Research Division
Federal Reserve Bank of St. Louis
Working Paper Series

Central Bank Intervention and Exchange Rate Volatility, Its Continuous and Jump Components

Michel Beine
Jérôme Lahaye
Sébastien Laurent
Christopher J. Neely
and
Franz C. Palm

Working Paper 2006-031B
http://research.stlouisfed.org/wp/2006/2006-031.pdf

May 2006
Revised August 2006

FEDERAL RESERVE BANK OF ST. LOUIS
Research Division
P.O. Box 442
St. Louis, MO 63166

Central Bank Intervention and Exchange Rate Volatility, Its Continuous and Jump Components*

Michel BEINE† Jérôme LAHAYE‡ Sébastien LAURENT§

Christopher J. NEELY¶ Franz C. PALM‖

August 2006

Abstract

We analyze the relationship between interventions and volatility at daily and intra-daily frequencies for the two major exchange rate markets. Using recent econometric methods to estimate realized volatility, we decompose exchange rate volatility into two major components: a continuously varying component and jumps. Some coordinated interventions affect the temporary (jump) part of the volatility process. Most coordinated operations are associated with an increase in the persistent (continuous) part of exchange rate volatility.

Keywords: Intervention, jumps, bi-power variation, exchange rate,volatility

JEL Codes: F31, F33, C34

---

*This text presents research results of the Belgian Program on Interuniversity Poles of Attraction initiated by the Belgian State, Prime Minister's Office, Science Policy Programming. The scientific responsibility is assumed by the authors.

†University of Luxembourg and Free University of Brussels; mbeine@ulb.ac.be

‡CeReFiM, University of Namur and CORE; Jerome.Lahaye@fundp.ac.be

§CeReFiM, University of Namur and CORE; Sebastien.Laurent@fundp.ac.be

¶Research Officer, Research Department, Federal Reserve Bank of St. Louis; neely@stls.frb.org

‖Maastricht University, Faculty of Economics and Business Administration and CESifo; F.Palm@ke.unimaas.nl

1 Introduction

During a period of twenty years (1985-2004), the central banks of the US, Japan and Germany (Europe) intervened more than 600 times in either the DEM-dollar (DEM/USD or EUR/USD after the introduction of the euro) or the yen-dollar (JPY/USD) market. On average, they intervened almost three times per month. It is not surprising that central banks should frequently intervene in markets that are of crucial importance for international competitiveness. Given the importance of understanding foreign exchange markets, for scientific and policy reasons, one would like to assess the impact of central bank interventions (CBIs hereafter) on exchange rates.

The large empirical literature on the impact of CBIs provides mixed evidence on the impact of CBI on exchange rate returns. In general, authors fail to identify effects on the conditional mean of exchange rate returns at a daily frequency (Baillie and Osterberg 1997). When effects on the spot exchange rate returns are detected, they are often found to be perverse, i.e. purchases of U.S. dollar leading to a depreciation of the dollar (Baillie and Osterberg 1997, Beine, Bénassy-Quéré, and Lecourt 2002). This perverse result tends to hold for both unilateral and coordinated interventions. This result has usually been interpreted as indicating a lack of credibility, or ascribed to inappropriate identification schemes in the presence of leaning-against-the-wind policies (Neely 2005b). Recent studies conducted at intra-daily frequencies nevertheless find that CBIs can move the exchange rate, at least in the very short run (Fischer and Zurlinden 1999, Dominguez 2003).

The empirical literature is much more conclusive with respect to the impact of CBIs in terms of exchange rate volatility. Most studies conclude that intervention tends to increase exchange rate volatility (Humpage 2003) and this result is robust to the use of any of the three main measures of asset price volatility: univariate GARCH models (Baillie and Osterberg 1997, Dominguez 1998, Beine, Bénassy-Quéré, and Lecourt 2002); implied volatilities extracted from option prices (Bonser-Neal and Tanner 1996, Dominguez 1998, Galati and Melick 1999); and realized volatility (Beine, Laurent, and Palm 2005, Dominguez 2004).

This paper looks at the relation between intervention and the components of volatility. We investigate how CBIs affect the continuous, persistent part of exchange rate volatility and the discontinuous, temporary, component. Our approach relies on bi-power variation Barndorff-Nielsen and Shephard (2004, 2005) to decompose exchange rate changes into a continuous part and a jump component. Bi-power variation consistently estimates the continuous volatility even in the presence of jumps (i.e. continuous-time jump diffusion process). And the realized volatility (sum of squared intradaily returns) consistently estimates the sum of both the continuous volatility and the discontinuities (jumps) in the underlying price process. Therefore the difference between realized volatility and the bi-power variation consistently estimates the contribution to the quadratic variation process due to the discontinuities (jumps).

Barndorff-Nielsen and Shephard (2005) suggest that jumps in foreign exchange markets are linked to the arrival of macroeconomic news, in line with the results of Andersen, Bollerslev, Diebold, and Vega (2003). In this respect, our findings can shed some light on the importance of interventions for explaining the dynamics of exchange rates and the extent to which interventions impact rates similarly to macroeconomic news.

Our investigation covers central bank activity on the two largest exchange rate markets. We focus on Fed, Bundesbank (ECB after 1998) and Bank of Japan interventions over the last twenty years. Using the method of bi-power variation with 5-minute exchange rate data, we identify the days in which exchange rates jumps occur. This allows us to investigate whether intervention days are unusually associated with the occurrence of these jumps.

To achieve this goal, we proceed in three steps.

First, we decompose realized volatility into a continuous component and a jump component. We investigate the relationship between CBIs and discontinuities in the JPY/USD and EUR/USD markets and find that while jumps are not more likely to occur on days of intervention, the jumps that do occur are larger than average. In particular only a few coordinated interventions could reasonably generate jumps. Coordinated CBIs do have an important link with the smooth, persistently varying component of realized volatility, however.

Second, to check for the direction of causality between jumps and coordinated CBIs, we carefully study the number of jumps and the timing of their occurrence during the intervention days. Most of the jumps on intervention days appear to have occurred during or after the period of the day at which both exchange markets were open, when most coordinated interventions take place. This analysis provides little evidence in favor of a causality where central bank jointly intervene in reaction to the occurrence of jumps. Instead it supports the view that coordinated interventions produced exchange rate jumps.

Third, a formal regression analysis confirms these findings.

We then discuss the economic interpretation of the findings, the implications for foreign exchange market policy of central banks and some extensions of the methodology.

The paper is organized as follows. Section 2 details the procedure used to identify the jump components of the realized volatilities. Section 3 provides some details on the data. Section 4 reports our empirical analysis relating the occurrence of jumps with CBIs while Section 5 proposes an interpretation of the main findings. Finally, Section 6 concludes.

2 Extracting the jump component

Let $p(t)$ be a logarithmic asset price at time t. Consider the continuous-time jump diffusion process

$$dp(t) = \mu(t)dt + \sigma(t)dW(t) + \kappa(t)dq(t), \qquad 0 \leq t \leq, T \tag{1}$$

where $\mu(t)$ is a continuous and locally bounded variation process, $\sigma(t)$ is a strictly positive stochastic volatility process with a sample path that is right continuous and has well defined limits, $W(t)$ is a standard Brownian motion, and $q(t)$ is a counting process with intensity $\lambda(t)$ ($P[dq(t) = 1] = \lambda(t)dt$ and $\kappa(t) = p(t) - p(t-)$ is the size of the jump in question). The quadratic variation for the cumulative process $r(t) \equiv p(t) - p(0)$ is the integrated volatility of the continuous sample path component plus the sum of the $q(t)$ squared jumps that occurred between time 0 and time t:

$$[r, r]_t = \int_0^t \sigma^2(s)ds + \sum_{0<s\leq t} \kappa^2(s). \tag{2}$$

Now, let us define the daily realized volatility as the sum of the corresponding intradaily squared returns:

$$RV_{t+1}(\Delta) \equiv \sum_{j=1}^{1/\Delta} r^2_{t+j\Delta,\Delta}, \tag{3}$$

where $r_{t,\Delta} \equiv p(t) - p(t - \Delta)$ is the discretely sampled Δ-period return.[1] So $1/\Delta$ is the number of intradaily periods (288 in our application).

Barndorff-Nielsen and Shephard (2004) show that the realized volatility converges uniformly in probability to the increment of the quadratic variation process as the sampling frequency of the returns increases ($\Delta \to 0$):[2]

$$RV_{t+1}(\Delta) \to \int_t^{t+1} \sigma^2(s)ds + \sum_{t<s\leq t+1} \kappa^2(s). \tag{4}$$

That means that the realized volatility is a consistent estimate for integrated volatility as long as there are no jumps.

[1] We use the same notation as in Andersen, Bollerslev, and Diebold (2005) and normalize the daily time interval to unity. We drop the Δ subscript for daily returns: $r_{t+1,1} \equiv r_{t+1}$.

[2] See also, for example, Andersen and Bollerslev (1998a), Andersen, Bollerslev, Diebold, and Labys (2001), Barndorff-Nielsen and Shephard (2002a), Barndorff-Nielsen and Shephard (2002b), Comte and Renault (1998).

