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Great Earthquakes, Exchange Rate Volatility and Government Interventions*

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Abstract

The Great East Japan Earthquake in 2011, as well as the Great Hanshin-Awaji Earthquake in 1995 and the Great Kanto Earthquake in 1923, resulted in disorderly movements of yen in the foreign exchange market. This paper investigates the exchange rate volatility shift after these three great earthquakes in Japan and examines if similar excess volatility after major earthquakes can also be observed in other countries. In addition, using a unique daily data set from the Great Kanto Earthquake period, the episode with the largest increased volatility among all three great earthquakes, we estimate a reaction function of foreign exchange market intervention, and evaluate the role of government intervention in stabilizing the foreign exchange market during the time of increased uncertainty caused by a large unexpected negative shock in the economy.

Keywords: foreign exchange intervention; natural disasters; propensity score

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1 Introduction

On March 11, 2011, the eastern area of Japan was hit by a major earthquake followed by tsunami, an event which resulted in an estimated capital stock losses of more than 210 billion US dollars. A week after this 'Great East Japan Earthquake,' in response to the resulting "excess volatility and disorderly movements" of the Japanese yen, the G-7 financial authorities announced that they would jointly intervene the foreign exchange market for the first time in ten years. While Japan is known for its very frequent earthquakes because of its geographical location surrounded by plate boundaries, devastating major earthquakes of this scale (magnitude) are considered rare events. In the past century, the two other major earthquakes prior to this one were the 'Great Kanto Earthquake,' which hit the Tokyo and Yokohama areas in 1923, and the 'Great Hanshin-Awaji Earthquake' which devastated the city of Kobe and its surroundings in 1995. Since all three great earthquakes occurred in populated areas, they had a larger negative impact on economic activities than any other natural disasters in modern Japanese economic history.

From the economic point of view, earthquakes can be interpreted as unexpected negative real shocks in the economy. Minor vibrations are frequently observed in Japan but they result only in negligible economic losses. In contrast, rare but disastrous quakes can significantly change nation's macroeconomic fundamentals, at least in the short-run. Because macroeconomic fundamentals are reflected in a nation's currency value in the foreign exchange market, we conjecture that increased uncertainty in fundamentals caused by major earthquakes increases the instability of exchange rates under the floating system. For example, the Japanese yen depreciated rapidly after the Great Kanto Earthquake in 1923, while it appreciated after both the Great Hanshin-Awaji Earthquake in 1995 and the Great East Japan Earthquake in 2011. In the past, the economic analysis of natural disasters has been conducted in various contexts.[1] However, to the best of our knowledge, there are no studies that focus on the effect

[1] For example, there are studies on natural disasters with foci on economic growth (Skidmore and Toya, 2002), national institutional quality (Kahn, 2005), international transfer (Strömberg , 2007) and consumption

of earthquakes or other natural disasters on the exchange rate volatility.

The objective of this paper is to empirically investigate the effect of earthquakes on the foreign exchange market and the role of subsequent government interventions, using historical time series data. In particular, we first statistically examine whether there was increased exchange rate volatility after the three great earthquakes in Japan. We show that, while the directions of change differed, all three great earthquakes were followed by a large exchange rate fluctuations in the short-run. We further examine if similar increased exchange rate volatility after earthquakes can be also observed in other countries under a flexible exchange rate regime. In the second half of the analysis, we focus on the Great Kanto Earthquake, the episode with the largest increased volatility among all three great earthquakes, and examine if government intervention was effective in stabilizing the foreign exchange market during the time of increased uncertainty caused by a large unexpected negative shock in the economy. By taking advantage of a unique data set from this period, we estimate a reaction function of foreign exchange market intervention and find that the Japanese monetary authorities were successful in stabilizing the exchange market.

Currency and financial crises, including the recent global financial crisis, are also well-known for generating instability in both the currency and equity markets, and their empirical characteristics have been extensively investigated using historical data by many studies including Kaminsky and Reinhart (1998, 1999), Eichengreen (2008) and Reinhart and Rogoff (2008, 2009), among others. Major earthquakes are similar to currency crises in the sense that they are negative shocks on economic activities that occur in much less often than in business cycle frequencies.[2] However, as argued in Kaminsky and Reinhart (1999), a currency crisis is often preceded by problems in the banking sector, and several types of warning indicators may be used to predict a future crisis. In contrast, the occurrence of earthquakes is impossible to predict so that a direct comparison of subsamples of before and after earthquakes is

risk-sharing (Sawada and Shimizutani, 2008).

[2] Using a representative consumer model, Barro (2009) shows that estimated welfare loss from rare disasters can be as large as 20 percent of real GDP compared to 1.5 percent loss from normal business cycle fluctuations.

possible.[3] This difference distinguishes our analysis from other empirical studies of economic crisis.

Our analysis is also closely related to the empirical literature on measuring the effect of foreign exchange market interventions (see Dominguez and Frankel, 1993, and Sarno and Taylor, 2001, for extensive surveys). A widely accepted view of the goal of government intervention is to stabilize the foreign exchange market.[4] Empirical evidence of the role of intervention in reducing the volatility of exchange rates is, however, rather mixed. For example, Baillie and Osterberg (1997) and Dominguez (1998) use daily data of interventions by US, German and Japanese central banks from the period around the Plaza and Louvre agreements and find weak evidence on reducing volatility. Further mixed evidence on the role of Japanese government intervention in reducing yen-dollar exchange rate volatility after 1990s is also reported by Chang and Taylor (1998), Nagayasu (2004), Watanabe and Harada (2006) and Hoshikawa (2008).

There are at least three notable features in our analysis of exchange market interventions that differ from the previous studies listed above. First, we use a newly constructed daily data set of exchange rates and interventions for the period before and after the Great Kanto Earthquake. This is the first formal empirical study on the effect of exchange market interventions in the 1920s. Second, unlike the previous analysis based on daily exchange rate data, our estimation suffers less from an endogenous bias problem because the fact of a slower decision-making process during 1920s has been confirmed by historical documents. In contrast, in the analysis based on the recent data, the endogeneity of the intervention needs to be incorporated by instrumental variables that are very difficult to find in daily data. Third,

[3]The Japanese government passed the Large-Scale Eathquake Countermeasure Act in 1978 so that the Japan Meteorological Agency (JMA) can operate a real-time monitoring system to detect any warning signals of major earthquakes. The system, however, failed to predict both the Great Hanshin-Awaji Earthquake in 1995 and the Great East Japan Earthquake in 2011.

[4]For example, in the recent post-earthquake coordinated intervention on March 18, 2011, G-7 financial authorities announced that: "As we have long stated, excess volatility and disorderly movements in exchange rates have adverse implications for economic and financial stability. We will monitor exchange markets closely and will cooperate as appropriate."

our data contains an official government target exchange rate, which helps us to identify the reaction function of monetary authorities. Because target rates are directly observed, there is no need for making assumptions on how target rates are determined.[5] We take advantage of the reaction function estimate and employ the propensity score method to evaluate the effectiveness of intervention in reducing the exchange rate volatility. This estimation strategy has been widely used to evaluate the average treatment effect in the microeconometric literature, but has recently attracted increasing attention in estimating the causal effect of policy variables using macroeconomic time-series, including Angrist and Kuersteiner (2011), among others.

The rest of the paper is organized as follows. In section 2, statistical evidence of increased volatility after major earthquakes is presented. Both historical results from three great earthquakes in Japan and earthquakes from other countries are reported. In section 3, using data from 1920s, we investigate the effectiveness of market interventions in reducing exchange rate volatility during a time of foreign exchange rate market instability caused by a major earthquake. Concluding remarks are provided in section 4.

2 Exchange Rate Volatility and Earthquakes

2.1 Japanese evidence

We first investigate the behavior of the daily yen-dollar exchange rate during the periods around three great earthquakes in Japan. Since earthquake occurrence cannot be predicted, it is safe to say that an earthquake has no effect on the exchange rates prior to the day of the earthquake. Thus, we can simply split the sample at the date each earthquake occurred and compare the behavior of exchange rates between two subperiods.[6] Figure 1 plots daily

[5] For example, Ito and Yabu (2007) assume that the target rate is determined as a function of past moving averages of exchange rates.

