign restriction that pure monetary policy shocks should move interest rates and stock prices in opposite directions, while information effects should move them in the same direction. Hence, for a measure of "pure" monetary policy shocks, the changes in the ten-year JGB futures may not be as beneficial as those in the Euroyen futures.

Table 1: List of Unscheduled Monetary Policy Meetings

(Dates)	(Policy Decision)
9/18/2008	Introduction of U.S. Dollar Funds-Supplying Operations against Pooled Collateral
9/29/2008	Amendments to the Principal Terms and Conditions for U.S. Dollar Funds-Supplying Operations against Pooled Collateral
10/14/2008	Amendments to the Principal Terms and Conditions for the Purchase/Sale of Japanese Government Securities with Repurchase Agreements
12/2/2008	Establishment of Temporary Rules regarding the Eligibility Standards for Corporate Bonds and Loans on Deeds to Companies
12/1/2009	Amendment to the Principal Terms and Conditions for Funds-Supplying Operations against Pooled Collateral
5/10/2010	Reestablishment of the Principal Terms and Conditions for U.S. Dollar Funds-Supplying Operations against Pooled Collateral
8/30/2010	Introduction of a six-month term in the fixed-rate funds-supplying operation against Pooled Collateral
3/14/2011	Policy in response to the Tohoku-Pacific Ocean Earthquake
11/30/2011	Coordinated Central Bank Action to Address Pressures in Global Money Markets

Note: The meeting on 3/14/2011 is unscheduled in that it was originally scheduled to be held over two days, but proceeded with the intention of concluding within a day. This meeting is also excluded in Nakashima, Shibamoto, and Takahasi (2019).

Table 2: Monetary policy shock effects on financial markets (OLS)

(*Daily*) Indep.var	USD/JPY	Nikkei 225 (%)	JGB futures	1 year (%)	2year (%)	5 year (%)	10 year (nominal, %)	10 year (real, %)
YE.factor	-37.32***	-31.69*	-13.24***	0.87**	1.05***	1.26***	1.26**	1.97**
	(-2.734)	(-1.725)	(-3.125)	(2.276)	(3.630)	(4.354)	(2.571)	(2.384)

Note1: We use the breakeven inflation rates (BEI) to estimate the real effects on the 10-year rate.
Note2: Robust t-statistics in parentheses.
***: Significant at the 1 percent level.
**: Significant at the 5 percent level.
*: Significant at the 10 percent level.

Table 3: Monetary policy shock effects on financial markets (TSLS)

(*Daily*) Indep.var	USD/JPY	Nikkei 225 (%)	JGB futures	2 year (%)	5 year (%)	10 year (nominal, %)	10 year (real, %)
JGB 1 year	-43.12**	-36.62	-15.30***	1.21***	1.46***	1.46**	1.60**
	(-2.069)	(-1.107)	(-3.922)	(4.235)	(5.377)	(2.591)	(2.420)
JGB 2 year	-35.59***	-30.22	-12.63***		1.20***	1.20**	1.51**
	(-2.762)	(-1.293)	(-4.977)		(5.147)	(2.512)	(2.308)
JGB 5 year	-29.60***	-25.13	-10.50***			1.00***	1.24**
	(-2.983)	(-1.464)	(-7.925)			(4.166)	(2.452)

Note1: Robust t-statistics in parentheses.
Note2: Euroyen futures data is used as an instrument.
***: Significant at the 1 percent level.
**: Significant at the 5 percent level.
*: Significant at the 10 percent level.

Table 4: Comparison between OLS and Rigobon estimates

	JGB futures	JGB 1 year	JGB 2 year	JGB 5 year
30-minute window		(%)	(%)	(%)
OLS	-13.24***	0.87**	1.05***	1.26***
	[-21.54, -4.94]	[0.12, 1.61]	[0.48, 1.61]	[0.70, 1.83]
Rigobon	-17.53**	0.96*	1.05***	1.19*
	[-31.41, -4.26]	[-0.16, 1.79]	[0.30, 1.78]	[-0.08, 1.83]
60-minute window				
OLS	-11.50**	0.56*	0.73***	1.03***
	[-17.06, -5.94]	[-0.01, 1.14]	[0.26, 1.19]	[0.63, 1.44]
Rigobon	-17.34**	0.67	0.86***	1.28***
	[-52.93, -5.81]	[-0.35, 1.51]	[0.26, 1.90]	[0.52, 2.62]
One-day window				
OLS	-7.58***	0.31**	0.53***	0.81***
	[-11.26, -3.91]	[0.03, 0.58]	[0.30, 0.75]	[0.52, 1.10]
Rigobon	-34.43	0.93	1.78	2.98
(68% CI)	[-84.51, -20.10]	[0.53, 1.98]	[1.19, 3.68]	[1.92, 6.35]

Note: 95 % confidence interval in parentheses, except for the case of Rigobon estimates for a one-day window.
***: Significant at the 1 percent level.
**: Significant at the 5 percent level.
*: Significant at the 10 percent level.

Table 5: Comparison between the estimation with/without unscheduled MPMs (OLS)

Indep.var	USD/JPY	Nikkei 225 (%)	JGB futures	1 year (%)	2 year (%)	5 year (%)	10 year (nominal, %)	10 year (real, %)
Scheduled only	-37.32***	-31.69*	-13.24***	0.87**	1.05***	1.26**	1.26**	1.97**
	(-2.734)	(-1.725)	(-3.125)	(2.276)	(3.630)	(4.354)	(2.571)	(2.384)
All MPMs	-27.58**	12.02	-4.76	0.41	0.43	0.39	0.60	1.71**
	(-2.105)	(0.706)	(-0.779)	(1.000)	(0.994)	(0.692)	(0.978)	(2.147)

Note1: We use the BEI to estimate the real effects to the 10 year rate.
Note2: Robust t-statistics in parentheses.
***: Significant at the 1 percent level.
**: Significant at the 5 percent level.
*: Significant at the 10 percent level.

Table 6: Monetary policy shock effects on yields

	1year (1)	2 year (2)	5 year (3)	10 year (4)
With dummies				
Specification in equation (4)				
Japan				
β	1.00**	1.42***	1.30*	0.40
	(1.987)	(3.561)	(1.836)	(0.436)
γ_1	-0.66	-0.80	1.72	6.75**
	(-0.743)	(-0.722)	(1.055)	(2.131)
γ_2	1.11	0.93	1.77**	3.16**
	(0.881)	(0.919)	(2.004)	(2.402)
γ_3	7.28	10.96**	8.59**	10.87**
	(1.344)	(2.268)	(2.138)	(2.461)
Without dummies				
Specification in equation (1)				
Japan				
β	1.00**	1.21***	1.46***	1.46**
	(2.276)	(3.630)	(4.354)	(2.571)
U.S. (Nakamura and Steinsson 2018)				
β	1.00***	1.06***	0.73***	0.38**
	(7.143)	(2.944)	(3.650)	(2.235)
U.S. (Gilchrist et al. 2015)				
Conventional				
β			1.00***	0.59***
			(6.958)	(4.607)
Unconventional (short)				
β			1.00***	0.99***
			(3.827)	(3.134)
Unconventional (long)				
β			1.00***	1.30***
			(6.689)	(13.474)

Note: Robust t-statistics in parentheses.
***: Significant at the 1 percent level.
**: Significant at the 5 percent level.
*: Significant at the 10 percent level.