In order to disentangle the continuous and the jump components of realized volatility, we need to consistently estimate integrated volatility, even in the presence of jumps in the process. This is done using the asymptotic results of Barndorff-Nielsen and Shephard (2004, 2005). The realized bi-power variation is defined as the sum of the product of adjacent absolute intradaily returns standardized by a constant:

$$BV_{t+1}(\Delta) \equiv \mu_1^{-2} \sum_{j=2}^{1/\Delta} |r_{t+j\Delta,\Delta}||r_{t+(j-1)\Delta,\Delta}|, \tag{5}$$

where $\mu_1 \equiv \sqrt{2/\pi} \simeq 0.79788$ is the mean of the absolute value of a standard normally distributed random variable. It can indeed be shown that even in the presence of jumps,

$$BV_{t+1}(\Delta) \to \int_t^{t+1} \sigma^2(s)ds. \tag{6}$$

Thus, the difference between the realized volatility and the bi-power variation consistently estimates the jump contribution to the quadratic variation process. When $\Delta \to 0$:

$$RV_{t+1}(\Delta) - BV_{t+1}(\Delta) \to \sum_{t<s\leq t+1} \kappa^2(s). \tag{7}$$

Moreover, because a finite sample estimate of the squared jump process might be negative (in Equation 7), we truncate the measurement at zero, i.e.

$$J_{t+1}(\Delta) \equiv max[RV_{t+1}(\Delta) - BV_{t+1}(\Delta), 0]. \tag{8}$$

One might wish to select only statistically significant jumps, to consider very small jumps to be part of the continuous sample path rather than genuine discontinuities. The Barndorff-Nielsen and Shephard (2004, 2005) results, extended in Barndorff-Nielsen, Graversen, Jacod, Podolskij, and Shephard (2005), imply:[3]

$$\frac{RV_{t+1}(\Delta) - BV_{t+1}(\Delta)}{\sqrt{(\mu_1^{-4} + 2\mu_1^{-2} - 5)\Delta \int_t^{t+1} \sigma^4(s)ds}} \to N(0,1), \tag{9}$$

when there is no jump and for $\Delta \to 0$, under sufficient regularity conditions. We need to estimate the integrated quarticity $\int_t^{t+1} \sigma^4(s)ds$ to compute this statistic. The realized tri-power quarticity measure permits us to estimate it consistently, even in the presence of jumps:

[3]Note that these results rely on the assumption that the joint process of the drift and volatility of the underlying process (μ, σ) is independent of the Brownian motion W. This rules out leverage effects and feedback between previous innovations in W and the risk premium in μ. Though this is empirically reasonable for foreign exchange markets, this is not for equity data.

$$TQ_{t+1}(\Delta) \equiv \Delta^{-1}\mu_{4/3}^{-3}\sum_{j=3}^{1/\Delta}|r_{t+j\Delta,\Delta}|^{4/3}|r_{t+(j-1)\Delta,\Delta}|^{4/3}|r_{t+(j-2)\Delta,\Delta}|^{4/3}, \tag{10}$$

with $\mu_{4/3} \equiv 2^{2/3}\Gamma(7/6)\Gamma(1/2)^{-1}$. Thus, we have that, for $\Delta \to 0$:

$$TQ_{t+1}(\Delta) \to \int_t^{t+1} \sigma^4(s)ds. \tag{11}$$

The implementable statistics is therefore:

$$W_{t+1}(\Delta) \equiv \frac{RV_{t+1}(\Delta) - BV_{t+1}(\Delta)}{\sqrt{\Delta(\mu_1^{-4} + 2\mu_1^{-2} - 5)TQ_{t+1}(\Delta)}}. \tag{12}$$

However, following Huang and Tauchen (2005) and Andersen, Bollerslev, and Diebold (2005), we actually implement the following statistic:

$$Z_{t+1}(\Delta) \equiv \Delta^{-1/2}\frac{[RV_{t+1}(\Delta)) - BV_{t+1}(\Delta)]RV_{t+1}(\Delta)^{-1}}{[(\mu_1^{-4} + 2\mu_1^{-2} - 5)max\{1, TQ_{t+1}(\Delta)BV_{t+1}(\Delta)^{-2}\}]^{1/2}}. \tag{13}$$

Huang and Tauchen (2005) show that the statistic defined in Equation (12) tends to over-reject the null hypothesis of no jumps. Moreover, they show that $Z_{t+1}(\Delta)$ defined in Equation (13) is closely approximated by a standard normal distribution and has reasonable power against several plausible stochastic volatility jump diffusion models. Practically, we choose a significance level α and compute:

$$J_{t+1,\alpha}(\Delta) = I[Z_{t+1}(\Delta) > \Phi_\alpha] \cdot [RV_{t+1}(\Delta) - BV_{t+1}(\Delta)]. \tag{14}$$

Of course, a smaller α means that we estimated fewer and larger jumps. Moreover, to make sure that the jump component added to the continuous one equals the realized volatility, we impose:

$$C_{t+1,\alpha}(\Delta) = I[Z_{t+1}(\Delta) \leq \Phi_\alpha] \cdot RV_{t+1}(\Delta) + I[Z_{t+1}(\Delta) > \Phi_\alpha] \cdot BV_{t+1}(\Delta). \tag{15}$$

Finally, still following Andersen, Bollerslev, and Diebold (2005), we use a modified staggered realized bi-power variation and tri-power quarticity measure to tackle first order autocorrelation due to microstructure noise issues:[4]

$$BV_{t+1}(\Delta) \equiv \mu_1^{-2}(1 - 2\Delta)^{-1}\sum_{j=3}^{1/\Delta}|r_{t+j\Delta,\Delta}||r_{t+(j-2)\Delta,\Delta}|, \tag{16}$$

$$TQ_{t+1}(\Delta) \equiv \Delta^{-1}\mu_{4/3}^{-3}(1 - 4\Delta)^{-1}\sum_{j=5}^{1/\Delta}|r_{t+j\Delta,\Delta}|^{4/3}|r_{t+(j-2)\Delta,\Delta}|^{4/3}|r_{t+(j-4)\Delta,\Delta}|^{4/3}. \tag{17}$$

[4]Considering first-order autocorrelation is sufficient in our application.

Barndorff-Nielsen and Shephard (2004) show that the absence of microstructure noise, the asymptotic distribution of the test statistic defined in Equation 13 remains asymptotically standard normal once the relevant components are replaced by the staggered ones.

3 Data

3.1 Exchange rate data

We analyze the interaction between jumps and interventions for the two major exchange rate markets, namely the the Japanese Yen (YEN) and the Deutsche Mark (DEM) (Euro after 1998) against the US Dollar (USD). For these two exchange rates, we have about 17 years of intradaily data for a period ranging from January 2, 1987 to October 1, 2004, provided by Olsen and Associates. The raw data consists of last mid-quotes (average of the logarithms of bid and ask quotes) of 5-minute intervals throughout the global 24-hour trading day. Next we obtain 5-min returns as 100 times the first difference of the logarithmic prices.

Following Andersen and Bollerslev (1998b), one trading day extends from 21.00 GMT on day $t-1$ to 21.00 GMT on date t. This redefinition will ensure that all interventions dated at day t (using local time) take place during this interval, even the Japanese interventions that may occur before 00.00 GMT.

It is important to get rid of the trading days that display either too many missing values or for which the prices did not move very much as a result of low trading activity. To this aim, we delete week-ends plus a set of fixed and irregular holidays.[5] Moreover we use three additional criteria. First, we do not consider the trading days for which there are more than 100 missing values at the 5-minute frequency. Second, days where we record more that 50 zero intra-daily returns are deleted. Finally, we suppress days for which more than 7 consecutive prices were found the same. Using these criteria leads us to suppress 48 and 85 days respectively for the EUR/USD and for the YEN/USD.

Figures 1 and 2 plot the evolution of the exchange rate and the return at a daily frequency over the whole sample for the EUR/USD and the JPY/USD.[6]

[5]Included fixed holidays are Christmas (December 24 - 26), New Year (December 31 - January 2), and July Fourth. Moving holidays include Good Friday, Easter Monday, Memorial Day, Labor Day, Thanksgiving and the day after, and July Fourth when it falls officially on July 3.

[6]The two figures are drawn using the filtered data. This means that some business days where the activity and/or the data quality is low were suppressed. We thus implicitly assume that during these removed days, the

Figures 3 and 4 plot the evolution of the three main measures of volatility: the realized volatility built from the 288 5-minute intradaily returns (first panel) as described in Equation (3) and its decomposition into the continuous sample path (second panel) and the jump component (third panel) as described respectively in equations (15) and (14). The significance of the jump component was assessed using a conservative 99.99 % confidence level, i.e. $\alpha = 0.9999$.