[6] Splitting the sample is a more difficult task in the analysis of financial or currency crisis. For example, a sudden depreciation of currency values in crisis is typically preceded by the overvaluation of the currency. Thus, to compare the empirical characteristics between the time of crisis and tranquil times, the latter is

yen-dollar exchange rate series from one year before the earthquake to one year after the earthquake.

Panel A of the figure shows yen-dollar exchange rates before and after the Great Kanto Earthquake, which occurred on September 1, 1923.[7] Prior to the earthquake, exchange rates were relatively stable around 2 yen per US dollar. After the earthquake, however, the yen depreciated dramatically and reached a level around 2.4 yen per US dollar during the first half of the following year. This 20 percent depreciation of the yen may reflect the market responses to the deterioration of macroeconomic fundamentals. According to Sawada and Shimizutani (2008), estimated housing property and capital stock losses from the Great Kanto Earthquake was 32.6 billion US dollars in 2003 prices, which is equivalent to 43.6 percent of Japanese GDP in 1923. In consequence, real GDP and export in 1923 dropped by 4.6 percent and by 10.3 percent, respectively, from the previous year.

Panel B of the figure shows yen-dollar exchange rates before and after the Great Hanshin-Awaji Earthquake, which occurred on January 17, 1995.[8] Unlike the yen's behavior after the Great Kanto Earthquake, within three months, the yen appreciated in this instance for about 20 percent. Within a year, however, the exchange rate swung back to the pre-earthquake level.

Panel C of the figure shows yen-dollar exchange rates before and after the Great East Japan Earthquake, which occurred on March 11, 2011. As in the case of the Great Hanshin-Awaji Earthquake, the yen appreciated rapidly to 76.25 yen per dollar, which was at that time the highest exchange rate recorded after World War II.

While the directions of change in the exchange rate differ, Figure 1 shows that all three great earthquakes seem to cause increased exchange rate fluctuations.[9] Let us turn to the

typically selected at 18 or 36 months prior to the crisis (see Kaminsky and Reinhart, 1998).

[7] The exchange rate series is constructed from the *New York Times* (see Data Appendix).

[8] The exchange rate series during this period as well as the period around the Great East Japan Earthquake is obtained from Bloomberg.

[9] A standard international real business cycle model predicts that an unexpected sudden reduction of the capital stock causes the appreciation of real exchange rates. While we focus on nominal exchange rate fluctuations in this paper, we also examine (monthly) real exchange rates around three great earthquakes

issue of possible change in a volatility. In this paper, we employ two measures of volatility, the absolute deviation and variance. Following the literature on the efficient market hypothesis, a white noise assumption is imposed on exchange rate growth, $\Delta s_t = s_t - s_{t-1}$, where s_t is the nominal yen-dollar exchange rate in logs. Since the mean exchange rate growth is not significantly different from zero, we here impose the zero drift condition and only report uncentered first absolute sample moments and uncentered second moments.[10] Table 1 shows the descriptive statistics on the volatility before and after the earthquakes, using various windows. The left panel of Table 1 shows the sample absolute deviation while the right panel shows the sample variance. The sizes of the windows in computing the statistics are measured in business days. On the whole, both measures show higher volatility after the earthquake than before the earthquake. This result, however, somewhat varies depending on the choice of windows. In the following analysis, we employ the 120-day-window pre-earthquake volatility as a benchmark value of tranquil times to compare with the post-earthquake volatility. While this choice of window is somewhat arbitrary, the good news is that the regime shift from the tranquil period is unpredictable so that the effect of earthquake is certainly excluded from the pre-earthquake volatility measure.

For post-earthquake volatility, the window choice should depend on the timing of regime shift from a turbulent regime to a tranquil regime. Unlike the abrupt transition at the time of an earthquake, however, a gradual transition is expected from a turbulent regime to a tranquil regime. Historical evidence from the Great Kanto Earthquake, which will later be explained in detail, also suggests that the effect of an earthquake on the economy persists for at least one year. Because of these issues, we consider both 120 business days (approximately six months) and 240 business days (approximately one year) as reasonable window sizes of the post-earthquake volatility measures. If we compare the benchmark pre-earthquake volatility

and find that yen-dollar rates appreciated for all three episodes, consistent with the economic theory. This is due to increased wholesale prices in Tokyo area immediately after the Great Kanto Earthquake. However, for both real and nominal exchange rates, volatility is increased after the earthquakes.

[10] Results are almost identical even if we replace uncentered sample moments with recentered (demeaned) sample moments.

measure based on a 120-day-window and the post-earthquake volatility measures based on 120- and 240-day-windows, volatility is higher after the earthquake for all three events. In the next section, we statistically test for regime shift in volatility as well as providing additional international evidence.

Before we move on to further analysis, let us briefly mention the frequency of government intervention during these periods. When we use a 120-day-window before and after the earthquake, the number of interventions increased from 12 to 29 during the period of Great Kanto Earthquake. In case of the Great Hanshin-Awaji Earthquake, the frequency of interventions increased from 19 to 36. In addition, coordinated interventions increased from 2 to 5. Finally for the Great East Japan Earthquake, the number increased from 0 to 2, and the first involved coordinated interventions by G7. In section 3, we further investigate the determinants and effects of the intervention using the data from the period around the Great Kanto Earthquake.

2.2 International evidence

We now extend our analysis of the previous section to international data to see if similar increased volatility in the exchange rate can be commonly observed across countries. For an obvious reason, we restrict our attention to the period after 1973 when the floating exchange system started among major countries. The EM-DAT is an international database on natural disasters compiled by the Center for Research of the Epidemiology of Disasters (CRED).[11] Among the natural disasters recorded in EM-DAT after 1973, we select countries and events that satisfy the following three conditions: (i) natural disasters classified as either earthquakes or tsunamis; (ii) estimated loss from the disaster is above 5 percent of GDP; and (iii) the exchange rate regime classified by IMF is neither fixed nor pegged to other currencies within ± 5 percent from the central rate.[12] When we apply these criteria, 8 countries and 9 episodes

[11] The data can be obtained from EM-DAT: The OFDA/CRED International Disaster Database (http: www.emdat.be), Université Catholique de Louvain, Brussels, Belgium.

[12] The classification is based on IMF's *Annual Report on Exchange Arrangements and Exchange Restrictions.*

are selected, and their daily exchange rate series from the period around the earthquakes are obtained from Bloomberg.[13] Note that earthquakes in Italy in 1980 and Greece in 1999 have been selected in our sample since the currency bands of two countries were within ± 6 percent and ± 15 percent, respectively, from the central rate. In contrast, the Sichuan earthquake of 2008 in China is excluded because the IMF classified China as a 'crawling peg' around the time of the earthquake. In addition, while the IMF's classification of Georgia was either 'independent floating' or 'managed floating with no pre-annouced path for the exchange rate' around the time of the earthquake in 2002, it is excluded from our sample since the daily exchange rate data shows that rates did not change for more than 70 percent of the time.

Table 2A summarizes the results of international comparison including the three great earthquakes in Japan. The first column shows the mean absolute deviation of tranquil time based on a 120-day-window. The volatility of tranquil times varies across countries. The smallest volatility is found in the pre-Great Kanto Earthquake period in Japan. The largest volatility is found in Algeria. The second and third columns show the absolute deviation ratios using post-earthquake period volatility based on 120-day- and 240-day-windows, respectively. The ratio above one corresponds to the case of increased volatility after earthquakes. The absolute deviation ratio is greater than one for 11 out of 12 events when a 120-day-window is used for both before and after the earthquake. The ratios clearly show that the Great Kanto Earthquake stands out in terms of the relative change in the volatility. When a 120-day-window for the post earthquake period is replaced by a 240-day-window, somewhat weaker evidence is obtained with the number of increased volatility reduced from 11 to 9. This indicates that a gradual transition from a turbulent regime to a tranquil regime may be completed between 6 months and 1 year in some countries. The fourth to sixth columns represent corresponding measures based on sample variance. Similar to the absolute deviation, increased variance is observed in majority of the countries.

