DEPARTMENT OF ECONOMICS AND FINANCE

COLLEGE OF BUSINESS AND ECONOMICS

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Central Bank Intervention and Exchange Rate Volatility: Evidence from Japan Using Realized Volatility

Ai-ru (Meg) Cheng, Kuntal Das, Takeshi Shimatani

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Department of Economics and Finance
College of Business and Economics
University of Canterbury
Private Bag 4800, Christchurch
New Zealand

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Ai-ru (Meg) Cheng[1], Kuntal Das[2*], Takeshi Shimatani[3]

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Keywords: Foreign exchange intervention, Realized volatility, Simultaneous equations, Tobit model

JEL Classifications: C34, E58, F31, F33

Acknowledgements: We thank seminar participants at the 27th International Conference of the American Committee for Asian Economic Studies (ACAES) and the Financial Econometrics Group (FEG) at Deakin University for valuable comments and discussions. All remaining errors are ours.

[1] Department of Economics, Northern Illinois University, DeKalb, Illinois, USA
[2] Department of Economics and Finance, University of Canterbury, New Zealand
[3] Bank of Japan, Japan
*Corresponding Author: kuntal.das@canterbury.ac.nz

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Ai-ru (Meg) Cheng[a,1], Kuntal Das[b,1], Takeshi Shimatani[c,1]

[a] *Northern Illinois University, DeKalb, Illinois, USA. e-mail: acheng1@niu.edu*
[b] *Department of Economics and Finance, University of Canterbury, New Zealand. e-mail: kuntal.das@canterbury.ac.nz*
[c] *Bank of Japan, Japan. e-mail:takeshi.shimatani@boj.or.jp*

Abstract

This paper presents new empirical evidence on the effectiveness of Bank of Japan's foreign exchange interventions on the daily realized volatility of USD/JPY exchange rates using high frequency data. Following Huang and Tauchen (2005) and Barndorff-Nielsen and Shephard (2004, 2006), we use bi–power variation to decompose daily realized volatility into two components: the smooth persistent and the discontinuous jump components. We model exchange rate returns, the different components of realized volatility and the central bank intervention using a system of simultaneous equations. We find strong support that interventions by Bank of Japan had increased both the continuous and the jump components of daily realized volatility. This suggests that the interventions by Bank of Japan had increased market volatility which not only caused short-lived positive jumps but were also persistent over time. We did not find any evidence that interventions were effective in influencing the exchange rate returns for the entire sample period.

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1. Introduction

The effect of foreign exchange intervention on exchange rates has been a constant topic of discussion in the academic and policy circle ever since the collapse of the Bretton-Woods system in the early 1970s. Despite the move to floating exchange rates, central banks of several countries have intervened heavily in the foreign exchange market to manipulate their nominal exchange rates and 'calm' disorderly markets[1]. The Bank of Japan (BOJ) on behalf of the Ministry of Finance (MOF) carried out extensive interventions in the FX market in efforts to reduce the value of the yen. During the period of April 1991 and August 2006, the total amount of interventions conducted by BOJ was about 68 trillion yen (approximately 600 billion U.S. dollars)[2]. These actions on the part of the Japanese monetary authorities are understandable given the role of the export sector in their economic recovery. Had the BOJ been effective in its intervention operations? Had the BOJ been successful in depreciating the yen and reducing the volatility of the yen? Given the significance of understanding how central bank interventions (CBIs hereafter) affect the FX markets, it is important to critically examine the answers to these questions.

Several authors have analyzed the effects of CBI on the FX market by looking at the impact on both the level and the volatility of exchange rate. In general, the literature is inconclusive about the impact of CBI on exchange rate returns. For example, Humpage (1988) and Baille and Humpage (1992) have found that intervention was ineffective in influencing the level of exchange rate. Baillie and Osterberg (1997) finds that the effect of CBI on spot exchange rate returns are counterproductive, i.e. purchase of US dollars leads to a depreciation of the US dollar[3]. This result holds for both unilateral and coordinated interventions. Others like Dominguez and Frankel (1993),

[1] These actions by the central banks have been implicitly defined in two major international agreements: the goal of the Plaza Accord in September 22, 1985 was to seek central bank cooperation to sharply depreciate the US dollar and the Louvre Accord in February 22, 1987 emphasized the need to stabilize the exchange rate volatility.

[2] Dominguez (2006) reports that during New York trading hours on May 31, 1995, BOJ and Fed coordinated their interventions: BOJ purchased $767.4 million against yen on one occasion and the U.S. government purchased a total of $500 million against yen on three occasions. This had resulted in a 2% increase in the value of dollar against yen over the course of the day.

[3] Similar result was obtained by Beine et al. (2002).

Fatum and Hutchison (2003), Dominguez (2003), Humpage (2003), and Ito (2003) conclude that CBI had a significant impact on the exchange rate, at least in the very short run, when it was publicly announced, coordinated, large, and infrequent.

The studies looking at the effect of interventions on the volatility of exchange rates are more conclusive. Most studies, employing different measures of volatility, conclude that the CBI tends to increase the exchange rate volatility. Using measures of implied volatility, Bosner–Neal and Tanner (1996) and Dominguez (1998) find that CBI increases exchange rate volatility. Other studies like Dominguez (1998) and Beine et al. (2002) using GARCH-type models, and Beine et al. (2009) and Dominguez (2006) using realized volatility models, arrive at the same conclusion. This finding is contrary to the aim of the central bank which intervenes to counter disorderly FX markets[4]. However, there are some studies that either do not find any impact of CBI on exchange rate volatility (Galati et al., 2005) or find that CBI is associated with less exchange rate volatility at least for parts of the sample period (Hillebrand and Schnabl, 2009)[5].

In this paper, we seek to further advance our understanding of the impact CBI on the two different components of exchange rate volatility - the 'continuous' persistent part and the discontinuous 'jump' component. To the best of our knowledge, no previous study, with the exception of Beine et al. (2007), has analyzed the relation between CBI and the volatility components. Beine et al. (2007) had captured the long memory in the volatility process with an ARFIMA specification in the spirit of Andersen et al. (1999). The authors, however, have not addressed the the problem of endogeneity of intervention and exchange rates which is a key issue in these studies[6]. We have modelled the different components of exchange rate volatility and intervention in a simultaneous equation framework, explicitly accounting for the endogeneity in the coefficient on contemporaneous interventions.