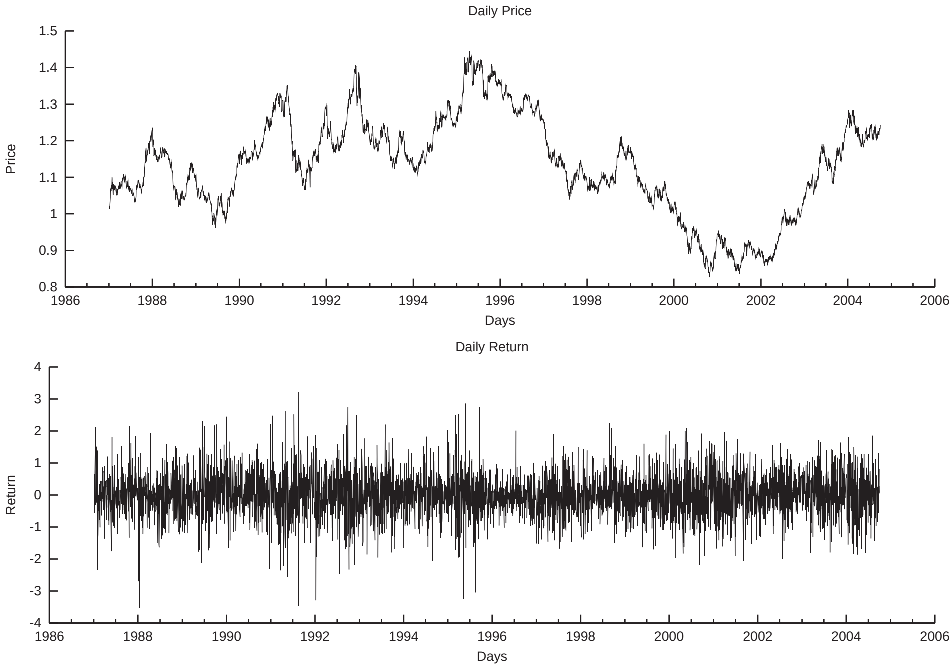

Figure 1: Dollar/Euro - Daily prices and daily returns

Tables 1 and 2 provide describe the realized volatility estimates as well as the estimated jump components for the EUR/USD and JPY/USD series. These tables also report information regarding the proportion of significant values over the whole sample. Two significance levels are used. We use first a very low level ($\alpha = 0.5$, variable denoted J in the table) for which at least one jump is detected almost every day: the proportion of days with jumps is above 90% for both markets. The use of such a significance level would of course result in an overestimation of the number of economically meaningful jumps. Therefore, we use a much more conservative significance level ($\alpha = 0.9999$, variable denoted $J9999$ in the table) for which the proportion of days with jumps is much lower (about 10 to 13% of the business days).

exchange rate did not change.

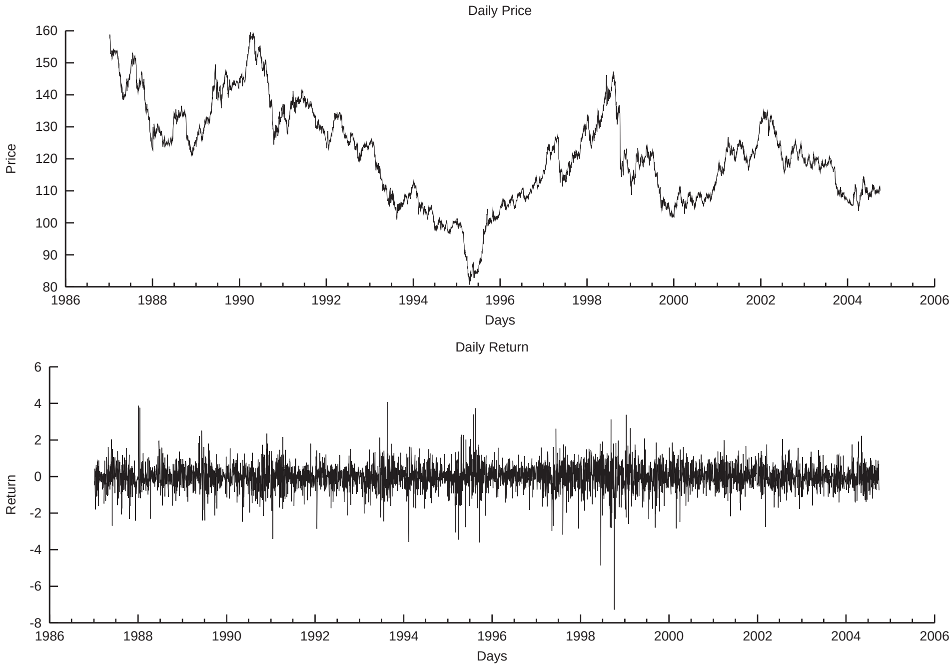

Figure 2: JPY/Dollar - Daily prices and daily returns

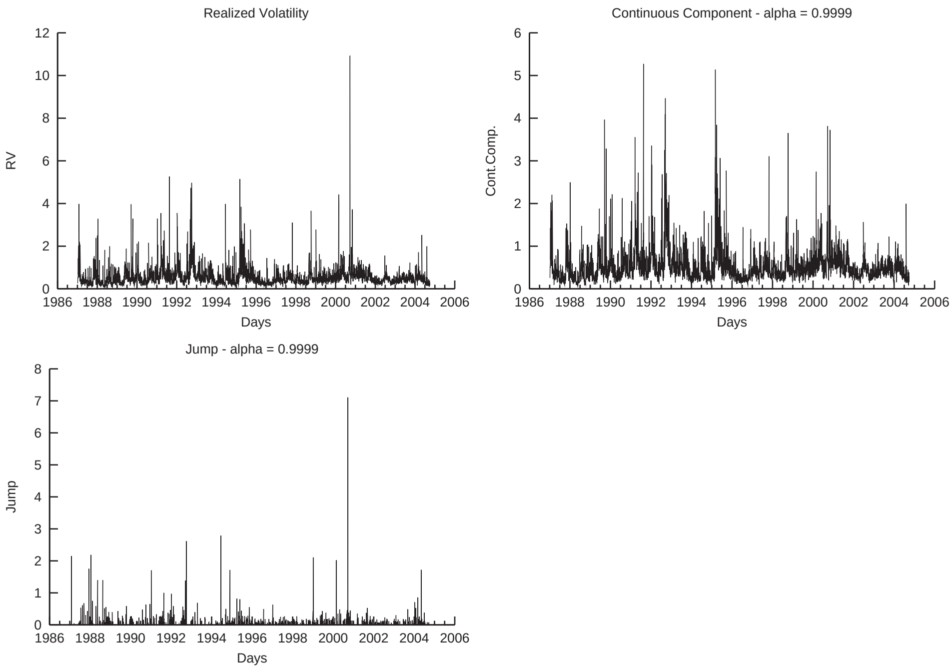

Figure 3: Dollar/Euro - Daily RV, continuous component and jumps

3.2 Intervention data

This paper uses official data on U.S., German (ECB after 1998) and Japanese interventions provided by those central banks. The investigation period is similar to the one observed for the

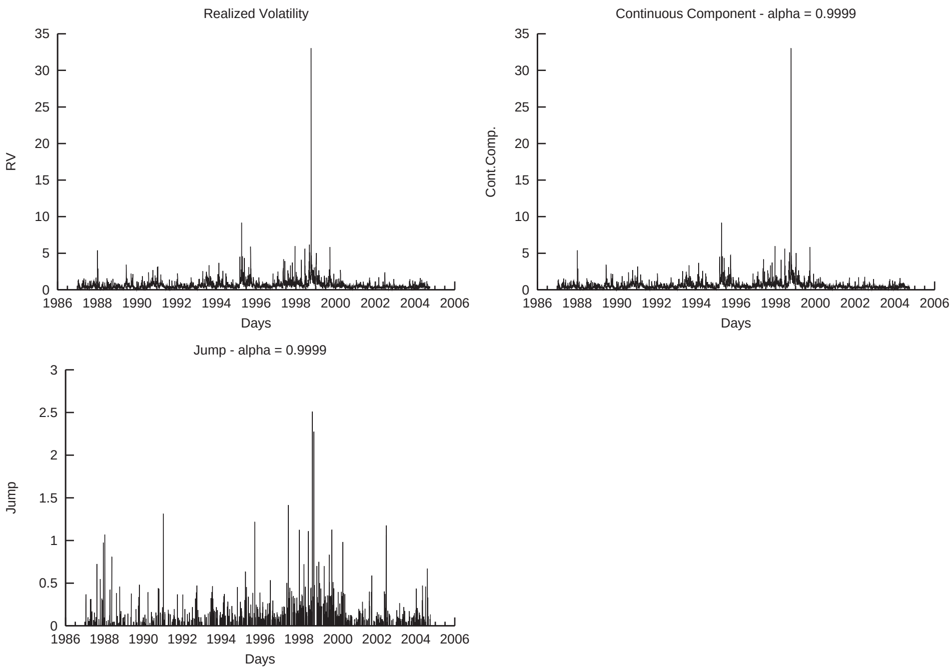

Figure 4: JPY/Dollar - Daily RV, continuous component and jumps

	RV	$log(RV)$	J	$J9999$
Prop.	-	-	0.9069	0.1034
Obs.	4360.	4360.	4360.	4360.
Mean	0.5577	-0.7727	0.07115	0.02575
St. Dev.	0.4593	0.5819	0.1761	0.1696
Skew.	5999	0.4120	19.47	22.21
Kurt.	82.48	3999	638.8	763.5
Min.	0.06499	-2734	0.0000	0.0000
Max.	10.92	2391	7109	7.109
LB(8)	3942.	8476.	55.76	4.173
Crit. Val	15.51	15.51	15.51	15.51

Table 1: Descriptive statistics on the EUR/USD. Descriptive statistics for realized volatility (RV), log realized volatility ($\log(RV)$), jumps ($J, \alpha = 0.5$), and significant jumps ($J9999, \alpha = 0.9999$). The rows are: proportion of jumps in the sample, number of observation, mean, standard deviation, skewness, kurtosis, minimum of the sample and maximum. We also provide the Ljung Box statistic LB with 8 lags (the number of lags = $\log(Obs)$) as well as the corresponding critical value.