Let V_t be a realized volatility measure defined either by $V_t = |\Delta s_t|$ or $V_t = (\Delta s_t)^2$. To

[13] An exception is Turkey which is obtained from the Central Bank of Turkey.

conduct a formal test on whether the volatility is increased after the earthquake, we run the following regression:

$$V_t = \alpha_0 + \alpha_1 DEQ_t + u_t \tag{1}$$

where u_t is a zero mean regression error term and DEQ_t is a dummy variable which takes a value 1 after the earthquake and 0 before the earthquake. In regression analysis, we use the same 120-day-window before and after the earthquake, which results in a sample of size 240. We report the heteroskedasticity- and autocorrelation-consistent (HAC) standard errors to incorporate the possibility of serial correlation. We further extend the simple regression analysis of the variance shift ($V_t = (\Delta s_t)^2$) to the time-varying conditional heteroskedasticity with a variance shift by estimating a GARCH(1,1) model given by

$$\begin{aligned} \Delta s_t &= \sqrt{h_t}\varepsilon_t \\ h_t &= \omega_0 + \omega_1 DEQ_t + \omega_2 \varepsilon_{t-1}^2 + \omega_3 h_{t-1} \end{aligned} \tag{2}$$

where $\omega_0 > 0$, $\omega_0 + \omega_1 > 0$, $\omega_2 \geq 0$, $\omega_3 \geq 0$ and $\varepsilon_t \sim iidN(0,1)$.

Table 2B reports ordinary least squares (OLS) estimates of the regression model (1) and maximum likelihood estimates of the GARCH model (2). Coefficients on earthquake dummies in two volatility regressions are significantly positive for the Great Kanto Earthquake and the Great Hanshin-Awaji Earthquake, and are positive but not significant for the Great East Japan Earthquake. In the GARCH model, coefficients on earthquake dummies are significantly positive for all three Japanese great earthquakes. In the case of Italy, all the coefficients from volatility regressions and GARCH estimation are significantly positive. In the case of both Taiwan and Algeria, estimates from GARCH model are positive and significant. For Sri Lanka, α_1's are significantly positive for two volatility dummy regressions but not for the GARCH estimate. If we consider testing the null hypothesis of $\alpha_1 \geq 0$ or $\omega_1 \geq 0$ against the alternative of $\alpha_1 < 0$ or $\omega_1 < 0$, the null cannot be rejected for all cases at the 5 percent level. Thus, on the whole, statistical evidence seems to support our conjecture of increasing volatility after major earthquakes.

3 Post-Earthquake Foreign Exchange Market Interventions: A Case Study

3.1 Data and historical background

Prior to WWI, Japan held foreign exchange reserves as well as gold. During the 1920s, as Japan recorded persistent current account deficits, the yen tended to be under strong downward pressures.[14] The monetary authorities used intervention to curb fluctuations of the yen. The government and the Bank of Japan (hereafter BOJ) started selling their foreign currency denominated assets to private banks in early 1919 (Saito, 1982). Previous studies reveal that, in the 1920s, sales were initially conducted to finance imports and then the purpose shifted into affecting the level of foreign exchange rates.[15]

The foreign exchange markets during the 1920s developed in terms of both the volume and technology.[16] London was the leading market and New York followed (Cassis, 2006).[17] The market participants were exchange brokers, dealers and for long term bills transactions, large commercial firms were active players as well. Japanese and other foreign banks fell in one of the important categories of dealers (Madden and Nadler, 1935). The practice of

[14] The yen at the time was floating as Japan was temporarily off the gold standard system. For details, see the Historical Appendix.

[15] Saito (1982) states that the object of the sales evolved into supporting yen exchange rates in October 1921 when the government directed the Yokohama Specie Bank to keep its quotation rates at 48 dollars per a hundred yen and sold foreign exchanges to it at the same time. Ito (1989) states that sales became policy tools to support exchange rates in September 1922 when the finance minister Ichiki explicitly showed the intention of conducting foreign exchange sales for the purpose of absorbing the negative effects of gold embargo on foreign exchange rates.

[16] The "generalized floating" with more opportunities for speculations led to an increase in trading volume in major trading centers, and the trading practices and technology were developed during this "boom" period. Before WWI, the brokers met bi-weekly at the Royal Exchange in London. In the post-WWI period, the trading through telephone or telegrams became more common in major markets (Takahashi, 2009; Evitt, 1931).

[17] Currencies of European countries, Canada, Mexico, China, India, the Philippine Islands, Java, Japan, Straits Settlement and South American countries were actively traded in the New York market (Madden and Nadler, 1935).

recording and publishing foreign exchange rates was prevalent in major trading centers by the late nineteenth century (Flandreau and Jobst, 2005). In some markets, such as London and New York, newspapers and magazines were the primary media for publication. Market rates in these media were the prices quoted by dealers and were collected by each paper or magazine (Evitt, 1931).

Considering the circumstances described above, we construct a daily series below for the purpose of investigating the effects of foreign exchange interventions around the time of the Great Kanto Earthquakes (for details, see the Data Appendix). First, two series of daily data sets for foreign exchange rates are constructed: yen exchange rates against the US dollar in the New York market; and official quotations of yen/dollar. It is likely that the latter refers to "official quotations by the Yokohama Specie Bank (*Shokin Tatene*)," which were supposed to be rates offered by the Yokohama Specie Bank (YSB) to its customers. However, they were considered as a kind of policy target by the government and quoted rates often diverged from actual trading rates.[18] Figure 2 shows the development of market yen-dollar exchange rates and target rates (official quotations by the YSB). The value of the yen against the US dollar peaked out in October 1922. The Great Kanto Earthquake occurred in September 1923 and its aftermath brought the depreciation of the yen rate to the level around 2.22 yen per dollar at the end of 1923 and then to 2.60 yen next year end.[19] The year of 1925 saw the reverse of this yen-depreciating trend. In the regression analysis, we denote this target rate in logs by s_t^*.

Second, data series for sales and purchases of foreign exchanges by the BOJ or by the

[18]For example, the YSB was instructed by the monetary authorities to keep its quotation at the level of 48 dollars per hundred yen in 1921 even though market rates fell below this line (Saito, 1982). The YSB had a mixed ownership, with the government holding a third of YSB's capital when it was established in 1880. The bank's primary role was to provide trade finance, and it played a large part in Japan's foreign exchange policies. It held reserves for official bodies as overseas agencies for the BOJ during the interwar period.

[19]The trade balance after the earthquake created a depreciating pressure on yen rates. The earthquake caused the sharp decline in exports as the City of Yokohama, which was heavily hit by the disaster, was the centre of raw silk exports. Stocks for exports there were lost owing to fire and the loss amount was equivalent as one tenth of raw silk exports in previous year. In the meantime, reconstruction materials were imported, leading to increase in imports (Bank of Japan Research Department, 1933; Shikata, 1926).

government through the BOJ are constructed from BOJ accounting books. Every single transaction by the BOJ, including those on behalf of the government regarding the sales of foreign currencies to private banks, is recorded in ledgers, and thus, the details of interventions such as dates, amounts and counterparties are available. Figure 3 shows the amounts of intervention. The dollar-selling interventions were conducted 60 times between April 1922 and September 1925, with the total amounts of 208 million dollars. There was only one example of the dollar-purchasing intervention on September 4 1924, and it was for the amount of 21 million dollars. Since one observation is not sufficient in statistical analysis, we focus on the dollar-selling interventions in the following section and use an intervention dummy variable, $IINT_t$, that takes a value one for such an intervention.

Third, the data series for outstanding foreign exchange reserves on a daily basis are constructed from the archival documents of the BOJ. Figure 4 shows the outstanding foreign exchange reserves, which will be denoted by FXR_t in the subsequent analysis. It follows declining trends in the 1920s, reflecting a series of interventions under the persistent current account deficits. In the mid 1920s, the government shifted its major policy tools for controlling foreign exchange rates from intervention to gold shipments.[20]

3.2 Volatility regression and government intervention

The daily exchange rate data shows a large amount of increased volatility after the Great Kanto Earthquake. At the same time, we observe that frequency of intervention increased after the earthquake. Since we are interested in knowing the interaction between increased volatility caused by the earthquake and government intervention, we focus on the effectiveness of intervention in terms of reducing the volatility of the exchange rate.