Table 7: Monetary policy shock effects on yields (OLS)
Independent variable: the baseline shocks (Euroyen futures, 30-minute window)

	1 year	2 year	5 year	10 year
Dep.var				(nominal)
YE.facor				
One-day	0.87**	1.05***	1.26***	1.26**
	(2.276)	(3.630)	(4.354)	(2.571)
Two-day	1.04**	1.69***	1.96***	2.00***
	(2.487)	(4.193)	(4.299)	(3.175)
Inter-MPM	0.88	1.51**	2.34**	2.64**
	(1.172)	(2.387)	(2.512)	(2.051)

Note: Robust t-statistics in parentheses.
***: Significant at the 1 percent level.
**: Significant at the 5 percent level.
*: Significant at the 10 percent level.

Table 8: First stage regression results in the Proxy SVAR

Indicator	30-minute	60-minute	One-day
JGB 1 year	177.82***	108.05**	42.15
	(5.344)	(2.149)	(1.048)
Robust F	28.56	4.62	1.10
JGB 2 year	186.51***	96.25	47.24
	(3.393)	(1.443)	(1.130)
Robust F	11.51	2.08	1.28

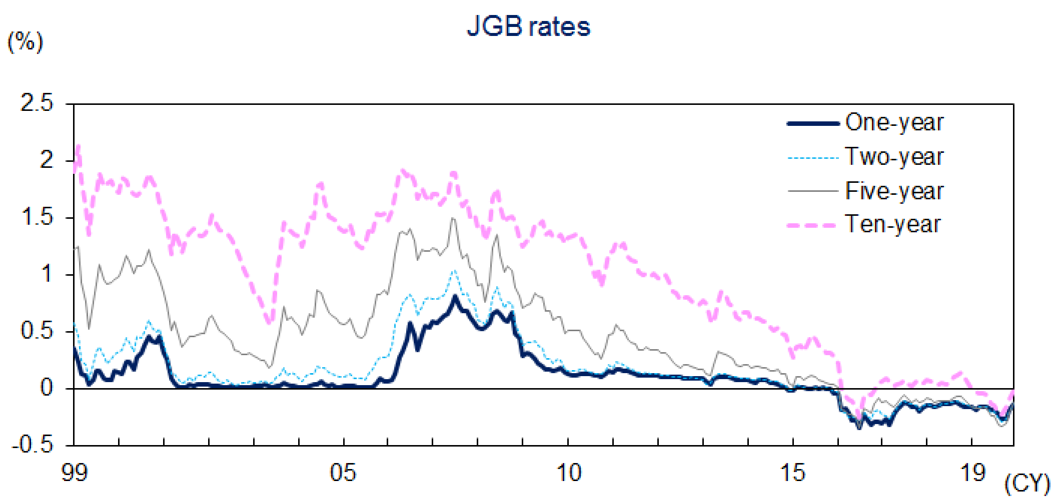
Note: Robust t-statistics in parentheses.
***: Significant at the 1 percent level.
**: Significant at the 5 percent level.
*: Significant at the 10 percent level.

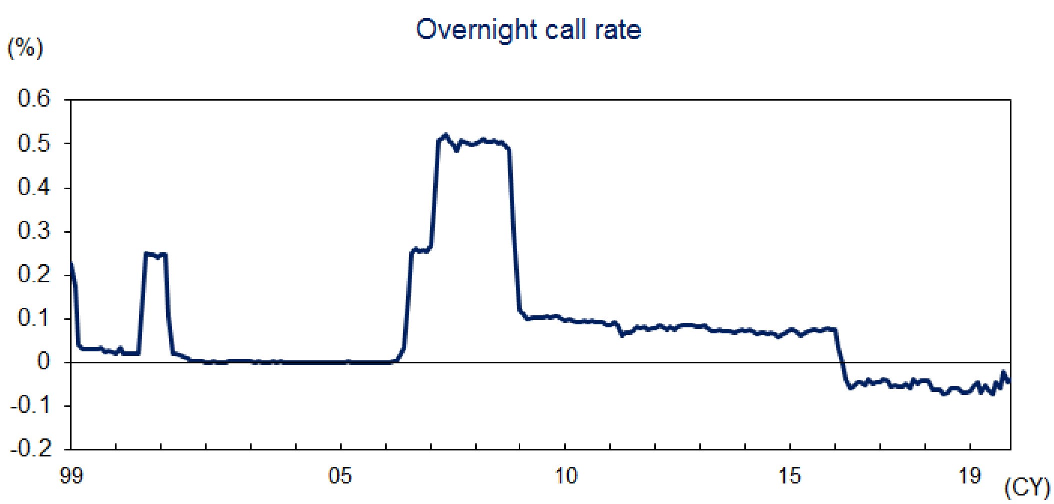
Table 9: Impacts of short and long shocks (sample period: 2005:01-2017:03)

(*Daily*) Indep.var	USD/JPY	Nikkei 225 (%)	1 year (%)	2 year (%)	5 year (%)	10 year (nominal, %)	10 year (real, %)
Short	-39.16***	-27.59	0.91**	1.10***	1.44***	1.56***	2.03**
	(-2.780)	(-1.423)	(2.306)	(3.646)	(5.311)	(3.708)	(2.431)
Long	-0.66	1.71	0.24*	0.33***	0.63***	0.82***	1.12**
	(-0.849)	(1.329)	(1.654)	(2.642)	(4.568)	(4.048)	(2.327)

Note1: We use the BEI to estimate the real effects on the 10-year rate.
Note2: Robust t-statistics in parentheses.
***: Significant at the 1 percent level.
**: Significant at the 5 percent level.
*: Significant at the 10 percent level.