	RV	$log(RV)$	J	$J9999$
Prop.	-	-	0.9424	0.1339
Obs.	4360.	4360.	4360.	4360.
Mean	0.6433	-0.6955	0.08284	0.02670
St. Dev.	0.7730	0.6636	0.1295	0.1081
Skew.	19.32	0.4597	6621	9.410
Kurt.	727.0	3964	77.92	146.0
Min.	0.04106	-3193	0.0000	0.0000
Max.	33.03	3497	2511	2.511
LB(8)	4066.	10920000	1337.	11.19
Crit. Val	15.51	15.51	15.51	15.51

Table 2: Descriptive statistics on the JPY/USD.Descriptive statistics for realized volatility (RV), log realized volatility ($\log(RV)$), jumps ($J, \alpha = 0.5$), and significant jumps ($J9999, \alpha = 0.9999$). The rows are: proportion of jumps in the sample, number of observation, mean, standard deviation, skewness, kurtosis, minimum of the sample and maximum. We also provide the Ljung Box statistic LB with 8 lags (the number of lags = $\log(Obs)$) as well as the corresponding critical value.

exchange rate data (January 1987-October 2004). While official data for the Fed and the Bundesbank are available at the daily frequency for the whole sample, official data for the Bank of Japan are available only after April 1991. As a result, we complement the official data set with days of perceived intervention of the BoJ. The perceived intervention days are days for which there were at least one report of interventions in financial newspapers (Wall Street Journals and Financial Times). While this might result in some underestimation of the true interventions, this procedure allows us to have similar samples of data for the two exchange rate markets and makes the comparison easier.

Table 3 reports the number of intervention days for the two FX markets. We distinguish between coordinated and unilateral interventions. Interventions are considered coordinated when both central banks intervened in the same market on the same day and in the same direction. Both theoretical and empirical rationales motivate such a distinction. Coordinated interventions are supposed to affect the market differently than unilateral operations, as the joint presence of the central banks sends a much more powerful signal to market participants. This conjecture is supported by empirical studies (Catte, Galli, and Rebecchini 1992, Beine, Laurent, and Palm 2005) showing that the response of the exchange rate to interventions is much stronger for coordinated operations.

	EUR/USD	JPY/USD
Coord.	111	115
FED	83	48
Bundesbank	97	-
BoJ	-	343

Table 3: Number of Official intervention days from January 2, 1987 to October 31, 2004. The Table reports the number of official intervention days for the Federal Reserve (FED), the Bundesbank ad the Bank of Japan (BoJ). For the Bank of Japan, data before April 1, 1991 are interventions reported in the Wall street Journal and/or the Financial Times.

4 Results

4.1 Jumps and CBIs at the daily frequency

As a first step to analyze the impact of CBIs on the two components of realized volatility, one can look at how often statistically significant jumps occur on days of interventions. At this stage, we ignore the question of causality between exchange rate dynamics and interventions (Neely 2005b) and simply look at the proportion of intervention days for which jumps are detected. We will confront the issue of causality between jumps and interventions later on, through a closer inspection of the intra-daily patterns of these jumps.

Table 4 provides some descriptive statistics for the significant jump components extracted on the non-intervention days on the EUR/USD market (first panel) and YEN/USD market (second panel) and on the intervention days. The three parts of the table correspond respectively to days without CBIs (labeled 'No CBIs'), with a unilateral or coordinated intervention (labeled 'CBIs of any type') and finally days associated with a coordinated intervention of the two involved central banks (labeled 'Coordinated Interventions'). Each parts of the table contain three columns corresponding to the significant jumps ($J9999$), continuous volatility ($CC9999$) and significant jumps conditional on a jump day, or in other words non-zero jumps ($J9999 > 0$). In each case, we chose $\alpha = 0.9999$.

	No CBIs			CBIs of any type			Coordinated Interventions		
	$J9999$	CC9999	$J9999 > 0$	$J9999$	CC9999	$J9999 > 0$	$J9999$	CC9999	$J9999 > 0$
EUR/USD									
Prop.	0.1041	-	-	0.09328	-	-	0.09434	-	-
Obs.	4092.	4092.	426.0	268.0	268.0	25.00	106.0	106.0	10.00
Mean	0.02390	0.5215	0.2295	0.05399	0.6906	0.5787	0.1066	0.8487	1.130
St. Dev.	0.1308	0.3728	0.3421	0.4540	0.6541	1.380	0.7096	0.6870	2.045
Skew.	12.15	3.708	4.501	14.23	3.365	4.233	9.185	2.669	2.444
Kurt.	191.6	26.85	26.17	218.4	18.15	20.06	89.73	11.29	7.338
Min.	0.0000	0.06499	0.01821	0.0000	0.08092	0.02400	0.0000	0.1227	0.06627
Max.	2.791	5.141	2.791	7.109	5.271	7.109	7.109	3.964	7.109
YEN/USD									
Prop.	0.1319	-	-	0.1502	-	-	0.1228	-	-
Obs.	3874.	3874.	511.0	486.0	486.0	73.00	114.0	114.0	14.00
Mean	0.02503	0.5938	0.1898	0.04000	0.7987	0.2663	0.03270	0.9041	0.2662
St. Dev.	0.1046	0.7364	0.2272	0.1320	0.8446	0.2359	0.1040	0.8282	0.1610
Skew.	10.45	23.89	5.174	4.809	4.320	1.870	3.564	2.895	0.4806
Kurt.	177.5	986.9	41.92	31.31	31.29	6.858	15.96	13.86	2.792
Min.	0.0000	0.04106	0.01962	0.0000	0.05862	0.03101	0.0000	0.1198	0.04015
Max.	2.511	33.03	2.511	1.176	9.164	1.176	0.6315	5.621	0.6315

Table 4: Descriptive statistics for significant jumps ($\alpha = 0.9999$) and the corresponding continuous component of RV as described in Equation (15). The three parts of the table correspond respectively to days without CBIs, with a unilateral or coordinated intervention and finally days associated with a coordinated intervention of both central banks. Note that the third column of each part contains descriptive statistics for significant jumps conditional on a jump day, i.e. the statistics are computed over non-zero jumps. The first Panel of the table corresponds to the EUR/USD market and the second to the YEN/USD. The rows are: proportion of jumps in the sample, observations, mean, standard deviation, skewness, kurtosis, minimum of the sample and maximum.

Two main results emerge from these tables. First, one cannot reject that the likelihood of a jump is independent of intervention. This result holds both for all intervention days and for the days in which concerted operations took place. For instance, the proportion of days with significant jumps when a coordinated intervention was conducted by the Fed and the Bundesbank (or the ECB) on the EUR/USD market is slightly lower (0.094) than the one observed on the non-intervention days (0.104). This suggests that if interventions affect exchange rate volatility, they are not associated with an abnormal probability of jumps. Second, while the proportion of jumps on the intervention days is not significantly higher, jumps are bigger when there is an intervention. This is obviously the case for the EUR/USD. The ratio of the size of jumps between intervention days and non-intervention days amounts to 2.52 and 4.92 for respectively all types of operations and concerted interventions. Therefore, while one cannot obviously claim that interventions systematically create jumps on exchange rates, there is evidence that a subset of these interventions were associated with large discontinuities in exchange rates. Because the evidence that intervention is associated with unusually large jumps is stronger for coordinated operations, the subsequent analysis will focus on such concerted operations.

4.2 Jumps and CBIs: some further causality analysis

The previous results suggest that several jumps occurred the day of a coordinated intervention.

Table 4 identifies 10 and 14 coordinated interventions days for which at least one significant jump was detected at the 1% level in the EUR/USD and the JPY/USD markets, respectively. Such a preliminary evidence does not imply that those interventions created the jumps in the FX markets, however, for two reasons.

The first reason is of course related to reverse causality. As emphasized by recent contributions in the literature (Kearns and Rigobon 2004, Neely 2005b, Neely 2005a), interventions are not conducted in a random way and tend to react rather to exchange rate developments. This implies that statistical analysis of interventions should devote special attention to determining the direction of causality. As pointed out by Neely (2005b), this is particularly important to account for when conducting the investigation at the daily frequency.

The second reason why causal links between interventions and jumps might be spurious is the presence of macroeconomic announcements. These macro announcements are known to create jumps in the FX markets (Andersen, Bollerslev, Diebold, and Vega 2003).

4.2.1 Jumps and CBIs: intra-daily investigation

One way to investigate the possible direction of the causality between jumps and interventions is to look at the intra-daily patterns of these events.