Theoretically, intervention can have an effect on the level of exchange rates, the volatility

[20]The Ministry of Finance issued the statement on September 16, 1926 entitled "The Statement on the Domestic Specie Shipments," declaring that "the government has decided to ship its domestic specie abroad if necessary. The first shipment will be carried out on the 20th of this month with four million dollars." (Materials on Japanese Monetary History, vol. 21, p.391, authors' translation).

of exchange rates or both the level and volatility at the same time. The effectiveness of intervention is typically justified either through the portfolio channel or signaling channel. Dominguez (1998) emphasizes the signaling channel and discusses the possibility of reducing the volatility without changing the level of exchange rate if intervention signals are fully credible and unambiguous and if the market is efficient.[21] She uses daily data on G-3 central bank interventions from the 1977-1994 period and finds that only overt interventions in the mid-1980s reduced volatility, but not overt interventions in other periods and secret interventions. In our analysis, we assume a simple random walk process for the exchange rate but consider the role of government intervention in stabilizing the foreign exchange market by estimating the variance structure of the random walk innovation.

In the evaluation of the effectiveness of interventions based on the recent data, the endogeneity of interventions needs to be incorporated either by using instrumental variables or specifying the full model. However, finding instrumental variables, which are correlated with the exchange rate but uncorrelated with the error term, is an extremely difficult task in the context of daily observations.

In contrast, unlike the previous analysis based on daily exchange rate data, our estimation suffers less from an endogenous bias problem because of the slower decision-making process that characterizes the 1920s. The typical decision making process for intervention is as follows. The government sets a policy of conducting sales operations in the foreign exchange market, which is often announced by high government officials.[22] Each private bank engaged in foreign exchange business requests the BOJ to sell its officially held foreign currencies, with the reason being its future shortage of foreign currencies. The bank in question, the BOJ and the Ministry of Finance (MOF) go through the negotiation process about the amounts

[21] In particular, Dominguez (1998, p. 167) states that "if the information being signalled via intervention is that the central bank is comitted to reducing volatility (potentially the Louvre Accord interventions), then we should expect intervention to be associated with no systematic effect on the level of the exchange rate and with lower exchange rate variances."

[22] For example, the Finance Minister Ichiki stated "considering the negative effect of the gold embargo on foreign exchange rates, we adopt this policy to enable us to sell foreign exchange reserves in future" on September 16, 1922 (Materials on Japanese Monetary History, vol. 21, p. 389, authors' translation).

of the sales and dates for transactions. When the negotiation is completed, the private bank submits the formal request form to the BOJ, and the BOJ passes the request to the MOF. The MOF then issues the permission for transactions. Usually the whole process took more than one business day.[23] In other words, within-day exchange rate movements cannot trigger interventions on the same day.

Another important issue considered in the literature of exchange rate intervention is the possibility of the regime shift. For example, Kearns and Rigobon (2005) proposed using simulated GMM with the assumption of a known break date of intervention policy change. Ito and Yabu (2004) also allow that parameters vary across regimes in Japan. Since, in the previous section, we found a structural shift in volatility at the time of the earthquake, we also consider the possibility that the effect of intervention is regime-dependent.

As discussed in Section 2, the end of the post-earthquake period is not clearly defined since a smooth transition from a turbulent regime to a tranquil regime is more likely than an abrupt transition. For this reason, we check the robustness of the result by using two different samples in which the end periods differ. Each end period is selected based on a notable policy event that is likely to reflect some change in the government's view on economic conditions. The first sample (labeled as Full sample 1) ends on September 16, 1925. This corresponds to the date that main exchange rate policy instrument of Japanese monetary authorities switched from interventions to gold shipments. The second sample (labeled as Full sample 2) ends on April 15, 1925. This is the date when the BOJ lowered the official interest rate. For both cases, the sample starts on April 1, 1922 which is the earliest possible date available in our data set.

[23] As an example, the Daihyaku Bank submitted the formal request to the BOJ on July 18, 1923, asking to provide 300,000 dollars on July 20. The letter from Daihyaku Bank to the BOJ dated on July 20 notified that it paid the Japanese yen equivalent as the amount paid by the BOJ in dollars on that day. On the same day, the BOJ sent a letter to the MOF, reporting that the dollar sales were conducted with Daihyaku Bank (source: Document 13266 in the data appendix). As another example, in the case of the dollar sales to the YSB settled on May 31, 1922, the record of the telephone conversation between the BOJ and the YSB reveals that the negotiation had started before May 24 (source: Historical Materials 0076 in the data appendix).

The volatility model that we estimate has the following linear specification:

$$\begin{aligned} V_t &= \alpha_0 + \alpha_1 DEQ_t + \alpha_2 V_{t-1} \\ &+ \alpha_3 IINT_t + \alpha_4 IINT_{t-1} + \alpha_5 DEQ_t \times IINT_t + \alpha_6 DEQ_t \times IINT_{t-1} \\ &+ \beta' Z_t + u_t \end{aligned} \tag{3}$$

where V_t is either $V_t = |\Delta s_t|$ or $V_t = (\Delta s_t)^2$, $IINT_t$ is an indicator that takes value 1 on days when there are dollar-selling (yen-purchasing) interventions and 0 otherwise, and Z_t is a vector of additional covariates. The earthquake dummy, DEQ_t, is an exogenous variable and thus there is no endogeneity. The intervention dummy, $IINT_t$, is typically treated as an endogenous variable but for the reason explained in the previous section, the OLS estimation remains valid. The lagged V_t is also included to allow for the possibility of GARCH effects when the variance measure is used.

Tables 3A and 3B show the results of the estimation based on the absolute deviation and variance, respectively, using both Full sample 1 and Full sample 2. For additional covariates included in Z_t, we consider lagged interest differentials between Japan and the US ($RJAPAN_{t-1} - RUS_{t-1}$) and the lagged deviation of the spot exchange rate from the target rate ($s_{t-1} - s^*_{t-1}$). Estimated coefficients on additional covariates are not reported in tables. For other coefficients, estimates are reported along with the HAC standard errors.

Let us first look at the coefficient on the earthquake dummy, namely, α_1. For both absolute deviation and variance measures, α_1's in all the specifications are positive and significant at the 5 percent level. These results are consistent with our previous finding of increased volatility after the earthquake. For the absolute deviation, the estimated coefficients α_2's on the lagged volatility are positive and significant. When variance is used, α_2's are also positive and significant unless additional covariates are included, implying some possibility of GARCH structure.

We are mainly interested in coefficients on the interaction term of the earthquake dummy and the intervention dummy, namely, α_5 and α_6. When absolute deviation is used, α_6 is significantly negative but α_5 is not significant for all the specification. For the variance measure, similar results are also obtained at a somewhat higher significance level. This shows that the intervention during the post-earthquake period is effective in reducing one-period-ahead volatility. In contrast, no instantaneous effect of interventions on volatility is found through our analysis. When we consider the market conditions at the time, the effect of intervention appearing on the next business day can be explained by the slow spread of information in the market. Typically, only a counterparty of the transaction, say the YSB, and monetary authorities knew about the intervention on the same day but not other market participants.[24]

The remaining coefficients α_3 and α_4 capture the effect of intervention during the pre-earthquake period. For all the cases, neither α_3 nor α_4 is significant. This shows there is no evidence supporting the role of intervention in reducing volatility during tranquil times.

In summary, our OLS estimates suggest that interventions reduce the exchange rate volatility of the next business day during the period after the Great Kanto Earthquake. In the next section, we use an alternative procedure to evaluate the effect of intervention by taking advantage of the target exchange rate series available in our data.