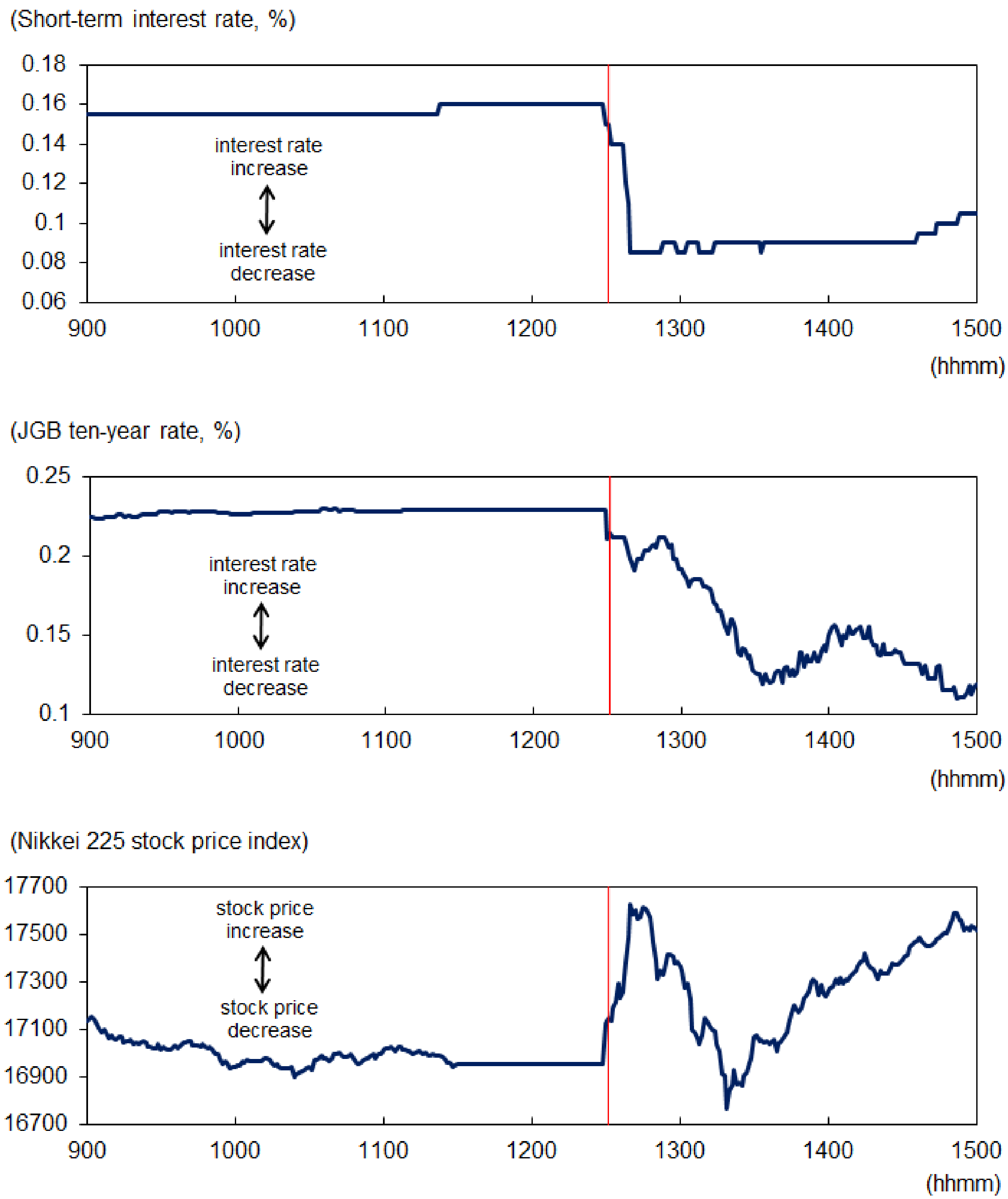
Figure 1: JGB interest rates and overnight call rate





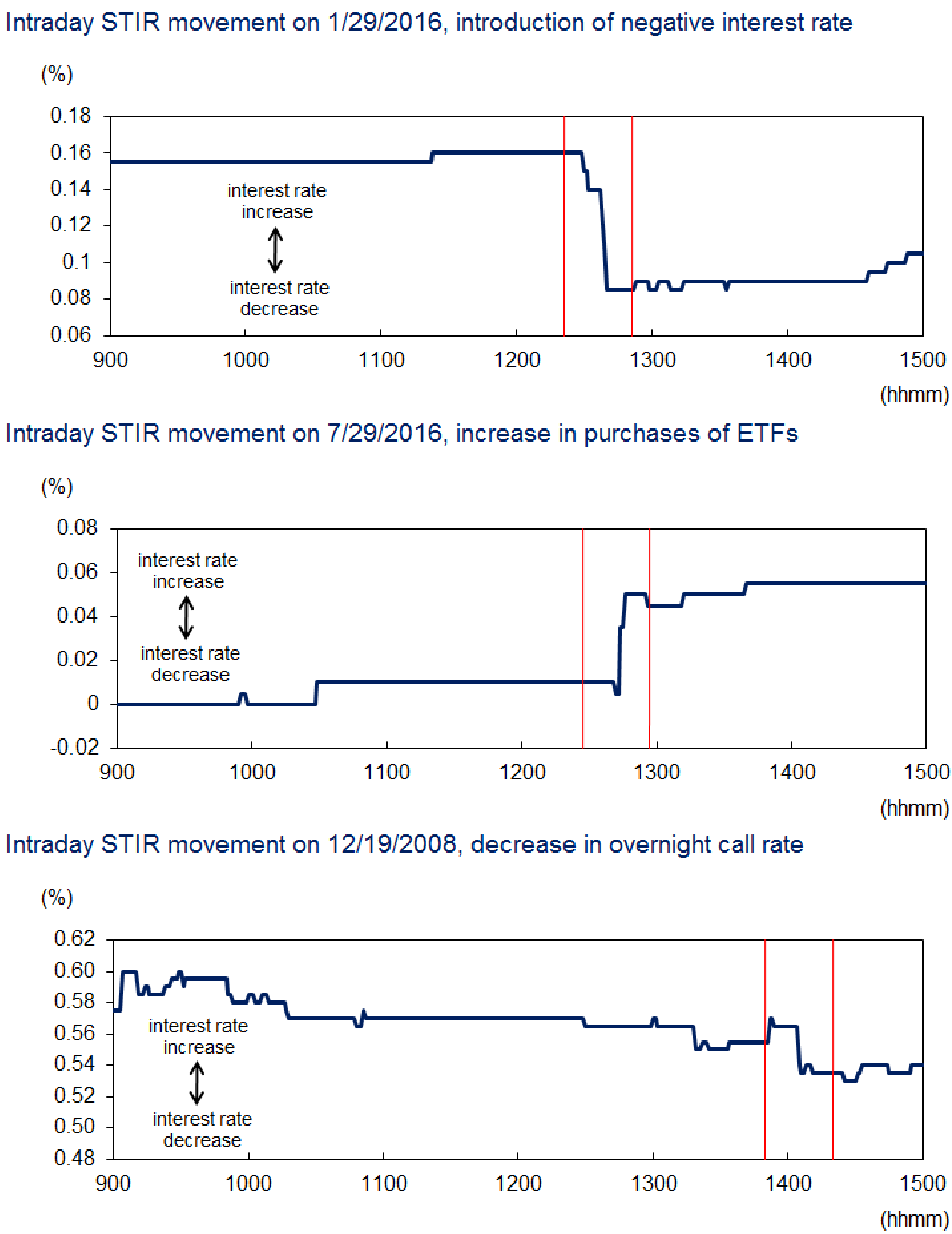
Source: Bloomberg.