The empirical literature examining the effect of CBI on exchange rate

[4]Article 40 of The Bank of Japan Law states that "The Bank shall buy and sell foreign exchange as an agent of the government, in accordance with the provisions of Article 36, Paragraph 1, when its purpose is to stabilize the exchange rate of the national currency."

[5]Hillebrand and Schnabl (2009) find that intervention by BOJ has decreased the yen-dollar exchange rate volatility since 2000.

[6]Kearns and Rigobon (2005) show that failing to account for the endogeneity will likely bias the coefficient on contemporaneous intervention downwards.

volatilities have mostly modeled volatility in the framework of GARCH-type models. However, recent developments in econometric methodology and the increasing availability of high-frequency data have shifted the paradigm from the discrete-time GARCH class of models to the non-parametric approach for modeling and forecasting time-varying daily market volatility. The empirical results in Andersen, Bollerslev, Diebold, and Labys (2003) strongly indicate that models of realized volatility outperform the popular GARCH-type and related stochastic volatility models in out-of-sample forecasting. Other studies such as Andersen and Bollerslev (1998), Andersen, Bollerslev, Diebold, and Labys (2001a, b), and Barndorff-Nielsen and Shephard (2004, 2006) have shown the importance of explicitly allowing for jumps, or discontinuities, in the estimation of continuous time stochastic volatility models[7]. In particular, it has been found that many (log) price processes are best described by a combination of a smooth and very slowly mean-reverting continuous sample path process and a discontinuous jump component. Thus it is important to distinguishing jump from non-jump movements. One advantage of separating out the smooth persistent volatility component and the much less persistent jump process is that it can describe price (exchange rate) processes in-sample better and also provide out-of-sample forecasts accurately[8].

Due to extreme market events or macro announcements, there might be presence of unusually large movements in the price processes relative to what continuous-time diffusive models in finance would suggest. Our approach to modelling exchange rate volatility builds directly on the theoretical results in Barndorff-Nielsen and Shephard (2004, 2006) and Huang and Tauchen (2005). We decompose the daily realized volatility into a jump and a persistent process using bi–power variation as indicated by the authors. It has been shown that realized volatility is a consistent estimator for both, the integrated variance and the jumps, in the return process. We calculate the realized bi–power variation based on adjacent absolute intra-daily returns. The jump component of the realized volatility is consistently estimated by the difference between the realized volatility and bi–power variation.

We examine the effect of BOJ's foreign exchange interventions on the

[7]Andersen et al. (2001a, b) provide an extensive examination of the statistical properties, modelling and forecasting of realized volatility of foreign exchange rates.

[8]Andersen et al. (2007) demonstrate important gains in accuracy at daily, weekly, and even monthly forecast horizons by explicitly differentiating the jump and continuous sample path components.

volatility of USD/JPY and DEM/JPY (EUR/JPY) exchange rates using intraday quotes from April 1, 1991 to July 31, 2006. We present new evidence on the efficacy of central bank interventions on the different components of exchange rate volatility. Our study adds to the literature in the following two ways. First, we model and estimate the effect of CBI on the 'continuous' persistent and the discontinuous 'jump' components of daily realized volatility. Our measure of realized volatility is an 'observed model-free' variable rather than a 'latent' one as is often used in the stochastic volatility or GARCH-type models. Realized volatility, computed as the sum of the squared intraday returns, captures all the price (foreign exchange rate) movements within each day. Second, we tackle the problem of endogeneity by estimating the contemporaneous interactions between central bank interventions, exchange rate returns, and the continuous and jump volatility components within a simultaneous equation framework.

We report the following findings. First, our testing reveals that interventions by BOJ were unsuccessful in stabilizing the daily realized market volatility. We show that both the continuous and discontinuous components of volatility increased due to CBI. These results are robust in the USD/JPY and DEM/JPY (EUR/JPY) markets. This suggests that the interventions by BOJ had increased market volatility which were not only short-lived but also persistent over time. We also look at coordinated interventions by BOJ with the Fed in the USD/JPY market. The results of such concerted efforts were still the same, i.e. it had a positive correlation with both the volatility components. We provide sub-sample analysis based on structural breaks identified from the literature. Our estimation results indicate that BOJ interventions were significant and positively correlated with the persistent volatility component in all the sub-periods. However, the effect on the jump component was insignificant for the first two sub-samples. This would suggest that the true transient component of the volatility were more significant after 1998 when the BOJ interventions were infrequent and large.

This paper is organized as follows. The next section gives details for realized volatility decomposition. Section 3 describes the estimation strategy and data. Section 4 discusses our main findings. Concluding remarks are offered in Section 5.

2. Exchange Rate Dynamics and Realized Volatility Decomposition

Let $p_t = \log(P_t)$ denote the logarithmic price of the asset or foreign exchange rate at day t and let $r_{t,i}$ be the intraday log return at time $t(i)$ between $t-1$ and t:

$$r_{t,i} = 100 \times [p_{t(i)} - p_{t(i-1)}]. \tag{1}$$

We decompose daily realized volatility into a continuous (persistent) and jump components by a method proposed by Huang and Tauchen (2005) and Barndorff-Nielsen and Shephard (2004, 2006). First, for each day t, we compute the daily realized variance (RV_t) as the sum of squared intraday returns:

$$RV_t = \sum_{i=1}^{M} r_{t,i}^2, \tag{2}$$

where M is the total number of intraday returns within day t. Since we use high-frequency data, the intraday return series can be contaminated by market microstructure noise, hence, it can bias our approximation of the daily variance. Andersen et al. (2000), we choose five-minute returns to compute the realized variance of exchange rate. The authors suggests that five minute is the "optimal" interval for the computation of RV_t to avoid contamination due to microstructure noises.