3.3 Policy propensity score and volatility treatment effects

Using the OLS method, we find that an intervention operation today, represented by $IINT_t$, reduces the exchange rate volatility on the next business day, represented by V_{t+1}, during the post-earthquake period. Because of the reason we stated before, our basic OLS estimates of the effect of intervention are not likely to suffer from an endogeneity problem. However, the validity of OLS estimates still relies on the assumption that the dynamic structure of exchange rate volatility is correctly described by equation (3). Alternatively, we can

[24] The details of the intervention often appeared in newspapers and other media that were not available on the day of intervention.

directly estimate the volatility treatment effect without specifying the full model of exchange rate volatility dynamics if a reliable estimate of government reaction function is available. In what follows, we employ an alternative estimation strategy using the propensity score method to evaluate the effect of $IINT_t$ on V_{t+1}.[25]

Our data contains the official government target exchange rate, which helps us to identify the reaction function of monetary authorities. Because target rates are directly observed, there is no need for making assumptions on how target rates are determined. We can thus take the advantage of the reaction function estimate and employ the propensity score method to evaluate the effectiveness of intervention in reducing the exchange rate volatility. While the idea of the propensity score has recently been employed by Fatum and Hutchison (2010) in their study on interventions, no studies have employed the propensity score-based method to investigate the effect on exchange rate volatility.[26]

As a reaction function of government intervention, we specify the probit model given by

$$IINT_t = \begin{cases} 1 \text{ if } y_t^* = \gamma' X_t + \varepsilon_t > 0 \\ 0 \text{ otherwise} \end{cases} \tag{4}$$

where

$$\gamma' X_t = \gamma_0 + \gamma_1 \Delta s_{t-1} + \gamma_2 (s_{t-1} - s_{t-1}^*) + \gamma_3 FXR_{t-1} + \gamma_4 IINT_{t-1}$$

and $\varepsilon_t \sim iidN(0,1)$.

Table 4 shows the results of maximum likelihood estimation of the probit model (4). The results can be summarized as follows. First, the estimated coefficient on the lagged exchange rate changes is negative, which implies the lean-in-the-wind intervention, but it is not statis-

[25] Angrist and Pischke (2008, p. 84) provide the rationale of using the propensity score as follows: 'A philosophical argument is that the propensity score rightly focuses researcher attention on models for treatment assignment, something about which we may have reasonably good information, instead of the typically more complex and mysterious process determining outcomes. This view seems especially compelling when treatment assignment is the product of human institutions or government regulations, while the process determining outcomes is more anonymous (e.g., a market).'

[26] In addition, Fatum and Hutchison (2010) used the nearest-neighbor propensity score matching method, which is known to be less efficient than the method used in our analysis.

tically significant. Second and most importantly, the coefficient on the lagged deviation from the target rate is positive and significant. This outcome shows that if closing rate of yen in the New York market is valued below the target rate, a yen-purchasing intervention is likely to be conducted. Third, the coefficient on the foreign exchange reserves is positive and significant. When reserves decrease, the result shows that monetary authority is likely to avoid the dollar-selling (yen-purchasing) intervention to prevent further decline in reserves. Finally, the coefficient on interventions on the previous business day is positive and significant, thus the intervention today is more likely to be followed by another intervention the next day.

Subsample estimates do not differ much from the full sample case except for the significance of some coefficients. Before the earthquake, the coefficient of the deviation from the target is still positive but not significant. For two subsample cases after the earthquake, the sign of lagged intervention coefficients is positive but not significant. For other coefficients, the results are very similar to the full sample case. Overall, our probit estimation of the reaction function is satisfactory, and thus we use the estimate to compute the policy propensity score.

Following Angrist and Kuersteiner (2011), we employ the conditional independence assumption (CIA) of the following form:

$$V_{t+1} \perp IINT_t | X_t$$

where $\perp$ denotes the independence, random variables to the right of the vertical bar are the conditioning sets and $V_t = |\Delta s_t|$ or $V_t = (\Delta s_t)^2$. Combining the CIA with the probit model (4) implies that, when X_t is given, the volatility does not depend on unobservable factors in the determination of the intervention which are represented by ε_t in (4). We define the volatility treatment effect by $VTE = E[V_{1t+1} - V_{0t+1}]$ where V_{1t+1} and V_{0t+1} are potential volatility outcomes at time $t + 1$ in case of an intervention and no intervention at time t, respectively. In the case of $V_t = (\Delta s_t)^2$, the volatility treatment effect corresponds to $\sigma_1^2 - \sigma_0^2$ where σ_1^2 is the variance of the random walk innovation with intervention and σ_0^2 is the variance of the random walk innovation without intervention.[27] If an intervention has an effect on reducing the exchange rate volatility, we expect the volatility treatment effect to be negative.

In what follows, we evaluate the volatility treatment effect by using the inverse propensity score weighting estimator given by

$$\widehat{VTE} = \sum_{t=1}^{T} \frac{(IINT_t - \widehat{p}(X_t))\, V_{t+1}}{\widehat{p}(X_t)\,(1 - \widehat{p}(X_t))}$$

where $\widehat{p}(X_t)$ is the estimated propensity score from equation (4). Under the CIA, this estimator is known to be free of selection bias even if not all potential outcomes are observed. We evaluate the precision of the estimate by reporting the 95 percent confidence intervals obtained from a block bootstrap method.[28] For the purpose of comparison with our inverse propensity score weighting estimator, we also report a simple estimator of volatility treatment effects using the regression adjustment based on the propensity score.[29]

Table 5 reports estimates of volatility treatment effects using various subsamples. First, for the full sample estimate, which ignores the effect of earthquake, the treatment effects are negative but small both in terms of absolute deviation and variance. The confidence interval contains both positive and negative values. This result is likely to be the reflection of mixing both pre-earthquake and post-earthquake samples even if the intervention works differently in two regimes. The regression adjustment estimates are very close to the inverse probability weighting estimate.

Second, for the pre-earthquake subsample, volatility treatment effects turn out to be positive. However, the confidence interval contains the negative range as well. This result is consistent with the OLS estimate in the previous subsection, and shows that intervention did

[27] A similar treatment effect on variance has also been considered by Firpo (2010) in the context of a policy effect on cross-sectional income dispersion.

[28] The block length in the bootstrap is set at five business days.

[29] The regression adjustment is based on an auxiliary regression of the form: $V_{t+1} = \alpha_0 + \alpha_1 IINT_t + \alpha_2 \widehat{p}(X_t) + u_{t+1}$ where α_1 is the volatility treatment effect. A symmetric confidence interval from a naive standard error is reported.

not contribute much in reducing the exchange rate volatility in the tranquil regime with low volatility.

Third, for the post-earthquake subsample, negative volatility treatment effects are obtained with much less negative value than the full sample case. Thus, during the post-earthquake period when volatility is high, intervention is effective in reducing the volatility of exchange rates. The confidence intervals show that their upper bounds are still less negative than the point estimate of the full sample case. This main finding of our paper is robust even if we change the measure of volatility from absolute deviation to variance, or use alternative post-earthquake subsample periods. The regression adjustment method also provides results similar to those from the inverse propensity score weighting method.

4 Conclusion

In the case of three great earthquake in Japan, we found evidence of increasing volatility of exchange rates in the post-earthquake period compared to the pre-earthquake period. For other countries suffering from earthquakes of similar magnitude in terms of economic losses, we also found evidence of increased volatility. We conjecture that these observations reflect the fact that a devastating earthquake increases uncertainty about the nation's future economic fundamentals.

Using data from the Great Kanto Earthquake episode, where increased relative volatility was highest among the three great earthquakes, we found that government intervention was indeed effective in reducing the volatility of exchange rates. We also note that the effectiveness of the intervention can only be found in the period of increased uncertainty caused by the earthquake but not in the tranquil times preceding the earthquake.

Data Appendix

Data used in the analysis of exchange market interventions from the 1920s are constructed from the following sources.

1. Yen exchange rates against the US dollar in the New York market (s_t): Closing rates in the New York market applied to transactions through cables (source: *New York Times*).

2. Official quotations of yen/dollar (s_t^*): It is likely that this series involves "official quotations by the Yokohama Specie Bank (*Shokin Tatene*)," judging from its development, although no notes are available in the historical material from which the data are taken. Figures after 1927 are identical as official quotations by the YSB in Table II, History of the Yokohama Specie Bank, vol. 6 (source: "Financial Summary Tables [Kinyu Yoryaku], Bank of Japan Institute for Monetary and Economic Studies Archives, documents 14277-14291).

3. Sales of foreign exchanges by the BOJ or by the government through the BOJ (used to construct $IINT_t$): In ledgers, the dates of the settlements for intervention are recorded. We assume the transaction dates are two business days prior based on the fact that two business days routinely elapsed from the submission of a formal request to the settlement of the transaction in four out of ten cases in which all documents regarding the intervention procedures are preserved in 1923 (sources: "Detailed Accounting Books for US dollar for the New York Agency [Nyu Yohku Dairiten Beika Meisai Cho], Bank of Japan Institute for Monetary and Economic Studies Archives, documents 46118, 46120, 46186; the Master Ledger for the US Dollar and Gold for the New York Agency [Nyu Yohku Dairiten Beika narabini Jigane Motocho], Bank of Japan Institute for Monetary and Economic Studies Archives, documents 46116, 46181; "Documents for the Sales of Overseas Specie [Zaigai Seika Baikyaku Kankei Syorui]," Bank of Japan Institute for Monetary and Economic Studies Archives, Document 13266).