Figure 2: Intraday market movement on 1/29/2016 (introduction of negative interest rate)



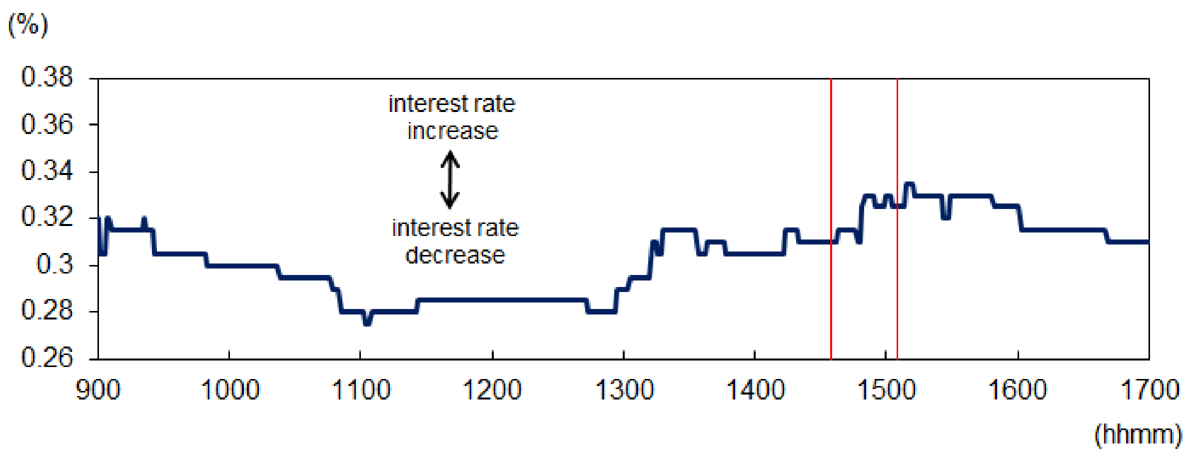
Note: The vertical lines indicate the time when the MPM ended.
Sources: Tokyo Financial Exchange Inc., Bloomberg.

Figure 3: Intraday Euroyen futures movements on 1/29/2016, 7/29/2016, and 12/19/2008



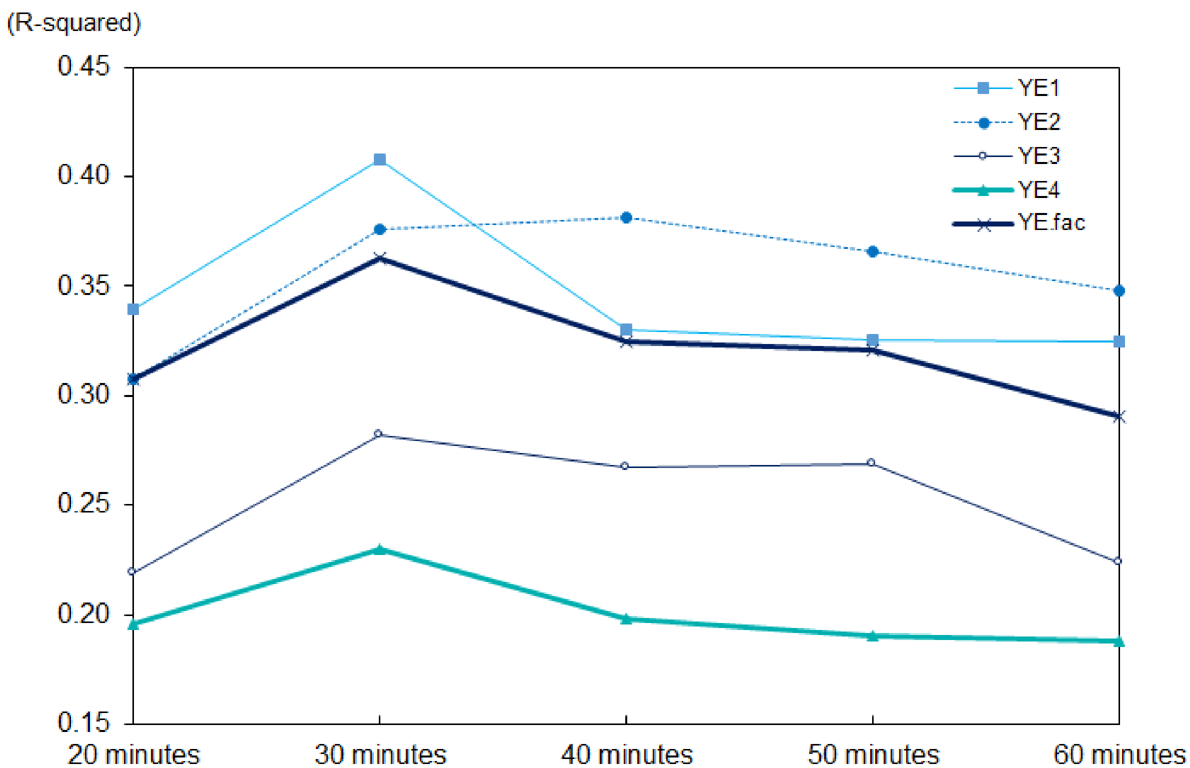
Note: In each panel, the vertical lines indicate the 30-minute window around the MPM announcement.
Source: Tokyo Financial Exchange Inc.