One natural measure for the smooth persistent part of RV_t is the realized bi-power variation as proposed by Barndorff-Nielsen and Shephard (2004):

$$BV_t = \frac{\pi}{2}\frac{M}{M-1}\sum_{i=2}^{M} |r_{t,i-1}||r_{t,i}|, \tag{3}$$

The authors have shown that as $M \to \infty$, BV_t converges to the daily integrated variance unaffected by jumps. As a result, the difference $RV_t - BV_t$ becomes a consistent measure for the jump component in the total daily realized variance. Based on the theoretical results in Barndorff-Nielsen and Shephard (2004), Huang and Tauchen (2005) proposes a jump statistic for detecting jumps on each day t:

$$
\begin{aligned}
z_t &= \frac{\frac{RV_t - BV_t}{RV_t}}{\sqrt{(\frac{\pi^2}{4} + \pi - 5)\frac{1}{M}\frac{TP_t}{BV_t^2}}}, && (4) \\
TP_t &= M\mu_{4/3}^{-3}\frac{M}{M-2}\sum_{i=3}^{M}|r_{t,i-2}|^{4/3}|r_{t,i-1}|^{4/3}|r_{t,i}|^{4/3}, && (5) \\
& && (6)
\end{aligned}
$$

where $\mu_k = 2^{k/2}\Gamma[(k+1)/2]/\Gamma(1/2)$ is a normalizing term and $\Gamma(p) = \int_0^\infty t^{p-1}e^{-t}dt$ for any positive p. Since

$$z_t \xrightarrow{M\to\infty} \mathbf{N}(0,1), \tag{7}$$

denoting the continuous and jump volatility components as C_t and J_t respectively, we compute both C_t and J_t as follows:

$$
\begin{aligned}
C_t &= \mathbf{1}_{z_t \leq z_\alpha} RV_t + \mathbf{1}_{z_t > z_\alpha} BV_t, && (8) \\
J_t &= \mathbf{1}_{z_t > z_\alpha}(RV_t - BV_t). && (9)
\end{aligned}
$$

where α is the upper 99.99%$-$quantile of $\mathbf{N}(0,1)$.

3. Empirical methodology

In this section, we estimate the relationship between central bank intervention and the different components of exchange rate volatility.

$$
\begin{aligned}
r_t &= 100 \times (p_t - p_{t-1}) && (10) \\
r_t &= \alpha_0 + \alpha_1 D_{I_t} + u_{rt}, && (11)
\end{aligned}
$$

In our model, central bank intervention on the exchange rate (I_t) is used as an exogenous variable. We assume that daily exchange rate returns (r_t) are linearly dependent on the intervention series. Since our preliminary study shows that the return process is more responsive to the occurrence of interventions relative to their exact value, we only include a dummy variable D_{I_t} for intervention events on the right-hand-side of the return equation.

$$\log C_t = \beta_0 + \beta_1|I_t| + \sum_{j=1}^{6}\beta_{j+1}\log C_{t-j} + u_{ct} \tag{12}$$

Since the smooth (continuous) part of the exchange rate volatility path is highly persistent, Eq. (12) is augmented with its lagged continuous components in order to obtain robust parameter estimates[9]. This specification is in the spirit of the Heterogeneous Autoregressive Realized Volatility model of Anderson, Bollerslev and Diebold (2007).

$$J_t^* = \gamma_0 + \gamma_1 |I_t| + u_{J^*t}, \tag{13}$$

$$\begin{array}{rcl} J_t = 0 & J_t^* & \leq & 0, \\ J_t = J_t^* & J_t^* & > & 0. \end{array}$$

The derived data on jump volatility component (J_t) are censored at zero. Hence we model it in the framework of a Tobit model to describe the relationship between the true jump volatility process (J_t^*) and central bank intervention[10][11].

3.1. Estimation strategy

Parameters in our model mentioned above are simultaneously estimated using Hansen's (1982) Generalized Method of Moments (GMM).

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[9] The number of lags are determined based on the $Q-$test for residual autocorrelations. Report of the $Q-$test statistics are available upon request.

[10] Analysis by Beine et al. (2007) strongly suggests that the causality between interventions and jumps is unidirectional; intervention normally causes jumps rather than reacting to it.

[11] We do not control for the effect of macroeconomic announcements on exchange rate volatility. There are two reasons for this. Firstly, one cannot obtain the precise timing of the interventions because such times are not recorded and published by the central banks. While one could use auxiliary information from newswire reports as proposed by Dominguez (2006), it is still unclear whether the timing of these reports is consistent and thus potentially flawed to use such information. Secondly, analysis by Beine et al. (2007) suggests that jumps are primarily the results of interventions and not macroeconomic announcements. The existing literature trying to combine intervention data with newswire reports suggest that the market is unaware of an intervention since these are carried out in secrecy. This is the so-called "secrecy puzzle" in the literature. See Sarno and Taylor (2001). Fatum (2009) reports that a firm report of intervention is typically on the newswire the day after the intervention is carried out. Therefore, intervention can play no role in the contemporaneous exchange rate responses.

Denote the error terms as $u_t = [u_{r_t}, u_{c_t}, u_{J_t}]$ and write the error term from Eq. (10), Eq. (12), and Eq. (13) as:

$$
\begin{aligned}
u_{r_t} &= r_t - \alpha_0 - \alpha_1 D_{I_t} && (14)\\
u_{c_t} &= \log C_t - \beta_0 - \beta_1 |I_t| - \sum_{j=1}^{6} \beta_{j+1} \log C_{t-j} && (15)\\
u_{J_t} &= J_t - \Phi(\gamma_0 + \gamma_1 |I_t|) \left[\gamma_0 + \gamma_1 |I_t| + \frac{\phi(\gamma_0 + \gamma_1 |I_t|)}{\Phi(\gamma_0 + \gamma_1 |I_t|)} \right] && (16)
\end{aligned}
$$

where $\Phi(.)$ and $\phi(.)$ are denoted as the cumulative probability density function and probability density function of a standard normal, respectively. Given a set of instrumental variables Z_t which belongs to the information set up to day t, we construct sample versions of the following restrictions to estimate model parameters:

$$
E[u_t \otimes Z_t] = 0 \tag{17}
$$

Our natural selection of the set of instruments incude a constant term, central bank interventions, and lagged continuous volatilities, i.e.

$$
Z_t = [1, I_t, \log C_{t-1}, \log C_{t-2}, \log C_{t-3}, \log C_{t-4}, \log C_{t-5}, \log C_{t-6}].
$$

This provides us with $nm = 24$ orthogonal conditions for a total number of $k = 12$ parameters in our model.