4. Foreign exchange reserves (FXR_t): The sum of deposits held by the government and the BOJ in foreign currency. The holdings of foreign exchanges by the government and the BOJ were called as overseas specie (zaigai seika in Japanese). Short-term securities held by the government and the BOJ, which are sometimes included in overseas specie, are excluded here. The effect of a one-off transfer from the gold account on August 30, 1922 is adjusted. For the details of the components of foreign exchange reserves, see Hatase and Ohnuki (2009) (source: "Financial Summary Tables [Kinyu Yoryaku]," Bank of Japan Institute for Monetary and Economic Studies Archives, documents 14277-14291). The foreign exchange reserves defined here indicate the availability of funds for foreign exchange intervention in the short run. If necessary, the government sold securities and funds obtained through the transaction was transferred to deposit accounts to replenish foreign exchange reserves. It should be noted that the overall foreign exchange policy at the time was affected not only foreign exchange reserves defined here but also by the total amount of specie including gold.

Regarding the timing of decisions on exchange market interventions, descriptions can be found in the following historical documents left by the BOJ, by the Ministry of Finance (MOF) and the Yokohama Specie Bank (YSB): "Documents for the Purchases of Overseas Specie by the Government and the BOJ 2/2 [Seifu oyobi Honko Zaigai Seika Kaiire Kankei Syorui]," Bank of Japan Institute for Monetary and Economic Studies Archives, Document 6517; "Documents for the Sales of Overseas Specie by the Government and the BOJ [Seifu oyobi Honko Zaigai Seika Baikyaku Kankei]," Bank of Japan Institute for Monetary and Economic Studies Archives, Document 13211; "Documents for the Sales of Overseas Specie [Zaigai Seika Baikyaku Kankei Syorui]," Bank of Japan Institute for Monetary and Economic Studies Archives, Document 13266; "Documents for the Sales of Specie [Seika Haraisage ni Kansuru Shorui]," Yokohama Specie Bank Historical Materials, Microfilm Edition, Second Period, 0076.

Historical Appendix

The international monetary system in the interwar period was under transition, from the pre-WWI classical gold standard system to the gold-exchange standard, with the intermission of gold convertibility by major countries. Under the classical gold standard, a country pegged the value of its currency to gold at a fixed official price and, consequently, to major currencies that were under the gold standard.

As pointed out by Eichengreen (1992), the early 1920s is considered as a generalized floating period as major countries suspended the gold standard after the outbreak of WWI in 1914. The restoration of the international gold standard system was delayed until the mid 1920s. When a country was off the gold, foreign exchange rates could freely fluctuate. It was common for the monetary authorities to use devices such as gold shipments, exchange-market interventions and exchange controls to dampen foreign exchange rate fluctuations (Eichengreen, 1992).

This period of floating was followed by the gold-exchange standard, under which foreign exchange reserves were included in addition to gold as the legal reserve against notes in circulation or against notes and sight deposits (Nurkse, 1944). The adoption of the gold-exchange standard was officially recommended at the Genoa Conference in 1922, and major countries followed this resolution in returning to gold.

According to Flandreau and Jobst (2005), Japan was considered at the time a peripheral country in the international monetary system, its monetary system developed with a certain extent of deviation from that of major countries. It declared a gold embargo in September 1917, and the yen-dollar rate departed from the pre-WWI parity, about 2.005 yen per dollar (49.875 dollars per a hundred yen). A series of negative factors, such as Japan's weak external position, the aftermath of the Great Kanto Earthquake and the financial crisis in 1927, prevented Japan from returning to the gold standard. The foreign exchange rates continued floating until January 1930 when Japan eventually returned to gold.

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Table 1. Exchange Rate Volatility Before and After Japanese Great Earthquakes

		Absolute Deviation				Variance			
		20days	60days	120days	240days	20days	60days	120days	240days
Great Kanto Earthquake	Before	0.028	0.033	0.055	0.055	0.002	0.003	0.010	0.010
1923/9/1	After	0.103	0.089	0.238	0.298	0.029	0.031	0.243	0.267
Great Hanshin-Awaji Earthquake	Before	0.402	0.342	0.411	0.466	0.348	0.224	0.300	0.441
1995/1/17	After	0.343	0.607	0.620	0.627	0.194	0.802	0.857	0.853
Great East Japan Earthquake	Before	0.301	0.360	0.374	0.444	0.162	0.235	0.239	0.403
2011/3/11	After	0.776	0.526	0.469	0.401	1.145	0.559	0.461	0.359

Notes: Sample absolute deviation and sample variance of changes in the log of yen/dollar exchange rates, Δs, based on 20-, 60-, 120- and 240-day-windows.

Table 2A. International Comparisons: Volatility Ratio

		Absolute Deviation			Variance		
		Benchmark	Absolute Deviation Ratio		Benchmark	Variance Ratio	
		Before	After / Before		Before	After / Before	
Country	Date	120days	120days/120days	240days/120days	120days	120days/120days	240days/120days
Japan	1923/9/1	0.055	4.302	5.390	0.010	23.435	25.717
	1995/1/17	0.411	1.507	1.524	0.300	2.858	2.843
	2011/3/11	0.374	1.254	1.073	0.239	1.927	1.499
Italy	1980/11/23	0.330	1.866	1.936	0.210	3.156	3.327
Turkey	1998/8/17	0.281	1.059	1.026	0.127	1.123	1.044
Greece	1999/9/7	0.452	1.077	1.119	0.356	1.213	1.249
Taiwan	1999/9/21	0.164	1.145	0.874	0.098	3.804	2.010
Algeria	2003/5/21	0.618	1.114	1.087	1.160	1.430	1.389
Sri Lanka	2004/12/26	0.100	2.286	1.686	0.024	9.682	5.314
Chili	2010/2/27	0.529	0.961	0.896	0.482	0.812	0.834
NZ	2010/9/4	0.355	1.045	1.114	0.211	1.054	1.201
	2011/2/22	0.371	1.142	0.953	0.222	1.295	0.953

Notes: Ratio of the post-earthquake period volatility to the pre-earthquake period volatility. Volatility measures are sample absolute deviation and sample variance. The (benchmark) pre-earthquake period volatility is based on 120-day-window. The post-earthquake period volatility is based on 120- and 240-day-windows.