Figure 4: Intraday Euroyen futures movement on 3/14/2011



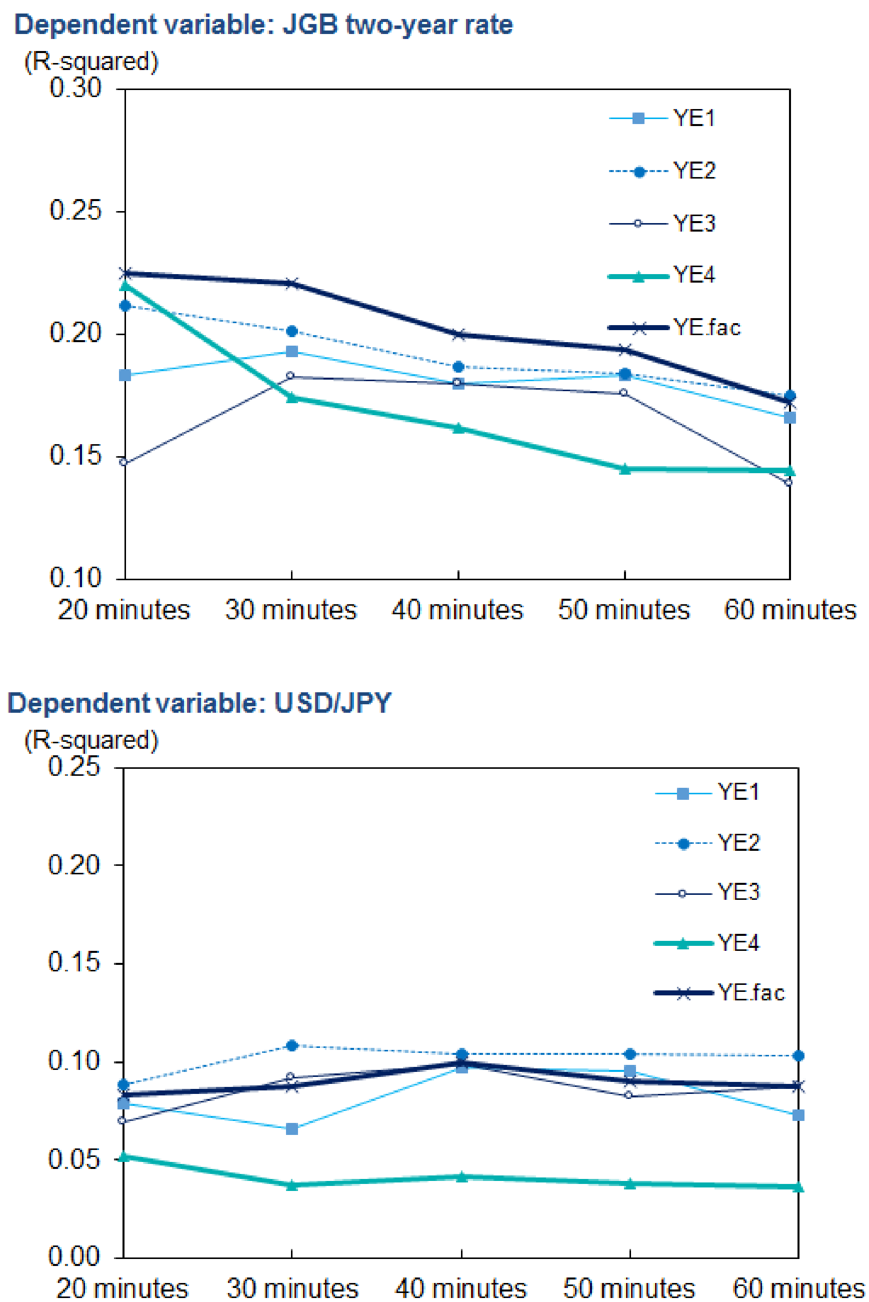
Note: The vertical lines indicate the 30-minute window around the MPM announcement.
Source: Tokyo Financial Exchange Inc.

Figure 5: R^2 across different windows



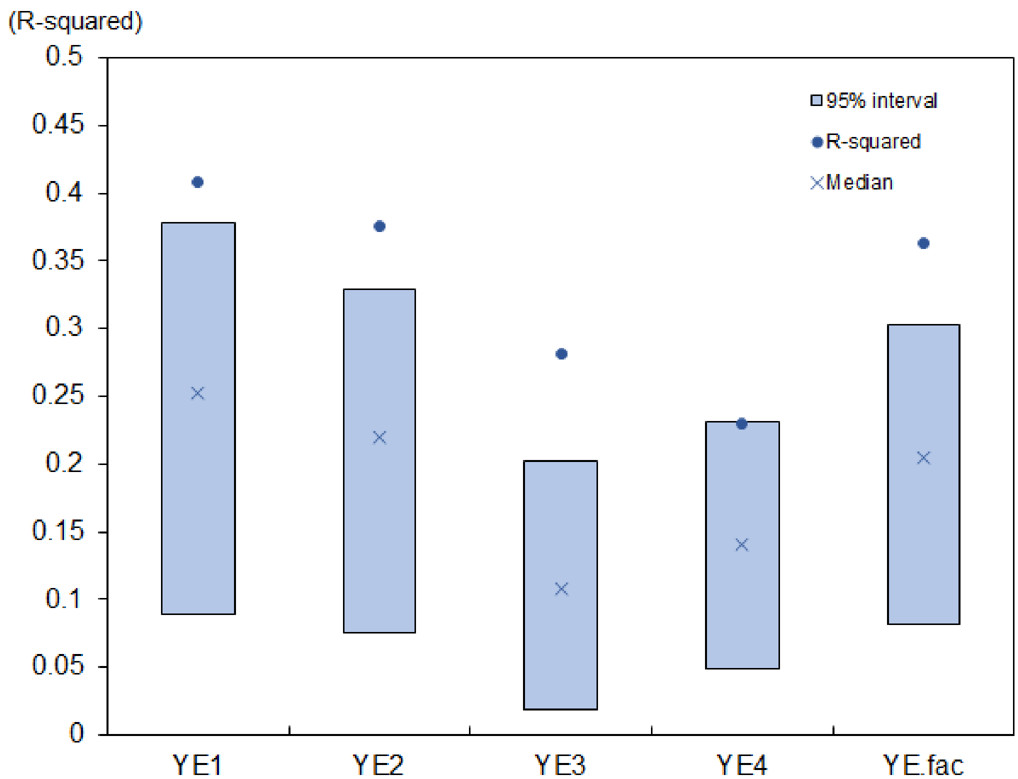
Source: Tokyo Financial Exchange Inc.

Figure 6: R^2 when the dependent variable is JGB two-year interest rate and USD/JPY



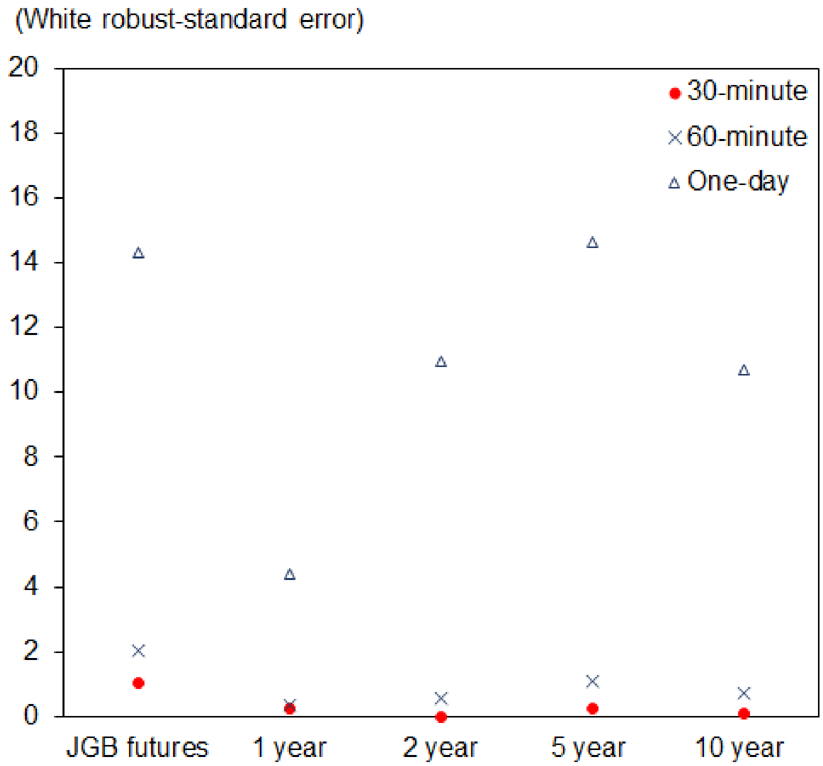
Sources: Tokyo Financial Exchange Inc., Bloomberg.