Let $\theta = [\alpha_0, \alpha_1, \beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7, \gamma_0, \gamma_1]$, and $m(\theta)$ contains nm number of sample means of the restrictions in Eq.(17). The GMM estimator of θ minimizes the criterion function:

$$
G_T = m(\theta)' W m(\theta), \tag{18}
$$

where W is a $nm \times nm$ optimal weighting matrix discussed in Hansen (1982). The optimal weight is calculated as the inverted variance-covariance matrix of sample moments ($\hat{S}$):

$$
\begin{aligned}
\hat{S} &= \hat{S}_0 + \sum_{i=1}^{q} w(i)[\hat{S}_i + \hat{S}_i'],\\
\hat{S}_i &= \frac{1}{T-k} \sum_{t=i+1}^{T} m_t(\hat{\theta}) m_{t-i}(\hat{\theta})'
\end{aligned}
$$

where $w(.)$ is the Newey and West (1987) kernel for the weight on each autocovariance of the sample moments m. According to Hansen (1982), when the weighting matrix is optimal, $\hat{W} = \hat{S}^{-1}$, one can compute the estimated variances of the GMM estimates as:

$$\hat{V} = [\hat{M}'\hat{S}^{-1}\hat{M}]^{-1}/T, \tag{19}$$

where $\hat{M} = \frac{\partial m(\hat{\theta})}{\partial \theta}$. Moreover, the test statistic TG_T is a measure for model specification's goodness of fit, where under the null,

$$TG_T \sim \chi^2_{nm-k}. \tag{20}$$

3.2. Data

We use five-minute high-frequency data on Japanese Yen to US Dollar (USD/JPY) from April 1, 1991 to July 31, 2006 for computing daily realized variances and the variance components (C and J). Also, we use five minute intra-daily data from April 1, 1991 to March 31, 2004 for measuring daily variations and their components of the returns on Japanese Yen to Deutsche Mark (Euro) ((DEM/JPY)(EUR/JPY))[12]. Since the foreign exchange market is on a 24-hour trading basis, we follow Andersen and Bollerslev (1998) and set each trading day to start at 21:00 GMT on day $t-1$ to 21:00 GMT on next day t. This setting ensures that the timing of foreign exchange returns and intervention data are aligned more correctly. Figure 1 presents the trading hours for five major foreign exchange markets based on the GMT time. Table 1 reports sample statistics of both returns and realized volatility components of USD/JPY and DEM/JPY(EUR/JPY) series. It shows that CBI operations seem to lower the averaged returns on USD/JPY. Furthermore, by comparing the means of volatility components on regular days and on the days with interventions, we find that intervention operations (unilateral and coordinated) increase the averaged levels of persistent and jump volatilities of both USD/JPY and DEM/JPY(EUR/JPY) series. The third and fourth sample moments of both C and $\log C$ indicate that when the persistent volatility component C is taken in logarithm, its empirical distribution can be better approximated by a Gaussian distribution. Figure 2 represents the averaged exchange rate movements of USD/JPY within a 24-hour trading period in our sample.

[12]The source of both high-frequency and spot exchange rate data is Olsen and Associates.

Our intervention data for USD/JPY and DEM/JPY(EUR/JPY) exchange rate series are downloaded from FRED at St. Louis Fed[13]. Due to the large scale of Japanese interventions in Yen, the unit of measurement for each Japanese intervention is one trillion yen. Among 4001 days between April 1, 1991 and July 31, 2006, the intervention data exhibits 333 days with Japanese interventions on USD/JPY. Most of the intervention observations are positive, i.e. buying US Dollar and selling Yen, except that at the beginning of our sample period (from year 1991 to 1992), where we find 32 days with negative interventions (buying Yen and selling US Dollar). Moreover, during April 1, 1991 to December 31, 2003, we observe 22 days with coordinated interventions from both Japan and US on USD/JPY market. This includes 4 days with negative interventions (buying Yen/selling Dollar) and 18 days with positive interventions (buying Dollar/selling Yen). Figure 3 plots the time series of daily returns on USD/JPY, the sample path of the continuous volatility and the jump volatility components. It also shows the days with BOJ unilateral interventions, and days with coordinated BOJ-Fed interventions.

For EUR/JPY, we only observe 19 days with unilateral Japanese interventions, all positive, i.e. buying Deutsche Mark (Euro)/selling Yen, out of a total number of 3392 days in our sample period. Figure 4 shows the time series of daily returns on DEM/JPY(EUR/JPY), the sample path of the continuous volatility component and the sample path of the jump volatility component. It also plots the days with unilateral BOJ interventions in the DEM/JPY(EUR/JPY) market[14].

4. Main findings

4.1. Results from the entire sample period: April 1, 1991 to July 31, 2006

Table 2 presents the results for the USD/JPY market for the entire sample period. Columns (2)–(4) represent the coefficient estimates for the unilateral interventions by BOJ. All coefficients are as expected. Most importantly, the coefficient of CBI in the log continuous and jump equations, suggests that unilateral intervention by BOJ tend to increase both the components of

[13] The data source is `http://research.stlouisfed.org/fred2/categories/32145`.

[14] We did not have data on the coordinated yen-deutsche mark (euro) interventions. Hence our analysis on coordinated interventions is only limited to the USD/JPY market.

daily realized volatility. The effects of intervention are strong and statistically significant. These suggest that the efforts of BOJ in stabilizing either the smooth persistent or jump components of realized volatility are counterproductive. This finding suggests the ineffectiveness of BOJ interventions in calming disorderly markets. Interventions by BOJ had increased market volatility which not only caused short-lived jumps but were also persistent over time. The coefficient estimates of the lagged log continuous volatility confirms the theory that the continuous component of the daily realized volatility are highly persistent. However, the effect of intervention in the mean equation is insignificant and ineffective. Table 2 shows that, on average, the sale of yen by the BOJ leads to an appreciation of the yen. This is consistent with some of the previous literature that suggest that unilateral interventions either have no causal effect or perverse effect on exchange rate returns.