Table 2B. International Comparisons: Regression Analysis

		OLS				GARCH			
		$V = \|\Delta s\|$		$(\Delta s)^2$					
Country	Date	α_0	α_1	α_0	α_1	ω_0	ω_1	ω_2	ω_3
Japan	1923/9/1	0.054**	0.182**	0.010**	0.234*	0.000	0.003**	0.159**	0.862**
		(0.008)	(0.072)	(0.003)	(0.143)	(0.000)	(0.001)	(0.056)	(0.040)
	1995/1/17	0.412**	0.211**	0.302**	0.562**	0.189**	0.187**	0.215**	0.286
		(0.034)	(0.084)	(0.045)	(0.201)	(0.064)	(0.071)	(0.070)	(0.193)
	2011/3/11	0.376**	0.095	0.241**	0.224	0.112**	0.076*	0.161**	0.416*
		(0.030)	(0.068)	(0.037)	(0.152)	(0.055)	(0.046)	(0.052)	(0.225)
Italy	1980/11/23	0.328**	0.285**	0.210**	0.456**	0.036**	0.121**	0.193**	0.620**
		(0.038)	(0.064)	(0.070)	(0.142)	(0.015)	(0.052)	(0.080)	(0.112)
Turkey	1998/8/17	0.279**	0.012	0.122**	0.013	0.066	0.004	0.000	0.266
		(0.011)	(0.016)	(0.012)	(0.017)	(0.074)	(0.011)	(0.000)	(0.819)
Greece	1999/9/7	0.446**	0.041	0.350**	0.085	0.118**	0.026	0.000	0.665**
		(0.028)	(0.046)	(0.050)	(0.084)	(0.040)	(0.019)	(0.000)	(0.100)
Taiwan	1999/9/21	0.164**	0.024	0.098*	0.276	0.048**	0.085**	0.354**	0.183**
		(0.033)	(0.087)	(0.059)	(0.240)	(0.008)	(0.008)	(0.112)	(0.078)
Algeria	2003/5/21	0.599**	0.091	1.105**	0.567	0.099**	0.158**	0.104**	0.765**
		(0.128)	(0.176)	(0.395)	(0.545)	(0.039)	(0.066)	(0.041)	(0.069)
Sri Lanka	2004/12/26	0.100**	0.128*	0.024**	0.212*	0.004**	0.001	0.439**	0.600**
		(0.015)	(0.066)	(0.006)	(0.129)	(0.001)	(0.002)	(0.100)	(0.046)
Chili	2010/2/27	0.529**	-0.025	0.484**	-0.097	0.079**	-0.002	0.174**	0.642**
		(0.063)	(0.074)	(0.117)	(0.127)	(0.017)	(0.023)	(0.054)	(0.034)
NZ	2010/9/4	0.355**	0.015	0.212**	0.011	0.055	0.002	0.000	0.746**
		(0.023)	(0.032)	(0.021)	(0.035)	(0.036)	(0.010)	(0.000)	(0.171)
	2011/2/22	0.371**	0.049	0.223**	0.061	0.207	0.056	0.000	0.074
		(0.023)	(0.033)	(0.028)	(0.043)	(0.351)	(0.104)	(0.000)	(1.549)

Notes: OLS estimates of equation (1) and maximum likelihood estimates of the GARCH model (2) with their standard errors in parentheses. Heteroskedasticity- and autocorrelation-consistent (HAC) standard errors for OLS. The number of observations is 240. **Significant at the 5 percent level. *Significant at the 10 percent level.

Table 3A. The Effect of Interventions: Absolute Deviation

	Full Sample1 1922/4/1-1925/9/16						Full Sample 2 1922/4/1/-1925/4/15					
	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(i)	(ii)	(iii)	(iv)	(v)	(vi)
α_0	0.062**	0.043**	-0.037	0.061**	0.043**	-0.047	0.062**	0.044**	0.026	0.061**	0.044**	0.007
	(0.007)	(0.006)	(0.102)	(0.007)	(0.006)	(0.100)	(0.007)	(0.006)	(0.127)	(0.007)	(0.006)	(0.123)
α_1	0.207**	0.153**	0.123**	0.208**	0.155**	0.121**	0.234**	0.177**	0.147**	0.233**	0.177**	0.141**
	(0.026)	(0.020)	(0.021)	(0.025)	(0.020)	(0.020)	(0.031)	(0.026)	(0.033)	(0.030)	(0.025)	(0.031)
α_2		0.275**	0.222**		0.275**	0.224**		0.259**	0.214**		0.259**	0.217**
		(0.049)	(0.055)		(0.048)	(0.054)		(0.052)	(0.059)		(0.051)	(0.057)
α_3	-0.033	-0.022	-0.034				-0.033	-0.022	-0.036			
	(0.042)	(0.040)	(0.041)				(0.042)	(0.040)	(0.041)			
α_4	0.109	0.104	0.095	0.098	0.097	0.084	0.109	0.104	0.094	0.098	0.097	0.083
	(0.112)	(0.110)	(0.112)	(0.105)	(0.103)	(0.105)	(0.112)	(0.110)	(0.112)	(0.105)	(0.103)	(0.105)
α_5	0.034	0.044	0.000				0.012	0.027	-0.011			
	(0.086)	(0.075)	(0.064)				(0.087)	(0.076)	(0.067)			
α_6	-0.274**	-0.266**	-0.309**	-0.263**	-0.256**	-0.301**	-0.297**	-0.284**	-0.320**	-0.288**	-0.276**	-0.310**
	(0.115)	(0.114)	(0.120)	(0.110)	(0.106)	(0.112)	(0.116)	(0.114)	(0.121)	(0.111)	(0.107)	(0.113)
Z	NO	NO	YES	NO	NO	YES	NO	NO	YES	NO	NO	YES
OBS	1051	1050	1050	1051	1050	1050	922	921	921	922	921	921
R^2	0.103	0.171	0.208	0.104	0.171	0.209	0.125	0.182	0.213	0.126	0.185	0.215

Notes: OLS estimates of equation (3) with dependent variable $V = |\Delta s|$. Heteroskedasticity- and autocorrelation-consistent (HAC) standard errors are given in parentheses. Inclusion of additional covariates in the regression is indicated by Z, and OBS denotes the number of observations.

**Significant at the 5 percent level.

*Significant at the 10 percent level.

Table 3B. The Effect of Interventions: Variance

	Full Sample 1 1922/4/1-1925/9/16						Full Sample 2 1922/4/1/-1925/4/15					
	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(i)	(ii)	(iii)	(iv)	(v)	(vi)
α_0	0.020**	0.016**	-0.092	0.017**	0.014**	-0.118	0.020**	0.017**	-0.008	0.017**	0.014**	-0.053
	(0.009)	(0.007)	(0.154)	(0.007)	(0.006)	(0.150)	(0.009)	(0.007)	(0.192)	(0.007)	(0.006)	(0.182)
α_1	0.185**	0.161**	0.103**	0.188**	0.165**	0.100**	0.222**	0.195**	0.133**	0.223**	0.197**	0.124**
	(0.041)	(0.041)	(0.030)	(0.040)	(0.040)	(0.027)	(0.052)	(0.053)	(0.049)	(0.050)	(0.051)	(0.044)
α_2		0.141**	0.100		0.141**	0.102		0.130**	0.096		0.130**	0.099
		(0.062)	(0.077)		(0.062)	(0.076)		(0.063)	(0.078)		(0.063)	(0.076)
α_3	-0.100	-0.097	-0.118				-0.100	-0.097	-0.119			
	(0.088)	(0.087)	(0.088)				(0.088)	(0.087)	(0.088)			
α_4	0.249	0.250	0.231	0.215	0.217	0.193	0.249	0.250	0.229	0.215	0.217	0.191
	(0.243)	(0.243)	(0.246)	(0.221)	(0.222)	(0.226)	(0.243)	(0.243)	(0.246)	(0.221)	(0.222)	(0.225)
α_5	0.109	0.112	0.035				0.078	0.085	0.021			
	(0.140)	(0.131)	(0.126)				(0.142)	(0.134)	(0.129)			
α_6	-0.406*	-0.407*	-0.481*	-0.371*	-0.372*	-0.448*	-0.437*	-0.434*	-0.495*	-0.406*	-0.402*	-0.461*
	(0.246)	(0.246)	(0.256)	(0.225)	(0.224)	(0.236)	(0.247)	(0.247)	(0.258)	(0.227)	(0.226)	(0.238)
Z	NO	NO	YES	NO	NO	YES	NO	NO	YES	NO	NO	YES
OBS	1051	1050	1050	1051	1050	1050	922	921	921	922	921	921
R^2	0.029	0.048	0.090	0.031	0.049	0.089	0.038	0.062	0.089	0.040	0.055	0.089

Notes: OLS estimates of equation (3) with dependent variable $V = (\Delta s)^2$. Heteroskedasticity- and autocorrelation-consistent (HAC) standard errors are given in parentheses. Inclusion of additional covariates in the regression is indicated by Z, and OBS denotes the number of observations.

**Significant at the 5 percent level.

*Significant at the 10 percent level.

Table 4. Reaction Function (Probit)

	Full Sample 1	Full Sample 2	Pre-Earthquake Subsample	Post-Earthquake Subsample 1	Post-Earthquake Subsample 2
	1922/4/1-1925/9/16	1922/4/1-1925/4/15	1922/4/1-1923/8/31	1923/9/1-1925/9/16	1923/9/1-1925/4/15
γ_0	-4.278**	-4.192**	-5.632**	-4.199**	-4.043**
	(0.505)	(0.531)	(2.119)	(0.507)	(0.545)
γ_1	-0.016	-0.014	-0.370	-0.028	-0.024
	(0.217)	(0.216)	(0.915)	(0.212)	(0.211)
γ_2	0.205**	0.201**	0.327	0.179**	0.172**
	(0.034)	(0.034)	(0.243)	(0.035)	(0.036)
γ_3	0.020**	0.019**	0.027*	0.021**	0.020**
	(0.004)	(0.004)	(0.015)	(0.004)	(0.004)
γ_4	0.604**	0.607**	1.271**	0.156	0.162
	(0.199)	(0.199)	(0.328)	(0.255)	(0.255)
OBS	1050	921	430	620	491
Pseudo R^2	0.085	0.078	0.088	0.109	0.095

Notes: Maximum likelihood estimates of equation (4) with their standard errors in parentheses. OBS denotes the number of observations.