Figure 7: R^2 for Euroyen futures price changes over an arbitrary 30-minute window



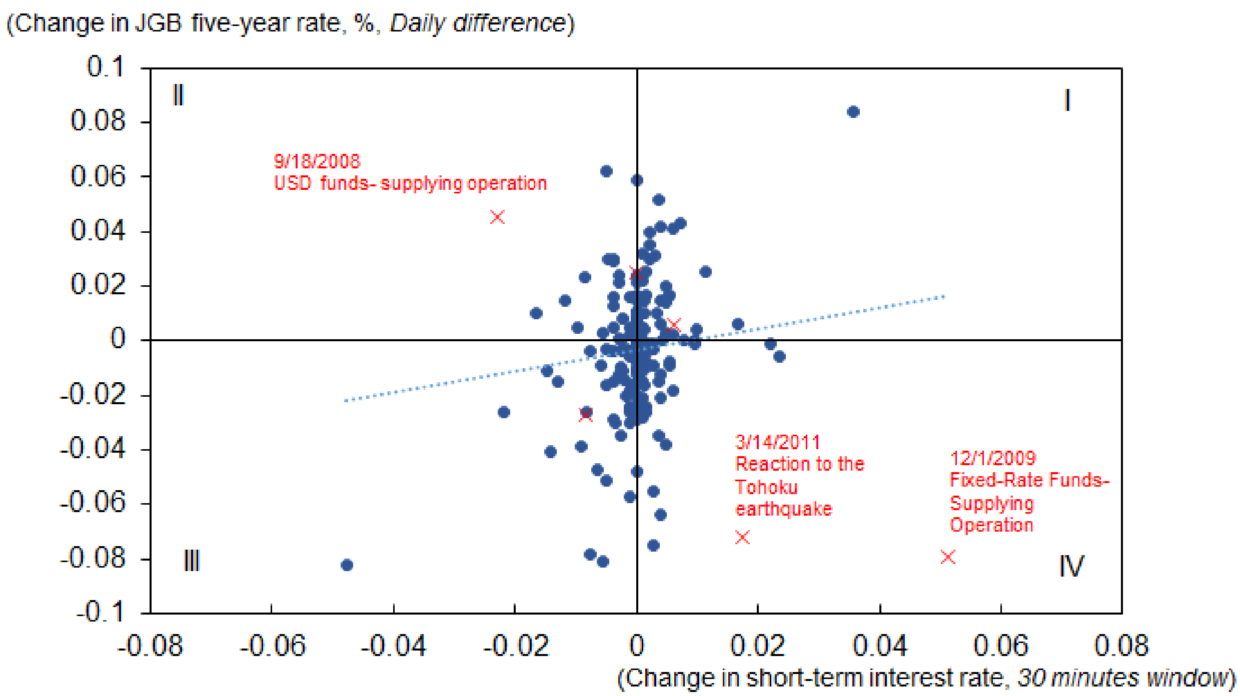
Note: YE.fac denotes the first principal component of the change in YE1 - YE4 prices.
Source: Tokyo Financial Exchange Inc.

Figure 8: The difference between OLS and Rigobon estimates



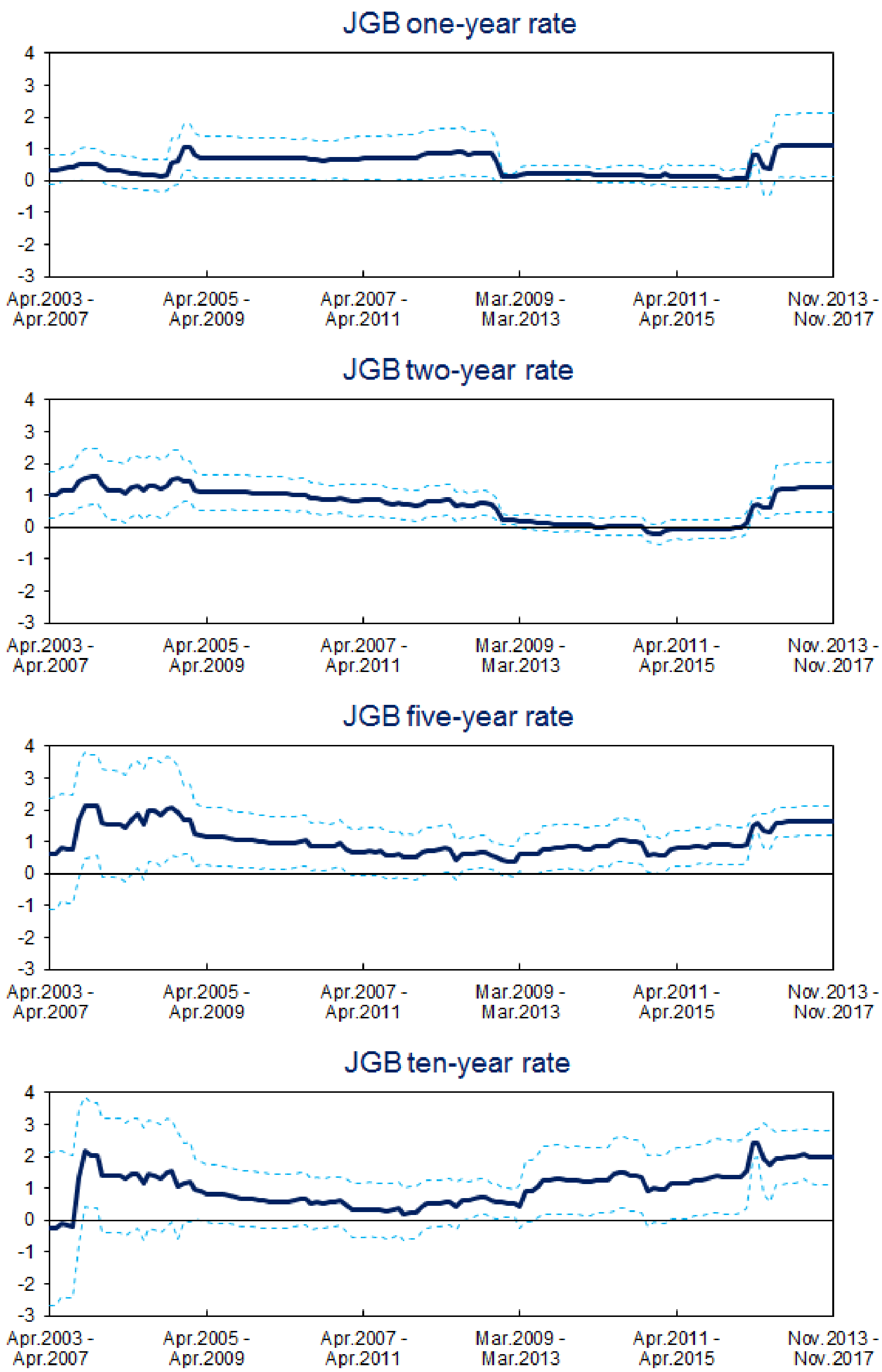
Note: The vertical axis indicates the difference between the OLS and Rigobon estimates, measured with the White robust-standard error of the OLS estimates being one unit.
Sources: Tokyo Financial Exchange Inc., Bloomberg.