In Columns (5)–(7) on Table 2, we consider the case where coordinated interventions were undertaken by both BOJ and the Fed. Some studies have argued that concerted intervention efforts were more effective in influencing the first and second order moments of exchange rate movements. See Catte et al.(1994) and Nagayasu (2004) for greater details. Nagayasu (2004) finds that coordinated interventions by BOJ and Fed were effective in influencing the exchange rate returns, but interventions were always associated with an increase in exchange rate volatility. The results from our analysis suggest that coordinated intervention efforts had a positive impact on the exchange rates returns, but these effects were statistically insignificant. The insignificant results we find are different from the ones in Nagayasu (2004) since our sample period is different from theirs. While Nagayasu's sample period ends in September 2001, our sample entends to July 2006. Most of the interventions in the early part of the sample were 'negative interventions', i.e. purchase of Japanese Yens and sale of US Dollars. Thus the interpretation of the coefficients are different. We find positive significant effects of intervention on exchange rate returns in the early part of the sample. Those are discussed in our sub-sample analysis in the next sub-section.

Coordinated interventions by BOJ and the Fed had, however, failed to stabilize the FX market volatility. These results are in line with the ones reported by Nagayasu (2004). We find that coordinated intervention increased both the continuous and the jump volatility components. Thus, neither unilateral interventions nor concerted interventions were able to reduce short-term transient or long-term persistent effects on daily realized volatility.

Next, we check if the intervention efforts by BOJ were unique to the USD/JPY market. Thus, we consider the effect of BOJ interventions for a different currency pair. Table 3 reports the results of unilateral intervention by BOJ in the DEM/JPY (EUR/JPY) market. During the sample period April 1, 1991 to March 31, 2004, BOJ interventions were very infrequent (for 19 days) in this market. The results indicate that interventions were ineffective - it led to an increase in both the persistent and the jump volatility components. The effect on the exchange rate returns remain ineffective. Thus, overall, unilateral interventions were neither able to stabilize the exchange rate volatility nor exchange rate returns. The model also shows that the log continuous volatility is highly persistent[15].

4.2. Results from sub-sample analysis

Some studies on the intervention on BOJ have found that FX interventions are actually effective during large and infrequent interventions, while they are ineffective during periods of small and frequent interventions[16]. Some studies divide the entire period of intervention into two main sub-periods: the pre-Sakakibara period and the post-Sakakibara period[17] The pre- and post- Sakakibara periods distinguish the small and frequent interventions from the large and infrequent ones. We consider this as the first structural break. Few other studies like Ito and Melvin (1999) suggest another break point in April, 1998.

Table 4 report the results for the unilateral BOJ interventions in the USD/JPY market for the three sub-samples: (1) 1 April, 1991 to 1 June 1995, (2) 2 June, 1995 to 1 April, 1998, and (3) 2 April, 1998 to 31 July, 2006[18]. Results in columns (2)–(4) report results for the first sub-sample. We find that intervention increased the log continuous component of the daily realized volatility. The coefficient of intervention on the jump component is, however, positive but insignificant. This suggests that BOJ did

[15]Since the number of intervention days are quite few, the J-statistic of over-identifying restrictions is high.

[16]See Fatum and Hutchison (2005), Hoshikawa (2008), and Hillebrand et al. (2009).

[17]Eisuke Sakakibara was the Director General of the International Finance Bureau and was known as "Mr Yen" for his active foreign exchange policy.

[18]We also conduct a sub-sample analysis with the Asian Financial Crisis of 2007 as the cut-off date. The qualitative results are similar. We do not report the results, but are available from the authors upon request.

not significantly influence the discontinuous jump volatility implying most of intervention operations in this sub-sample period were not interpreted as a 'one-time' event. Since interventions were small and frequent, markets expected this intervention to persist. This did not cause jumps in the volatility, but increased the persistent continuous component of daily volatility. Our method of decomposing and estimating the different components of daily volatility is able to distinguish these two effects which none of the previous studies had identified.

We also find that the coefficient of intervention in the return equation is negative and significant. The interventions in the early part of the sub-sample (till 1992) were negative (i.e. BOJ purchased Yens for Dollars) and the later part of the sub-sample (1993 and 1994) had all positive interventions (i.e. BOJ had sold Yens for Dollars). The results indicate that BOJ interventions were effective in influencing the exchange rate returns. However, since we had both positive and negative interventions in this sub-sample, the results should be interpreted with caution and cannot be taken seriously.

Columns (5)–(7) in Table 4 presents results for the second sub-sample. The results for the effect on volatility components are qualitatively similar; indicating that interventions did not have the desired effect for realized volatility. It had increased the smooth continuous component, but the persistent effect had diminished from the first sub-sample. This is consistent with the fact that the pre- and post- Sakakibara period was characterized by low and frequent versus high and infrequent interventions. As intervention operations became infrequent, the expectations in the market diminished. The impact on jumps was positive and insignificant, which is similar to the first sub-sample.

The effect on FX returns was negative and significant. This implies that BOJ interventions in the second segment was counterproductive. Purchase of US dollars led to an appreciation of the Japanese Yen. As interventions became infrequent, it had perverse effect on the exchange rate returns. This result is consistent with the findings of the previous studies.

In Columns (8)–(10) of Table 4, the results of the last sub-sample are provided. The coefficient of intervention in both the log continuous and the jump equations are positive and significant. Therefore, BOJ interventions became infrequent, it had more persistent effect on realized volatility. During this period, interventions were also large. Thus the effect on jumps, the short-lived transient volatility, was also high and significant. The effect on the mean equation remained negative, but the results were insignificantly different from zero.

In summary, we find mixed evidence of the success of BOJ interventions over time in the sub-sample analysis. We find some evidence that the low and frequent intervention regimes was characterized by high and persistent volatility with relatively little impact on jumps. As interventions became smaller and more frequent, it increased jump component of realized volatility as well. For exchange rate returns, our results indicate a mixed response over the three sub-samples.

5. Conclusion

We analyze the effectiveness of interventions by Bank of Japan on the USD/JPY and DEM/JPY(EUR/JPY) exchange rate series on influencing the returns and exchange rate volatility. We use realized volatility to measure the uncertainty of exchange rate movements because it is a model-free estimate and it provides an accurate proxy to the market volatility. We decompose the realized volatility into a persistent continuous component and a discontinuous jump component and model these interactions along with returns using a simultaneous equation model. Using this framework, we distinguish the effect of CBI on the different components of daily realized volatility that most of the previous studies using GARCH-type models have overlooked. One advantage of separating the smooth persistent volatility component and much less persistent jump process is that it can better describe price (exchange rate) processes in-sample and also provides out-of-sample forecast accuracy. We also address the issue of endogeneity by using a simultaneous equation framework.