Unfortunately, one cannot obtain the precise times of intervention because such times were not recorded by the trading desks of most major central banks. Auxiliary information permits this unavailability to be overcome. One possibility is to use the timings of the newswire reports of those operations, as proposed by Dominguez (2004) for Fed interventions. While potentially useful, this approach presents drawback in that it is unclear whether the timing of the reports is consistent with that of the actual operations. Using real-time data of the interventions of the Bank of Swiss, Fischer (2005) shows that significant discrepancies in terms of timings emerge between Reuters reports of the interventions and the actual operations of the Swiss monetary authorities. Some of these differences are expressed in hours and not in minutes.

An alternative approach to the use of these reports is to start from the stylized fact that most of the central banks tend to operate within the predominant business hours of their countries (Neely 2000). An investigation of the empirical distributions of the report timings of the Fed, the Bundesbank and the BoJ interventions corroborates this stylized fact (Dominguez 2004). Furthermore, European and US, monetary authorities tend to intervene in concert during the overlap of European and U.S. markets to maximize the signalling content of these operations. This stylized fact is supported by the timing of Reuters news collected over the 1989-1995 period.[7] Although the timing of the Reuters reports should be used with some caution, most coordinated intervention headlines fall within the overlap of the markets, suggesting that the assumption that coordinated interventions occur in the afternoon European time is not too strong.This means that at least for the EUR/USD market, the timing of these jumps can be compared to this time range. Jumps occurring before the overlap period probably cannot be ascribed to these coordinated interventions.Instead, such jumps might motivate intervention. Intervention might well cause the discontinuities observed during the overlap.

Intra-daily timing of jumps

We first assume that coordinated interventions occur during the overlap in the opening hours of the financial markets in Europe and the US. To get a precise time for the jumps, we find the maximum intra-daily absolute exchange rate return. For both exchange rates (dollar/euro

[7] Olsen and Associates provided Reuters headlines for the days of G-3 intervention from 1989 to 1995. Dominguez (2002) previously used these data for intraday analysis.

and JPY/dollar), we focus on days on which there was both intervention and a discontinuity in the exchange rate. Panel 1 of Figure 5 reports the distribution of the time interval with the highest intra-daily return for all the intervention days (coordinated or unilateral interventions) in the EUR/USD, while Panel 2 gives the same information but only for days of coordination interventions.

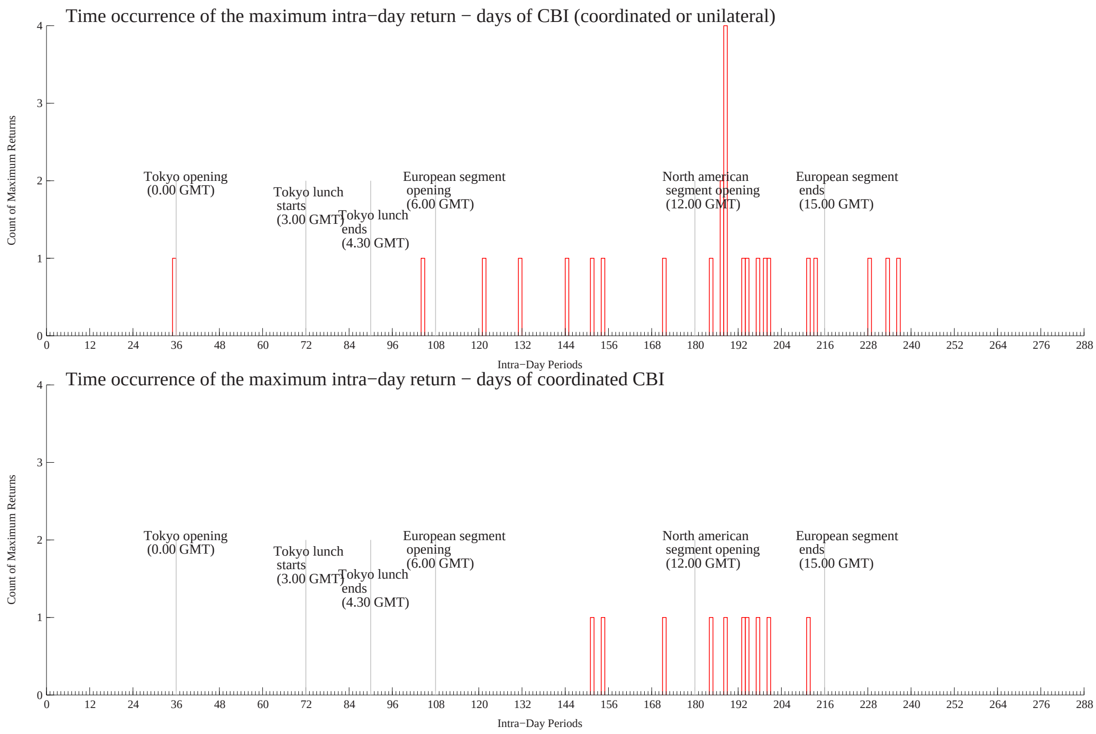

Figure 5: **Dollar/Euro - Fed and BB intervention days (Panel 1: coordinated or unilateral. Panel 2: coordinated) where a jump occurred)**. Count of daily maximum intra-day returns per intra-day periods. The graph shows, for each intra-day period, how many days have their maximum intra-day return at the intra-day interval in question.

Panel 2 of Figure 5 shows that for 7 out of 10 events, the maximum intra-daily exchange rate return falls within the short overlap period of U.S. and European markets. Therefore, for those 7 coordinated intervention episodes, coordinated operations might have created the jumps. Of course, other events, like macro announcements also might have created the discontinuities. Panel 1 of Figure 5, however, also includes days of unilateral interventions. In the case of unilateral operations, the central banks can intervene over the full course of the day because there is not need to coordinate. Interestingly, the discontinuities were much more dispersed on the days of unilateral intervention. This is consistent with the idea that intervention is related to the jumps.

The same investigation might also be conducted for the interventions days on the JPY/USD market. In this case, however, the lack of overlap between U.S. and Japanese markets leaves the likely timing of coordinated intervention ambiguous. Nevertheless, for the sake of completeness, we provide the corresponding figures for the all-type intervention days as well as the days of coordinated interventions (see Figure 6).

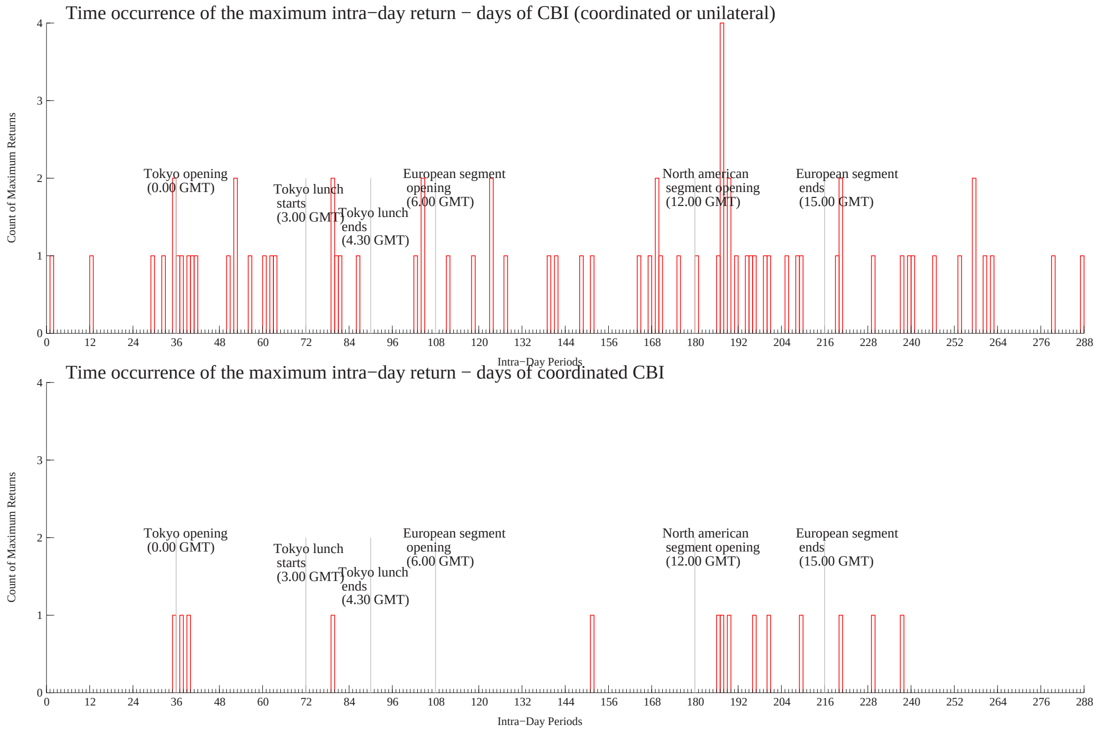

Figure 6: **JPY/Dollar - Fed and BoJ intervention days (Panel 1: coordinated or unilateral. Panel 2: coordinated) where a jump occurred)**. Count of daily maximum intra-day returns per intra-day periods. The graph shows, for each intra-day period, how many days have their maximum intra-day return at the intra-day interval in question.