Figure 9: Scatter plot for all MPMs



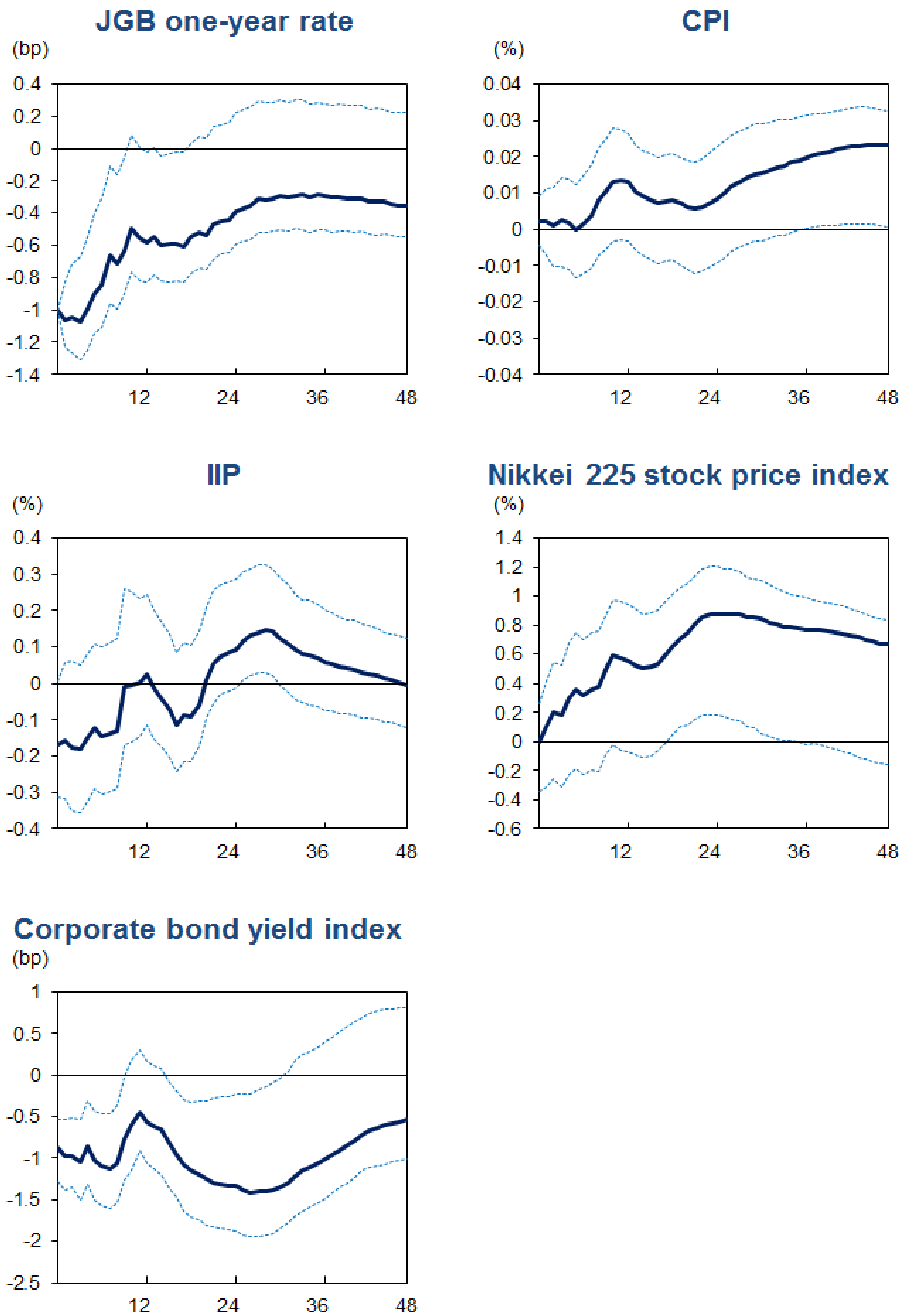
Sources: Tokyo Financial Exchange Inc., Bloomberg.

Figure 10: Result of rolling estimation



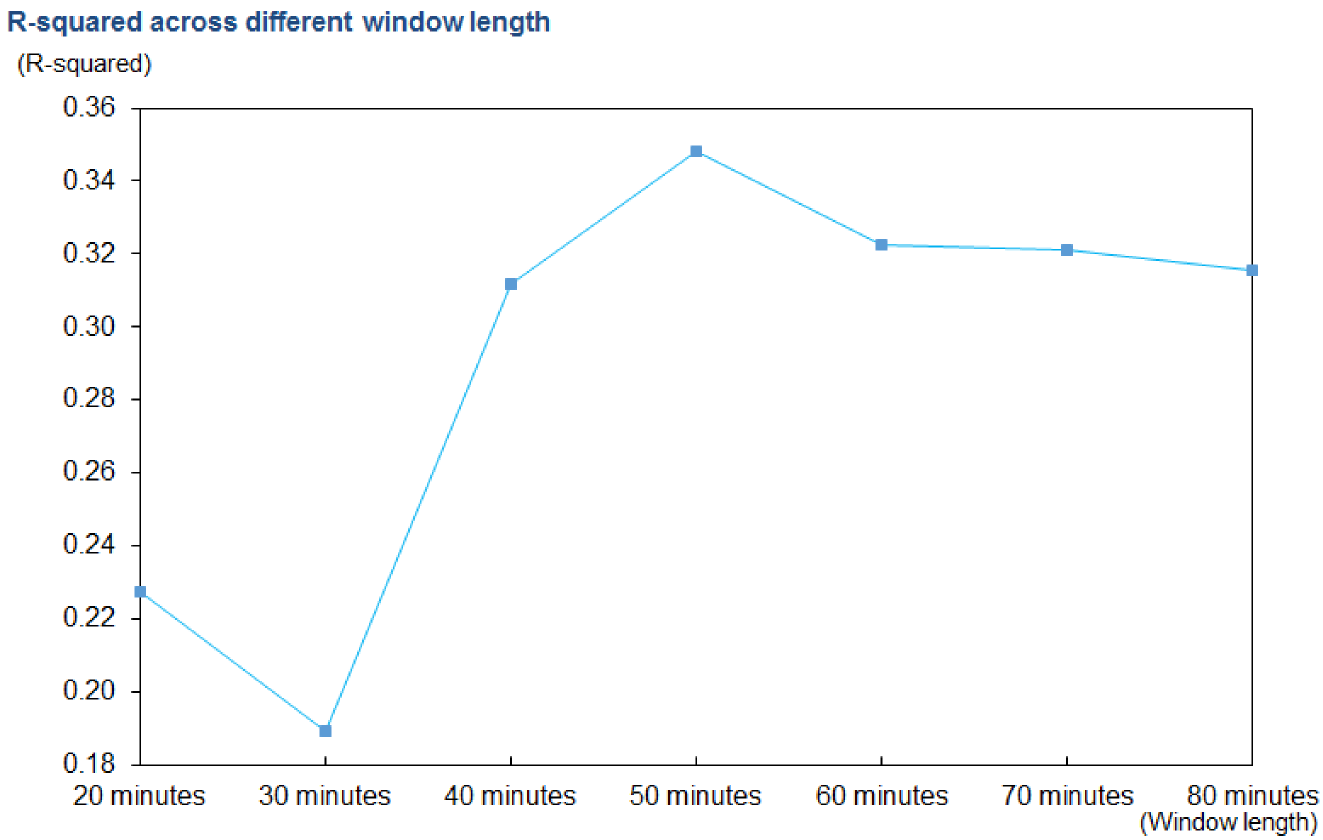
Note: The size of the rolling window is four years. The 90 percent confidence interval is denoted by the dotted lines.
Sources: Tokyo Financial Exchange Inc., Bloomberg.