We find that intervention by Japanese monetary authority is ineffective in influencing the exchange rate returns or stabilizing either components of daily realized volatility. Our results show that both the continuous components and jumps in the realized volatility increased substantially by the BOJ interventions. This result holds for both the USD/JPY and the DEM/JPY(EUR/JPY) series. The result is also robust to unilateral interventions by BOJ and coordinated interventions by BOJ and Fed. We also take into account the structural breaks in the USD/JPY series by differentiating between frequent and low interventions with infrequent and high interventions. We find that the effect on persistent component of the realized volatility is positive and highly significant in all the three sub-samples. However, the effect of BOJ interventions on the jump component is only significant in the last sub-sample when interventions were infrequent and high. This is in contrast to some of the previous studies.

The effect on daily exchange rate returns are less clear. In particular, when BOJ intervenes by selling or buying yen, there is insignificant impact on the USD/JPY exchange rate returns. This result holds for the coordinated intervention by BOJ and Fed in the USD/JPY market and unilateral intervention by BOJ in the DEM/JPY(EUR/JPY) market. In the sub-sample analysis, the result in only strongly negative for unilateral interventions by BOJ in the USD/JPY market, i.e. selling of Yen by BOJ appreciates the Yen. Overall, we do not find any evidence that interventions by BOJ are successful in stabilizing the exchange rates or influencing the returns in the proper direction. On the contrary, BOJ interventions are associated with increasing both the persistent and the jump components of daily realized volatility.

Our future work is to model the relation between the volatility and central bank intervention using an extreme value theory, so that the estimation results are not subject to any scaling constraints. Another direction of research is to first uncover a few common factors that drive the joint dynamics of level of the exchange rate, its volatility components and intervention in a state–space factor model.

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7. Appendix

7.1. Derivatives of the Tobit Model

A Tobit model can be expressed as:

$$\begin{aligned} y_t^* &= x_t'\beta + \epsilon_t, \quad \epsilon_t \sim (0, \sigma^2) \\ y_t &= 0 \quad y_t^* \leq 0 \\ y_t &= y_t^* \quad y_t^* > 0 \end{aligned}$$

Since the observations on jumps in volatility are censored, the moment conditions for the jump censored model (equation 13) is based on the error term e_t:

$$e_t = y_t - E(y_t|x_t) \tag{21}$$

where[19]

$$E(y_t|x_t) = \Phi\left(\frac{x_t'\beta}{\sigma}\right)(x_t'\beta + \sigma\lambda_t) \tag{22}$$

$$\lambda_t = \frac{\phi(x_t\beta/\sigma)}{\Phi(x_t\beta/\sigma)} \tag{23}$$

Let

$$\frac{\partial\lambda_t}{\partial\beta} = \frac{-\phi(x_t\beta/\sigma)(x_t'\beta/\sigma)(x_t/\sigma)}{\Phi(x_t'\beta/\sigma)} - \frac{\phi^2(x_t'\beta/\sigma)(x_t/\sigma)}{\Phi^2(x_t'\beta/\sigma)} \tag{24}$$

Hence, the derivatives of e_t with respect to β are:

$$\frac{\partial e_t}{\partial\beta} = -\phi(x_t'\beta/\sigma)(x_t'\beta + \sigma\lambda_t)x_t/\sigma - \Phi(x_t'\beta/\sigma)(x_t + \sigma\frac{\partial\lambda_t}{\partial\beta}) \tag{25}$$

[19] $\phi(x)$ and $\Phi(x)$ are the standard normal probability density function and cumulative probability function, respectively.

Figure 1: Opening hours of major foreign exchange markets

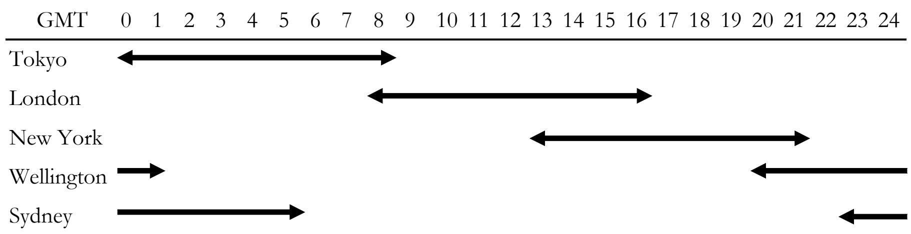

Figure 2: Daily periodicity of USD/JPY

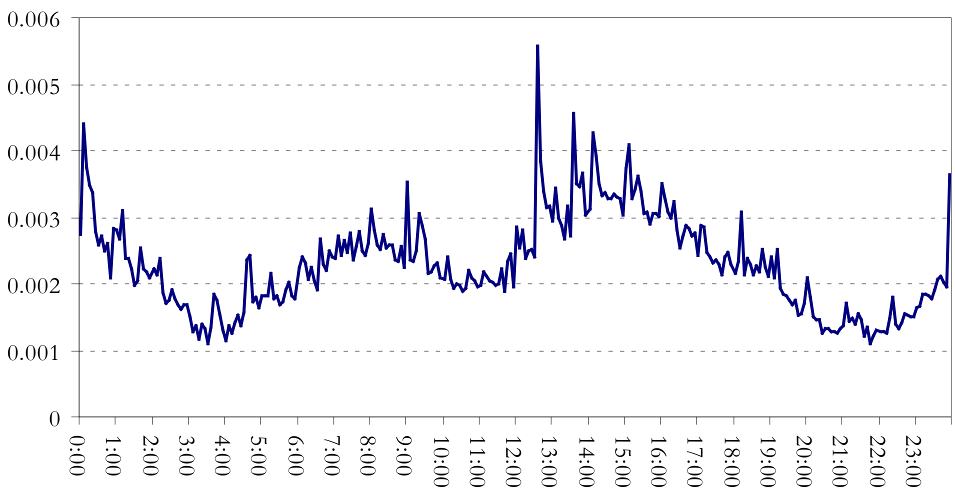

Figure 3: Time series of daily returns, volatility components and interventions on USD/JPY