The previous informal timing evidence can be complemented by a more robust statistical analysis of the intra-daily patten of the exchange rate returns. The previous analysis neglects the fact that more than one jump can occur on a particular day. For instance, a second jump on the EUR/USD might occur during the overlap period, restoring the possibility that coordinated operation between the Fed and Bundesbank creates this jump. Therefore, it is possible that the previous conclusion regarding the causality link for a couple of interventions is misleading.

Tables 5 and 6 provide additional information with respect to the 10 CBI days where a jump occurred on the Euro/dollar market, and the equivalent 14 days for the JPY/dollar. For each date, we report the number of jumps we identify using the following procedure.If a day is found to contain one or more significant jumps, we neutralize the highest intra-day return (i.e. we fix it to zero) and re-estimate RV and BV. We then check whether we still observe a statistically significant jump quantity. If it is the case, we reiterate the procedure all over again: we set the second highest intra-day return to zero, re-estimate the jump and so on. We do so until the BV method fails to reject the null of no jumps. This allows to precisely identify which discontinuities contributed to make $\sum \kappa^2$ a statistically significant quantity. Tables 5 and 6 provide the number of significant jumps, the timing of the three highest intra-daily returns, the magnitude of $\sum \kappa^2$ and its ranking in the global unconditional sample.

Date	# jumps	Max #1 time	Max #2 time	Max #3 time	$\sum \kappa^2$	Global rank
1987-12-10	1	13.40	-	-	1.753219	8
1988-04-14	2	12.40	12.45	-	0.585892	31
1988-09-26	1	13.10	-	-	0.066267	383
1989-02-03	1	14.35	-	-	0.394049	59
1989-10-05	1	13.05	-	-	0.330991	70
1991-02-12	10	9.50	15.40	8.45	0.083371	340
1991-03-11	1	9.35	-	-	0.218730	122
1992-08-11	1	12.20	-	-	0.299545	77
1992-08-21	1	13.25	-	-	0.460832	46
2000-09-22	2	11.15	12.05	-	7.108620	1

Table 5: **Dollar/Euro - 10 days where a coordinated intervention occurred and a discontinuity ($\sum \kappa^2$) is detected.** For each date, we provide the number of jumps (# jumps), the time at which the three greatest intra-day returns occurred, the magnitude of the detected jump ($\sum \kappa^2$) and its rank in the global jump ranking (in the unconditional sample).

Table 5 suggests that two of the three intervention days, for which the highest intra-daily return occurred before the overlap period, had more than one significant jump. For these two days (February 12, 1991 and August 22, 2000), coordinated interventions during overlap period might have created the second jump, which occurred during the overlap period. For only one of the 10 days of coordinated interventions (March 11, 1991), there was no significant jump during

Date	# jumps	Max #1 time	Max #2 time	Max #3 time	$\sum \kappa^2$	Global rank
1987-04-10	2	12.35	0.10	-	0.310725	102
1987-04-24	1	3.35	-	-	0.312094	101
1987-11-30	1	0.05	-	-	0.086187	421
1988-04-14	1	12.45	-	-	0.424126	51
1988-10-31	3	14.25	8.00	16.20	0.122487	316
1989-09-29	1	0.15	-	-	0.236308	140
1989-10-05	1	13.20	-	-	0.337824	85
1989-11-20	1	16.45	-	-	0.040149	553
1990-01-18	1	13.40	-	-	0.043575	544
1992-02-18	5	9.35	8.10	0.40	0.196976	181
1994-05-04	1	12.30	-	-	0.283198	114
1994-11-02	1	16.05	-	-	0.454362	42
1995-04-03	1	23.55	-	-	0.631489	23
1995-07-07	11	15.20	12.50	13.40	0.247987	132

Table 6: **JPY/Dollar - 14 days where a coordinated intervention occurred and a jump ($\sum \kappa^2$) is detected.** For each date, we provide the number of jumps (# jumps), the time at which the three greatest intra-day returns occurred, the magnitude of the detected jump ($\sum \kappa^2$) and its rank in the global jump ranking (in the unconditional sample).

the overlap, which suggests that coordinated intervention was less likely to produce the jump.

The assumption that coordinated interventions take place only during the overlap is supported by some evidence but tenuous. Coordinated interventions might occur before or after the overlap period, suggesting that some other type of information should be used. One possibility is to use the timing of the Reuters reports of interventions for the 10 days for which jumps and interventions were detected on the Euro/dollar market. Nevertheless, the timing of these news reports is reliable only between 1989 and 1995. Before 1989, we infer timing of intervention from the level of exchange rate at which the reported intervention took place, obtained from news reports. Since it is likely that over the full course of the trading day this exchange rate level will be crossed several times, the are several possible timings for this report. We also must disregard the days for which multiple jumps were detected, such as December 12, 1992. All in all, we scrutinize 4 occurrences to infer the nature of the causal relationship between jumps and interventions.

Date	Timing of first jump	Timing of first report
1989-10-05	13.05	12.10
1991-03-11	9.35	9.45
1992-08-11	12.20	12.23
1992-08-21	13.25	13.34

Table 7: **Dollar/Euro - 4 days where a coordinated intervention occurred and one discontinuity ($\sum \kappa^2$) is detected.** For each date, we provide the date, the timing of the first jump and the timing of the Reuters news.

Table 7 report the date, the timing of the first jump and the timing of the Reuters news for these 4 days. For one day, the report of intervention comes before the jump, suggesting that we can reject the idea that intervention reacted to this jump in the exchange rate. For the three other days, the discrepancy in the timing between jump and intervention report is negative but rather small. Reports of intervention come at most 10 minutes after the occurrence of the jump. The fact that the reports of intervention follow the maximal return so very closely indicates to us that the intervention is likely to have preceded the jump and caused it, rather than the other way around. CBs need time to detect the jump, to react and to implement the currency orders. It is difficult to imagine that the CB is able to react in less than 3 minutes to the occurrence of jumps. Further, there is a lag between intervention and the time it is reported on the newswire, as documented by Fischer (2005). We believe that the most plausible interpretation is that intervention preceded and caused the jumps, but was reported after. We find it somewhat less plausible, but possible, that intervention created jumps that were used by traders to detect intervention (and to report the CB's presence in the market). This story is supported by some evidence provided by Gnabo, Laurent, and Lecourt (2006) for the yen/dollar market. While it is once more difficult to formally check this sequence of events with the current dataset, the evidence provided here tends to shed some doubts on a causal relationship running from jumps to interventions. Of course, given the very small sample, further investigation should be conducted in order to have more evidence on the possibility of a reversed causation, i.e. interventions creating jumps.

4.3 Regression analysis

Up to now, we have investigated the relationship between CBIs and the jump component of the RV. In seems that CBIs create only a small number of jumps.For instance, out of the 106 coordinated interventions of the Fed and the Bundesbank, only 7 or 8 interventions seem to have induced some jumps on the exchange rate, about as many as one would expect by chance. Although the probability of a jump seems to be independent of intervention, the intraday data do seem to strongly suggest that some coordinated interventions are very closely related to jumps and are plausibly the cause of those few jumps.

Most of the previous empirical studies of the impact of CBIs on exchange rate volatility find that CBIs tend to increase exchange rate volatility (see Humpage, 2003 for a recent survey). In particular, Dominguez (2004) and Beine, Laurent, and Palm (2005) find that intervention has a strong and robust impact on the realized volatility of the major exchange rates. The latter paper found that this result holds for concerted interventions, with impact lasting for a couple of hours. The analysis was carried out using hourly intra-daily returns for the EUR/USD market and focused on the period ranging from 1989 to 2001.

We first extend this regression by regressing $\log(RV_t)$ computed at 21.00 GMT on the dummies capturing days of interventions as well as a set day-of-the-week dummies to capture intra-weekly variation in the volatility of exchange rates.[8] In contrast to Beine, Laurent, and Palm (2005), the estimates of realized volatility are built from 5-minute intra-daily returns. Due to the fact that these estimates of daily volatility include the 288 previous squared returns, the impact of the interventions should be captured by the daily estimates of volatility event though this impact displays a low degree of persistence.

More formally, we allow for long memory in the volatility process and, following Andersen, Bollerslev, Diebold, and Labys (1999), estimate several specifications of the following ARFIMA$(1, d, 0)$ model:

$$(1 - \phi L)(1 - L)^d \left[\log(\sigma_t^2) - \mu\right] = \epsilon_t + \alpha_t + \mu_t, \tag{18}$$

where σ_t^2 is the daily realized volatility or its continuous component, and d (the fractional integration parameter), ϕ, μ are parameters to be estimated. We control for day-of-the-week seasonal effects through α_t

$$\alpha_t = \alpha_1 MONDAY_t + \alpha_2 TUESDAY_t + \alpha_3 WEDNESDAY_t + \alpha_4 THURSDAY_t, \tag{19}$$

[8] The extension of the investigation period is not trivial in the sense that it leads to a big increase in the number of days of coordinated and unilateral interventions. Indeed, while we observed 58 coordinated interventions over the 1989-2001 period, the inclusion of the years 1987 and 1988 leads to the inclusion of 48 additional coordinated interventions. This might be explained by the fact that this period belongs to the so-called post-Louvre agreement period during which concerted operations were conducted in order to get rid of excessive exchange rate volatility.

where $MONDAY_t$, $TUESDAY_t$, $WEDNESDAY_t$, and $THURSDAY_t$ are day-of-the-week dummies and α_1 to α_4 are additional parameters to estimate. Though we control for these variables, we do not report the estimates because that falls beyond the scope of this paper.