Figure 11: Impulse responses to a monetary policy shock (horizontal axis: month)



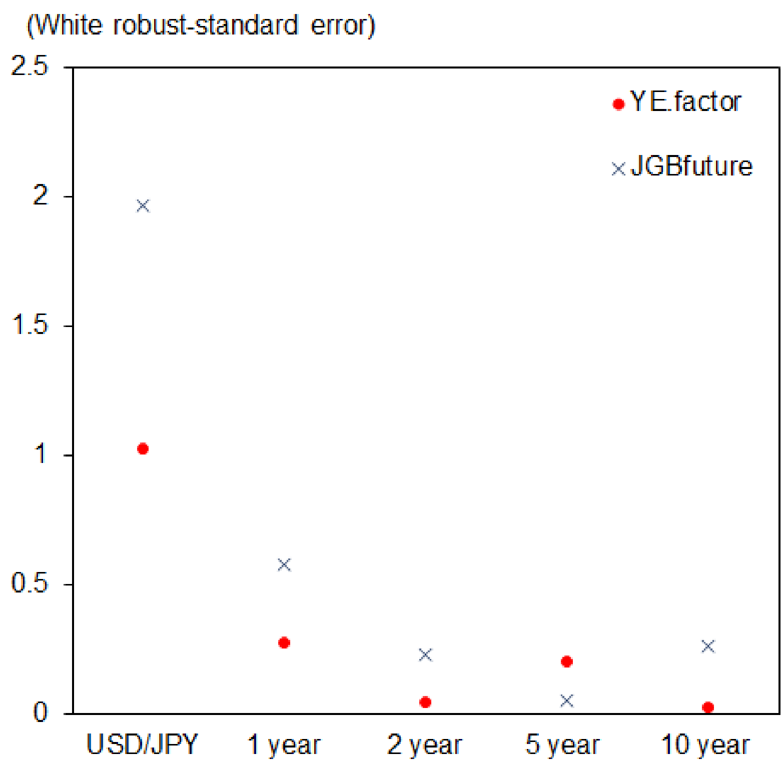
Sources: Ministry of Internal Affairs and Communications, Ministry of Economy, Trade, and Industry, Bloomberg.

Figure 12: R^2 across different windows for JGB futures



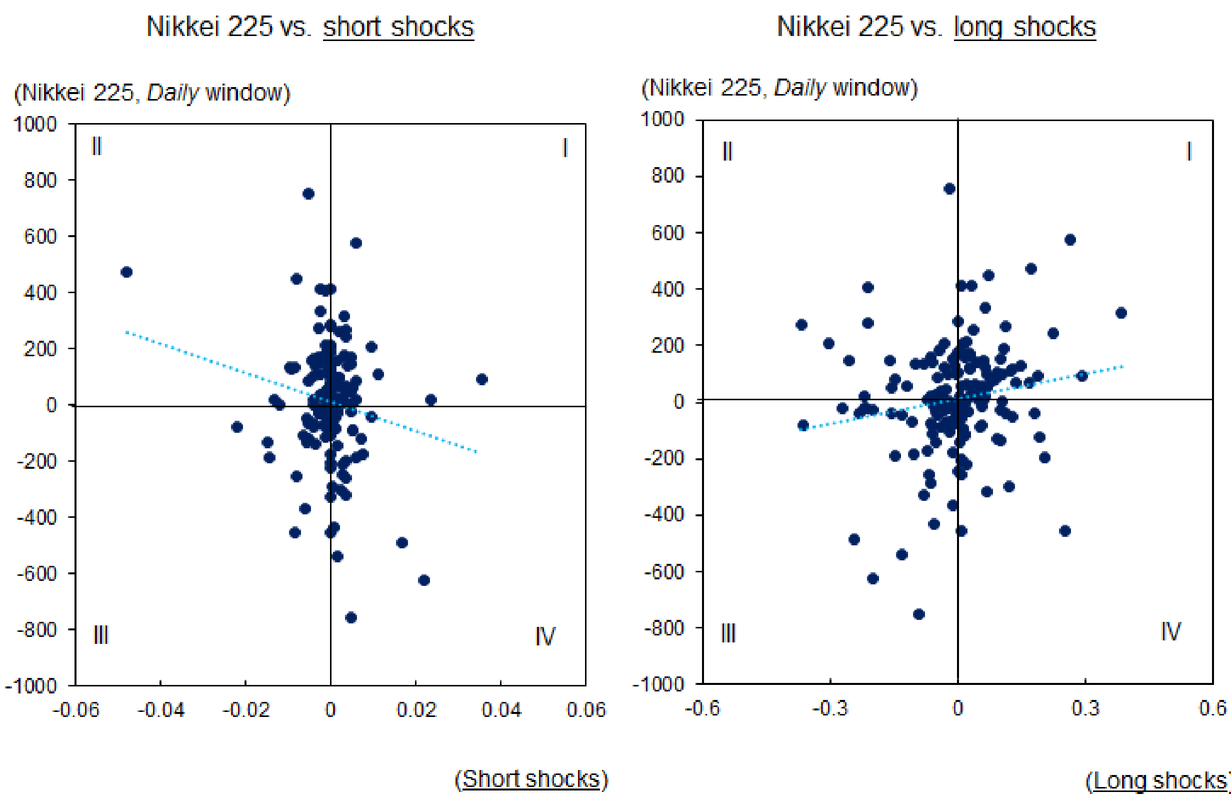
Sources: Nikkei NEEDS.

Figure 13: The difference between OLS and Rigobon estimates



Sources: Tokyo Financial Exchange Inc., Bloomberg, Nikkei NEEDS.

Figure 14: Scatter plots for Nikkei 225, short shocks, and long shocks



Sources: Tokyo Financial Exchange Inc., Bloomberg, Nikkei NEEDS.