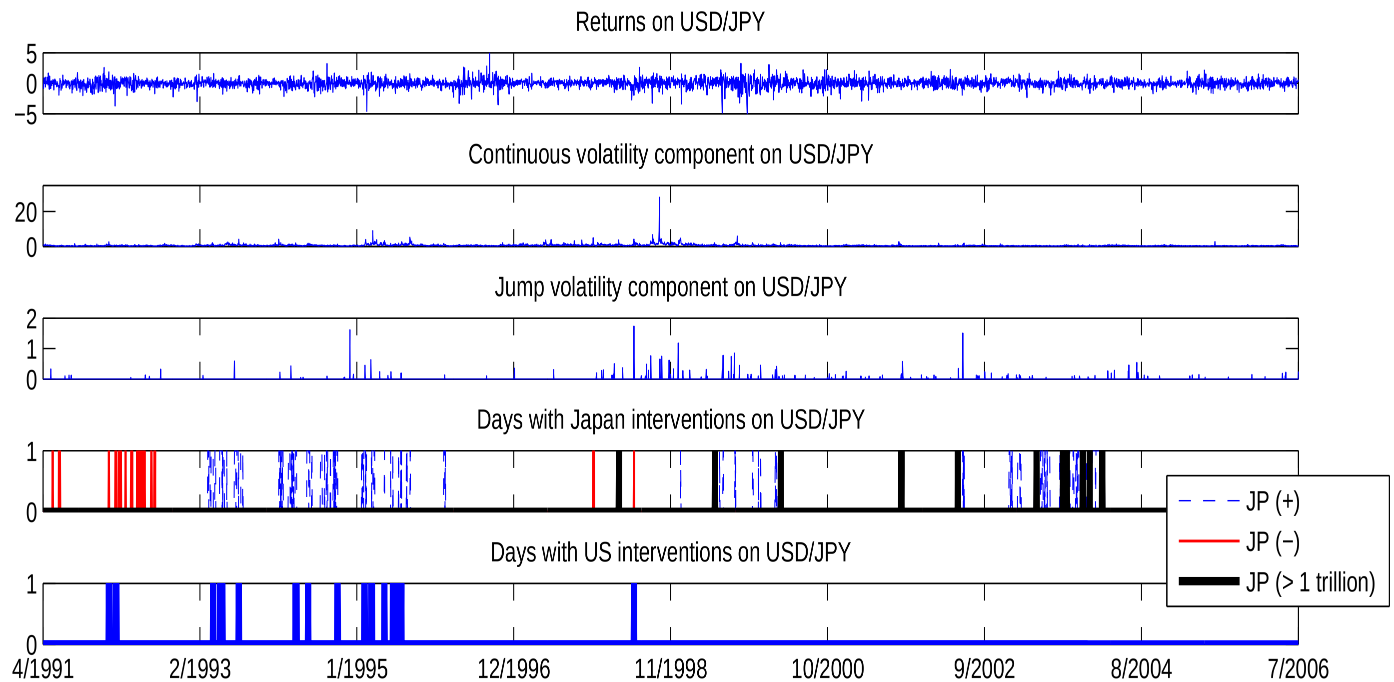

Figure 4: Time series of daily returns, volatility components and interventions on EUR/JPY

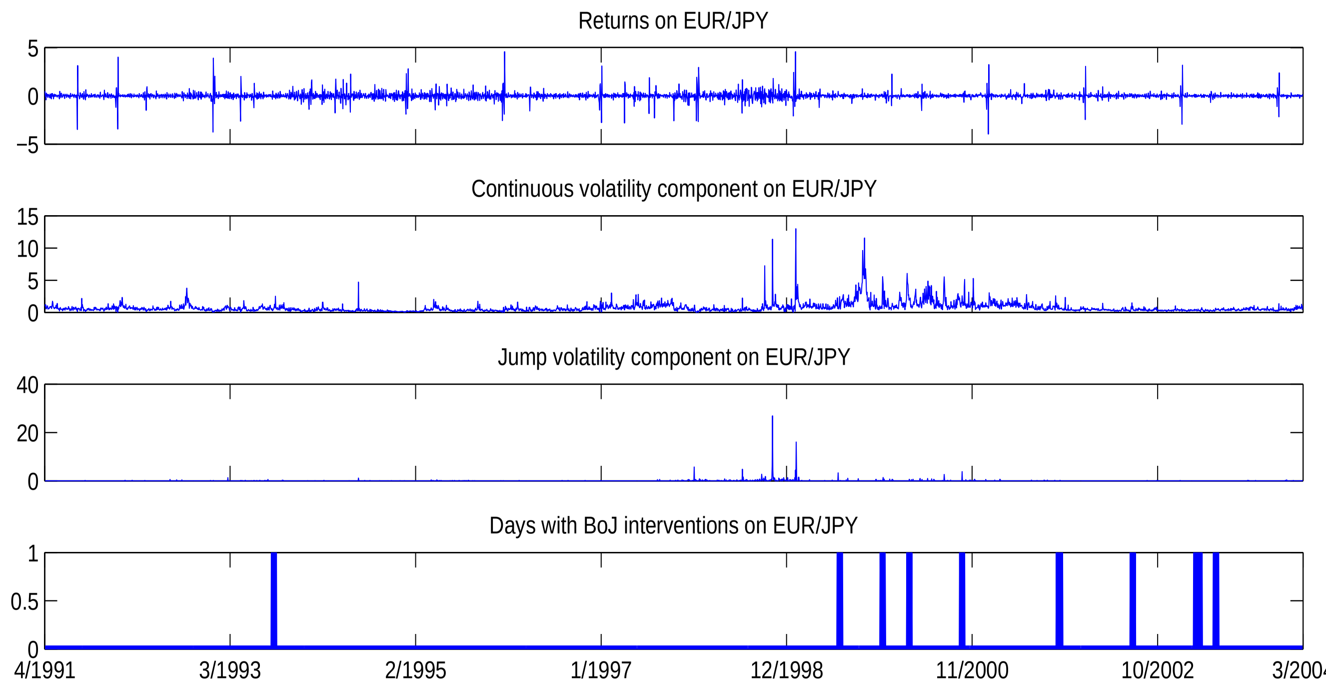

Table 1: Descriptive statistics of the returns and continuous and jump variance components of USD/JPY and EUR/JPY