Moreover, we present results for two different specifications of μ_t. First, μ_t includes binary variable for unilateral and coordinated interventions of central banks on their respective markets (i.e. we consider effects of Fed and Bundesbank interventions, unilateral and coordinated, on the EUR/USD, and Fed and BoJ interventions, unilateral and coordinated, on the JPY/USD):

$$\text{EUR/USD: } \mu_t = \beta_1 BBU_t + \beta_2 FEDU_t + \gamma COORD_t, \tag{20}$$

$$\text{JPY/USD: } \mu_t = \beta_1 BOJUY_t + \beta_2 FEDUY_t + \gamma COORDY_t, \tag{21}$$

where α's, β's and γ are parameters to be estimated. BBU_t, $FEDU_t$, and $COORD_t$ are dummies for unilateral Bundesbank interventions, unilateral Fed interventions, and coordinated Bundesbank-Fed interventions on the EUR/USD market, respectively. $BOJUY_t$, $FEDUY_t$, and $COORDY_t$ are, mutatis mutandis, the corresponding dummies for unilateral BoJ interventions, unilateral Fed interventions, and coordinated BoJ-Fed interventions on the JPY/USD market.

Secondly, we look for a different relation of volatility with coordinated interventions on days with and without significant jumps ($\alpha = 0.9999$). The variables $COORD_t$ and $COORDY_t$ are thus splitted in two parts: $COORDJ$ and $COORDYJ$ for coordinated interventions on jump days, and $COORDNOJ$ and $COORDYNOJ$ for coordinated interventions on days where no jumps were detected. We then have the following specifications for μ_t:

$$\text{EUR/USD: } \mu_t = \beta_1 BBU_t + \beta_2 FEDU_t + \delta_1 COORDJ_t + \delta_2 COORDNOJ_t, \tag{22}$$

$$\text{JPY/USD: } \mu_t = \beta_1 BOJUY_t + \beta_2 FEDUY_t + \delta_1 COORDYJ_t + \delta_2 COORDYNOJ_t, \tag{23}$$

where δ's are additional parameters to estimate.

The results for the EUR/USD, reported in the left panel of Table 8, suggest that both unilateral interventions and coordinated interventions of the Fed and the BB tend to increase exchange rate volatility (second columns labeled '$\log(RV)$'). This is especially obvious for coordinated interventions whose impact is much bigger to those associated to unilateral operations.

Columns labeled '$\log(C)$' in Table 8 reports the same results for the log of the continuous part of the realized volatility as described in Equation (15). These results suggest that this component was related to intervention.The magnitude of the coefficients are quite similar between the second and third columns. Their level of significance is also strikingly similar. This suggests that CBIs

	EUR/USD				YEN/USD			
	$\log(RV)$	$\log(C)$	$\log(RV)$	$\log(C)$	$\log(RV)$	$\log(C)$	$\log(RV)$	$\log(C)$
d	0.427	0.440	0.430	0.441	0.449	0.453	0.450	0.453
	(0.017)	(0.017)	(0.017)	(0.017)	(0.017)	(0.017)	(0.017)	(0.017)
ρ	-0.026	-0.005	-0.025	-0.005	0.002	0.020	0.002	0.020
	(0.023)	(0.023)	(0.023)	(0.023)	(0.023)	(0.023)	(0.023)	(0.023)
μ	0.008	-0.218	0.039	-0.209	-0.553	-0.735	-0.551	-0.734
	(0.432)	(0.493)	(0.448)	(0.500)	(0.606)	(0.648)	(0.610)	(0.647)
β_1 (BBU/BOJUY)	0.078	0.078	0.078	0.078	0.233	0.215	0.233	0.215
	(0.045)	(0.043)	(0.045)	(0.043)	(0.024)	(0.024)	(0.024)	(0.024)
β_2 (FEDU/FEDUY)	0.122	0.116	0.122	0.117	0.136	0.120	0.136	0.120
	(0.047)	(0.044)	(0.047)	(0.044)	(0.065)	(0.064)	(0.065)	(0.064)
γ (COORD/COORDY)	0.429	0.401	-	-	0.403	0.400	-	-
	(0.040)	(0.038)	-	-	(0.040)	(0.040)	-	-
δ_1 (COORDJ/COORDYJ)	-	-	1.145	0.616	-	-	0.618	0.358
	-	-	(0.129)	(0.123)	-	-	(0.113)	(0.112)
δ_2 (COORDNOJ/COORDYNOJ)	-	-	0.353	0.378	-	-	0.373	0.406
	-	-	(0.042)	(0.040)	-	-	(0.043)	(0.043)
Log-Lik	-2277.267	-2052.033	-2260.172	-2050.332	-2439.464	-2397.787	-2437.415	-2397.706

Table 8: **Maximum likelihood estimation results for EUR/USD and YEN/USD**. This tables shows results for the estimation of the ARFIMA$(1, d, 0)$ model $(1-\phi L)(1-L)^d\left[\log(\sigma_t^2)-\mu\right] = \epsilon_t + \alpha_t + \mu_t$ where the dependent variable σ_t^2 represents the realized volatility (RV) or its continuous component (C) of the EUR/USD (left panel) and YEN/USD (right panel). α_t includes day-of-the-week dummies whose parameters are not reported here. Two specifications are retained for μ_t: $\mu_t = \beta_1 BBU_t + \beta_2 FEDU_t + \gamma COORD_t$ and $\mu_t = \beta_1 BBU_t + \beta_2 FEDU_t + \delta_1 COORDJ_t + \delta_2 COORDNOJ_t$ for the EUR/USD and $\mu_t = \beta_1 BOJUY_t + \beta_2 FEDUY_t + \gamma COORDY_t$ and $\mu_t = \beta_1 BOJUY_t + \beta_2 FEDUY_t + \delta_1 COORDYJ_t + \delta_2 COORDYNOJ_t$ for the YEN/USD. Standard errors reported in parenthesis.

are closely related to the continuous part of the realized volatility.

The last two columns of each panel of Table 8 report the same results obtained from regressing the log of realized volatility and the log of the continuous component on the intervention dummies. In contrast to the previous regressions, the specification accounts for a break down coordinated interventions between those found associated with the jumps (denoted $COORDJ$ in the Tables, 10 occurrences) and the remaining ones (denoted $COORDNOJ$, 96 occurrences). Coordinated interventions that are potentially associated with jumps have a strong correlation with realized volatility. This confirms the previous findings that when CBIs are associated with a jump, the size of the jump is higher and thus the impact on realized volatility is substantial. We find that coordinated interventions associated with jumps have also some impact on the continuous part. This is due to the fact that the decomposition of realized volatility between jumps and its continuous part is not perfect in the sense that the continuous component still includes a residual part of the jumps.

The right panel of Table 8 presents the same results for the JPY/USD. Reassuringly, the results are consistent with those obtained for the EUR/USD. To sum up, we found clear relation between coordinated interventions, realized volatility and its continuous component. Interventions associated with jumps display a bigger correlation with realized volatility and still have a relation with continuous volatility.

5 Interpretation of the findings and significance for central bank foreign exchange market policy

The empirical findings of this paper yield evidence that realized volatility of exchange rates between major currencies is driven by a persistent continuous component and an unpredictable jump component. The method of bipower variation permitted us to decompose realized volatility into these two components (see Barndorff-Nielsen and Shephard, 2004, 2005, and Andersen, Bollerslev, and Diebold, 2005).

The findings indicate that the jump component is important in the major foreign exchange markets. Coordinated interventions seem to generate jumps, though to a small extent. A more extended study of the factors that explain the occurrence of jumps would be interesting and relevant from a scientific point of view, as well as being potentially useful for hedging applications

On the whole, the findings confirm that CBIs are associated with increased exchange rate volatility.[9] Furthermore, there is some evidence that interventions tend to create jumps in the exchange rate volatility. A small number of interventions are found to be associated with jumps but jumps associated with interventions tend to be larger than normal. However, when this occurs, the size of the jumps is much bigger than the average size of jumps in the market. As a result, CBIs tend, on average, to be associated with high exchange rate volatility. Interventions are associated with the continuous part of the volatility process as well. This is confirmed by the regression analysis, in particular by the striking similarity between the results for realized volatility as a dependent variable and for the continuous component of exchange rate volatility.

The method for decomposing realized volatility into two components yields approximate results. There may be a remaining part of the jump left in the continuous component. If interventions had in fact been aimed at attenuating or eliminating jumps only, the finding that CBIs affect the continuous part could be due to an approximation error in the decomposition.

From the analysis of the timing of the occurrence of jumps there is much less evidence that the central banks react (almost instantaneously) to jumps in foreign exchange rates. This finding indicates that the causation is unidirectional in the sense that coordinated interventions by central banks affect jumps.Contrary to what one might have expected, there is little evidence of causation in the opposite direction from discontinuities to interventions.But interventions sometimes appear to produce significant discontinuities and are associated with higher a persistent continuous component of realized volatility.