**Significant at the 5 percent level.

*Significant at the 10 percent level.

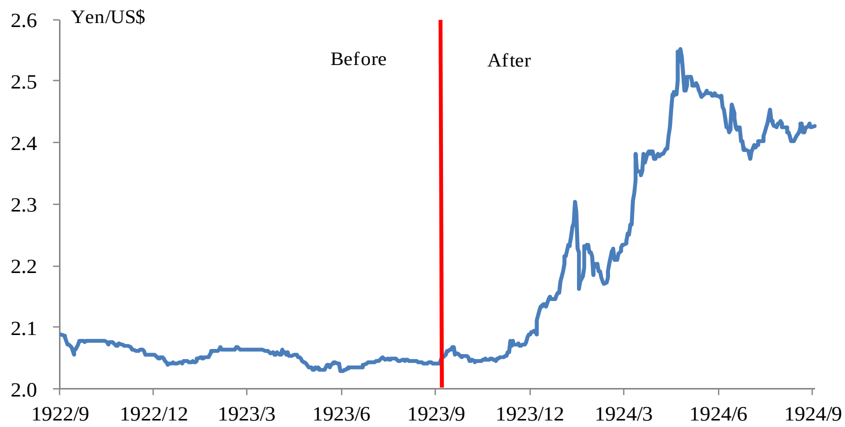
Table 5. Volatility Treatment Effect

V	Full Sample 1	Full Sample 2	Pre-Earthquake Subsample	Post-Earthquake Subsample 1	Post-Earthquake Subsample 2
	1922/4/1-1925/9/16	1922/4/1-1925/4/15	1922/4/1-1923/8/31	1923/9/1-1925/9/16	1923/9/1-1925/4/15
(i) Regression Adjustment					
$\|\Delta s\|$	-0.087	-0.087	0.112	-0.211	-0.215
	[-0.171, -0.004]	[-0.174, -0.001]	[0.039, 0.184]	[-0.331, -0.091]	[-0.342, -0.088]
$(\Delta s)^2$	-0.069	-0.071	0.251	-0.236	-0.242
	[-0.206, 0.069]	[-0.216, 0.075]	[0.131, 0.370]	[-0.442, -0.032]	[-0.470, -0.013]
(ii) Inverse Propensity Score Weighting					
$\|\Delta s\|$	-0.081	-0.081	0.133	-0.223	-0.227
	[-0.151, 0.014]	[-0.156, 0.020]	[-0.048, 0.465]	[-0.286, -0.160]	[-0.296, -0.157]
$(\Delta s)^2$	-0.026	-0.026	0.332	-0.209	-0.212
	[-0.149, 0.161]	[-0.154, 0.167]	[-0.011, 0.975]	[-0.303, -0.131]	[-0.319, -0.126]
OBS	1050	921	430	620	491

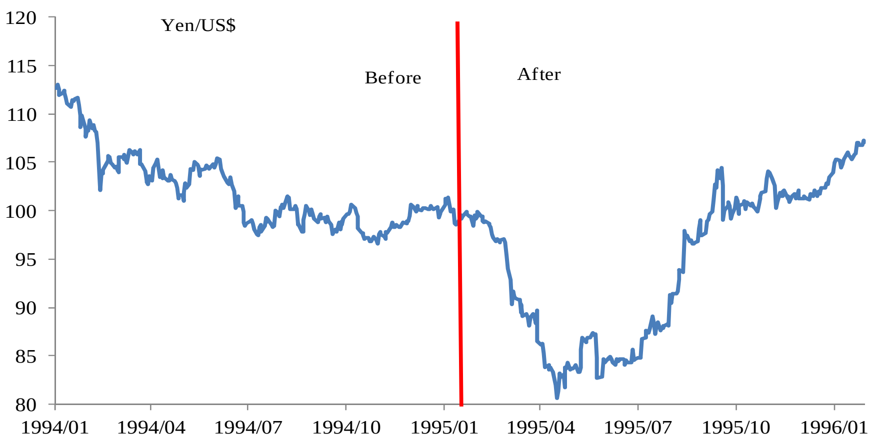
Notes: The upper panel shows the regression adjustment estimates of α_1 in the auxiliary regression: $V_{t+1} = \alpha_0 + \alpha_1 IINT_t + \alpha_2 \widehat{p}(X_t) + u_{t+1}$. The lower panel shows the inverse propensity score weighting estimates $\widehat{VTE}$. Numbers in brackets are the 95 percent confidence intervals. The confidence intervals for the regression adjustment estimates are based on heteroskedasticity- and autocorrelation-consistent (HAC) standard errors. The confidence intervals for the inverse propensity score weighting estimates are constructed using the block bootstrap method with a block length set at 5. The number of bootstrap replications is $10,000$. OBS denotes the number of observations.

Figure 1. Yen/Dollar Exchange Rate

(A) The Great Kanto Earthquake, September 1, 1923



(B) The Great Hanshin-Awaji Earthquake, January 17, 1995



(C) The Great East Japan Earthquake, March 11, 2011

Figure 2. Yen/Dollar Exchange Rate and Target Rate

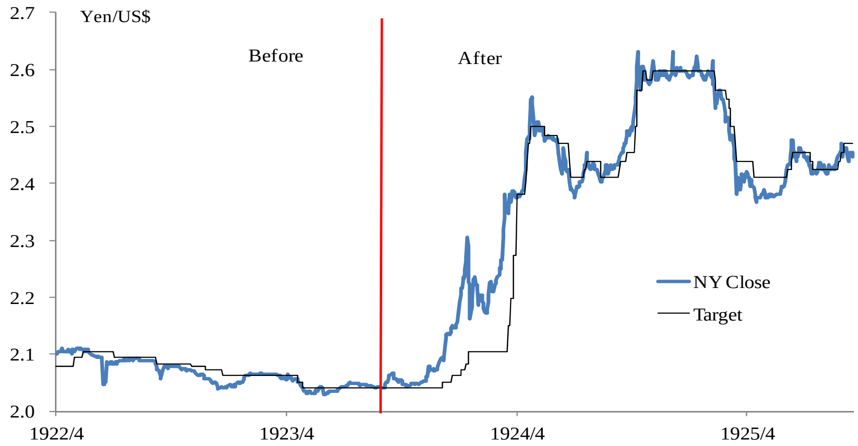


Figure 3. Amounts of Intervention

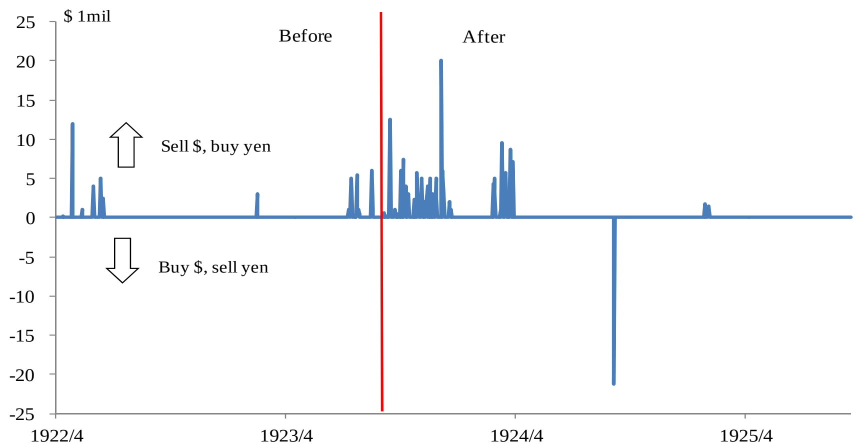


Figure 4. Foreign Exchange Reserves