	USD/JPY					
	Mean	Std. Dev.	Skew.	Kurtosis	Min	Max
r	-0.01	0.7	-0.48	8.33	-6.34	5.27
r on Intervention days (Unilateral)	-0.05	0.69	-0.48	8.33	-6.34	5.27
r on Intervention days (Coordinated)	-0.03	0.93	-0.48	3.06	-1.97	1.86
C	0.62	0.79	21.56	842.68	0.04	34.15
C on Intervention days (Unilateral)	0.85	0.92	3.89	26.66	0.04	9.09
C on Intervention days (Coordinated)	0.93	0.65	2.05	7.05	0.03	3.1
$\log C$	-0.74	0.65	0.59	4.39	-3.32	3.53
$\log C$ on intervention days (Unilateral)	-0.53	0.85	0.05	3.12	-3.19	2.21
$\log C$ on Intervention days (Coordinated)	-0.25	0.57	0.67	3.06	-1.07	1.13
J	0.01	0.07	14.26	271.2	0	1.74
J on Intervention days (Unilateral)	0.03	0.15	8.26	81.73	0	1.74
J on Intervention days (Coordinated)	0.04	0.14	3.84	16.64	0	0.64
	EUR/JPY					
r	0.00	0.42	0.79	35.67	-3.97	4.58
r on Intervention days	0.00	0.09	-0.36	35.67	-3.97	4.58
C	0.77	0.83	5.77	59.74	0.00	14.07
C on Intervention days	1.21	1.44	2.42	8.6	0.25	6.17
$\log C$	-0.56	0.74	0.06	5.40	-6.37	2.64
$\log C$ on Intervention days	-0.23	0.85	0.83	2.84	-1.38	1.82
J	0.05	0.6	33.89	1378.9	0	26.88
J on Intervention days	0.24	0.88	3.83	16.08	0	3.81

Table 2: Estimation of model (11) through (13) in the USD/JPY market for sample April 1, 1991 to July 31, 2006: GMM estimates of 3 equations (12 parameters). 9 instrumental variables and the Newey-West Spectral density with 15 lags have been used. The GMM χ^2 (Hansen's $J-statistic$) for the validity of overidentifying restrictions is 10.129 ($p-value$ = 0.605) for the unilateral intervention model and 8.743 ($p-value$ = 0.725) for the coordinated intervention model.

	Unilateral Intervention Model			**Coordinated Intervention Model**		
Model	r	$\log C$	J	r	$\log C$	J
α_0	-0.003			-0.008		
	(0.013)			(0.018)		
α_1	-0.035			0.3		
	(0.076)			(1.929)		
β_0		-0.115			-0.212	
		(0.015)			(0.066)	
β_1		0.664			11.036	
		(0.301)			(6.699)	
β_2		0.415			0.379	
		(0.021)			(0.065)	
β_3		0.138			0.085	
		(0.018)			(0.044)	
β_4		0.076			0.054	
		(0.017)			(0.042)	
β_5		0.081			0.097	
		(0.017)			(0.033)	
β_6		0.136			0.174	
		(0.019)			(0.04)	
β_7		0.017			0.022	
		(0.017)			(0.037)	
γ_0			-2.152			-2.443
			(0.053)			(0.283)
γ_1			1.625			3.114
			(0.433)			(0.826)

Table 3: Estimation of model (11) through (13) in the DEM/JPY(EUR/JPY) market for sample April 1, 1991 to March 31, 2004: GMM estimates of 3 equations (12 parameters). 9 instrumental variables and the Newey-West Spectral density with 10 lags have been used. The GMM χ^2 (Hansen's $J-statistic$) for the validity of overidentifying restrictions is 26.684 (p-value = 0.0086).

Model	r	$\log C$	J
α_0	-0.161		
	(0.267)		
α_1	-1.336		
	(2.321)		
β_0		-0.057	
		(0.012)	
β_1		1.637	
		(0.644)	
β_2		0.374	
		(0.023)	
β_3		0.161	
		(0.0163)	
β_4		0.09	
		(0.015)	
β_5		0.093	
		(0.015)	
β_6		0.104	
		(0.036)	
β_7		0.077	
		(0.022)	
γ_0			-1.484
			(0.086)
γ_1			5.257
			(4.27)

Table 4: Estimation of model (11) through (13) in the USD/JPY market for sub-samples: (1) April 1, 1991 to June 1, 1995 (2) June 2, 1995 - April 1, 1998, and (3) April 2, 1998 - July 31, 2006: GMM estimates of 3 equations (12 parameters). 9 instrumental variables and the Newey-West Spectral density with 10 lags have been used. The GMM χ^2 (Hansen's $J - statistic$) for the validity of overidentifying restrictions is 28.76 ($p - value = 0.004$) for sample 1, 23.437 ($p - value = 0.024$) for sample 2 and 15.529 ($p - value = 0.214$) for sample 3.

	Sub-sample 1			**Sub-sample 2**			**Sub-sample 3**		
Model	r	$\log C$	J	r	$\log C$	J	r	$\log C$	J
α_0	-0.026			0.035			0.002		
	(0.02)			(0.023)			(0.016)		
α_1	-0.165			-0.62			-0.069		
	(0.069)			(0.31)			(0.071)		
β_0		-0.179			-0.101			-0.141	
		(0.017)			(0.02)			(0.022)	
β_1		5.431			0.899			0.568	
		(0.973)			(0.323)			(0.082)	
β_2		0.407			0.418			0.395	
		(0.024)			(0.042)			(0.027)	
β_3		0.113			0.118			0.14	
		(0.03)			(0.033)			(0.023)	
β_4		0.093			0.085			0.077	
		(0.028)			(0.025)			(0.021)	
β_5		0.066			0.02			0.087	
		(0.03)			(0.029)			(0.021)	
β_6		0.142			0.108			0.132	
		(0.025)			(0.053)			(0.022)	
β_7		-0.006			0.041			0.03	
		(0.031)			(0.032)			(0.021)	
γ_0			-6.971			-5.193			-2.05
			(575.14)			(8839.94)			(0.056)
γ_1			0.972			0.895			0.889
			(390.68)			(1219.55)			(0.198)