Allowing for differences in the impact δ_i of interventions between days on which jumps occurred and days without jumps a likelihood ratio test leads conclude that the δ_i's significantly differ for $\log(RV)$ for the EUR/USD whereas for $\log(C)$ they are not significantly different form each other. For the JPY/USD, the δ_i's do not significantly differ from each other for $\log(RV)$ and for $\log(C)$. These findings suggests that on both markets, coordinated CBIs had the same positive association with the persistent part of realized volatility whether the market was prone to turbulences in the form of jumps (generated by interventions or by other factors) or not. On the EUR/USD market instead, coordinated CBIs seem to create jumps that are more than three times as large as those observed on other days.

Finally, it is worthwhile to point out that unilateral interventions by the Federal Reserve Bank and by the Bank of Japan are significantly positively associated with realized volatility and its

[9] See e.g. Beine, Laurent, and Palm (2005), Dominguez (1998) and Dominguez (2003).

continuous component. Unilateral interventions by the European Central Bank in the EUR/USD market are associated with higher volatility, but not to a statistically significant degree.

The finding of a positive association of CBIs with market volatility is consistent with predictions from both the inventory-based approach and the information-based approaches in the microstructure literature. The inventory-based approach (see e.g. O'Hara, 1995, and Lyons, 2001) emphasizes the balancing problem on foreign exchange markets resulting from (stochastic) inflows and outflows deviations. Such deviations could be the result of a policy intervention. Theory predicts that these deviations will be temporary and last until portfolios have been rebalanced. The information-based approach focuses on the process of learning and price formation on markets. In high volatility periods, much trading can take place as informed trades can easily hide the volume of their transactions. This approach predicts an increase in transactions volume and volatility following a CBI. Once the intervention news has been revealed, transaction volume, prices and volatility should revert to their pre-intervention levels. Longer-run effects are related to factors such as information processing. Turbulent market conditions might require more time to revert to their initial levels. Our findings are in line with both theoretical explanations. One should nevertheless realize that both approaches provide little insight into how long-run adjustment takes place.

6 Conclusion

Over the period 1985-2004, the Federal Reserve, the Bank of Japan and the Bundesbank/the European Central Bank intervened, on average, almost three times per month. It is perhaps not surprising to see central banks frequently intervening in markets that are of crucial importance for the international competitiveness.

In this paper, we studied the association of exchange rate volatility in the EUR/USD and the JPY/USD markets with a subset on CBIs. Our study is focused on the impact of coordinated CBIs on days on which these markets experienced turbulences in the form of jumps.

Next, this paper studied the causation in discontinuities and CBIs. This analysis provided evidence in favor of a unidirectional causation from interventions to the appearance of jumps.

In the analysis, coordinated CBIs were found to be significantly associated with both realized volatility and on its continuous component. These interventions might have had a short-run effect on volatility. They affect the jump component of realized volatility and they are also associated with the more persistent continuous component of foreign exchange rate volatility. Our analysis extended the existing literature by distinguishing continuous and jump components and by studying the impact of coordinated interventions on the jump components. The main findings that interventions are associated with higher exchange rate volatility however is in line with previous empirical studies and with predictions from the theoretical literature on the inventory-based and the information based approaches.

Before drawing strong conclusions about possible unintended adverse effects of CBIs on volatility in foreign exchange markets it would be sensible to study more deeply the caution issue. Questions which require more attention are for instance: Do central bank have insight information allowing them to predict turbulences and act on them on short notice? Would the turbulences/jumps in volatility have been more severe if central banks had not intervened? What is the role of macroeconomic announcements in generating turbulences on foreign exchange markets?

References

ANDERSEN, T. G., AND T. BOLLERSLEV (1998a): "Answering the Skeptics: Yes, Standard Volatility Models do Provide Accurate Forecasts," *International Economic Review*, 39, 885–905.

——— (1998b): "DM-Dollar volatility: intraday activity patterns, macroeconomic announcements and longer run dependencies," *The Journal of Finance*, 53, 219–265.

ANDERSEN, T. G., T. BOLLERSLEV, AND F. X. DIEBOLD (2005): "Roughing It Up: Including Jump Components in the Measurement, Modeling and Forecasting of Return Volatility," NBER Working Paper 11775.

ANDERSEN, T. G., T. BOLLERSLEV, F. X. DIEBOLD, AND P. LABYS (1999): "Realized Volatility and Correlation," L.N. Stern School of Finance Department Working Paper 24.

——— (2001): "The Distribution of Realized Exchange Rate Volatility," *Journal of the American Statistical Association*, 96, 42–55.

ANDERSEN, T. G., T. BOLLERSLEV, F. X. DIEBOLD, AND C. VEGA (2003): "Micro Effects of Macro Announcements: Real-Time Price Discovery in Foreign Exchange," *The American Economic Review*, 93, 38–62.

BAILLIE, R. T., AND W. P. OSTERBERG (1997): "Why do Central Banks Intervene ?," *Journal of International Money and Finance*, 16, 909–919.

BARNDORFF-NIELSEN, O., J. GRAVERSEN, J. JACOD, M. PODOLSKIJ, AND N. SHEPHARD (2005): "A central Limit Theorem for Realized Power and Bipower Variation of Continuous Semimartingale," in *From Stochastic Analysis to Mathematival Finance, Festschrift for Albert Shiryaev*, ed. by Y. Kabanov, and R. Lipster. Springer Verlag.

BARNDORFF-NIELSEN, O., AND N. SHEPHARD (2002a): "Econometric Analysis of Realised Volatility and its use in Estimating Stochastic Volatility Models," *Journal of the Royal Statistical Society*, 64, 253–280.

——— (2002b): "Estimating Quadratic Variation Using Realized Variance," *Journal of Applied Econometrics*, 17, 457–478.

——— (2004): "Power and bipower variation with stochastic volatility and jumps (with discussion)," *Journal of Financial Econometrics*, 2, 1–48.

——— (2005): "Econometrics of testing for jumps in financial economics using bipower variation," forthcoming in *Journal of Financial Econometrics*.

Beine, M., A. Bénassy-Quéré, and C. Lecourt (2002): "Central Bank Intervention and Foreign Exchange Rates: New Evidence from FIGARCH Estimations," *Journal of International Money and Finance*, 21, 115–144.

Beine, M., S. Laurent, and F. Palm (2005): "Central Bank Forex Interventions Assessed Using Realized Moments," Working Paper.

Bonser-Neal, C., and G. Tanner (1996): "Central Bank Intervention and the Volatility of Foreign Exchange Rates: Evidence from the Options Market," *Journal of International Money and Finance*, 15, 853–878.

Catte, P., G. Galli, and S. Rebecchini (1992): "Exchange Markets Can Be Managed!," Report on the G-7, International Economic Insights.

Comte, F., and E. Renault (1998): "Long Memory in Continuous Time Stochastic Volatility Models," *Mathematical Finance*, 8, 291–323.

Dominguez, K. M. (1998): "Central Bank Intervention and Exchange Rate Volatility," *Journal of International Money and Finance*, 17, 161–190.

——— (2003): "The Market Microstructure of Central Bank Intervention," *Journal of International Economics*, 59, 25–45.

——— (2004): "When Do Central Bank Interventions Influence Intra-daily and Longer-Term Exchange Rate Movements," Forthcoming in *Journal of Financial Economics*.

Fischer, A., and M. Zurlinden (1999): "Exchange Rate Effects of Central Bank Interventions: An Analysis of Transaction Prices," *Economic Journal*, 109, 662–676.

Fischer, Andreas, M. (2005): "On the Inadequacy of Newswire Reports for Empirical Research On Foreign Exchange Interventions," Swiss National Bank Working Papers 2005-2.

Galati, G., and W. Melick (1999): "Central Bank Intervention and Market Expectations: an Empirical Study of the YEN/Dollar Exchange Rate, 1993-1996," BIS Working Paper 77.

Gnabo, J., S. Laurent, and C. Lecourt (2006): "Does Transparency in Central Bank Intervention Policy Bring Noise in the Market? The case of the Bank of Japan," mimeo, University of Namur.

Huang, X., and G. Tauchen (2005): "The relative contribution of jumps to total price variation," *Journal of Financial Econometrics*, 3, 456–499.

Humpage, O. F. (2003): "Government Intervention in the Foreign Exchange Market," Federal Reserve Bank of Cleveland, Working Paper 03-15.

Kearns, J., and R. Rigobon (2004): "Identifying the Efficacy of Central Bank Interventions: Evidence from Australia and Japan," Forthcoming in *Journal of International Economics*.

Lyons, R. K. (2001): *The Microstructure Approach to Exchange Rates*. The MIT Press, Cambridge, MA.

Neely, C. J. (2000): "The Practice of Central Bank Intervention: Looking Under the Hood," Federal Reserve Bank Working Paper no. 2000-028.

——— (2005a): "An analysis of recent studies of the effect of Foreign Exchange Intervention," Federal Reserve Bank of Saint Louis, Working Paper no. 2005-03B.

——— (2005b): "Identifying the Effect of US Interventions on the Level of Exchange Rates," Federal Reserve Bank of Saint Louis, Working Paper no. 2005-031B.

O'Hara (1995): *Market Microstructure Theory*. Basic Blackwell, Basic Blackwell.