Rare Disasters and Exchange Rates: An Empirical Investigation of South Korean Exchange Rates under Tension between the Two Koreas[1]

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Abstract: We investigate the implications of the disaster hypothesis proposed that changes in the probability of the outbreak of a rare disaster and/or expected damage caused by a rare disaster can make exchange rates fluctuate. Assuming that news articles reporting North Korea's actions that raise tensions on the Korean peninsula affect the probability and expected damage of a disastrous war in the region, we find that the South Korean exchange rate depreciates significantly in response to such news articles with the application of a nonparametric approach. We also show through an event study that the South Korean exchange rate depreciates significantly immediately after nuclear tests, although the duration of the significant depreciation is short. These findings are another piece of evidence for the exchange rate disconnect puzzle. Finally, we observe that the response of the exchange rate to news escalating tension levels in Korea varies over time and that the time variability of the response is similar to the habituation learning process.

Keywords: Rare disasters; Exchange rate; Nonparametric regression; Event study

JEL Classification: F31; G12; G14; G15.

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I. Introduction

Economists have thought that investors' consideration of rare but extreme disasters (e.g. World War I, the Great Depression, World War II, the Global Financial Crisis, etc.) has played an important role in the puzzling behaviors of financial assets. This idea was initiated by Rietz (1988) and has been revived and formalized by Barro (2006), Barro and Ursua (2008), Barro and Jin (2011), Wachter (2013), and Farhi and Gabaix (2016). The main idea of rare disaster models is that since rare but extreme disasters lower future consumption and productivity substantially, the risk of such disasters is an important factor in the determination of financial asset prices in spite of the low probability of their occurrence. Recently, Farhi and Gabaix (2016) extended this idea to an open-economy setup to explain exchange rate movements under the assumption that countries have different exposures to disasters. The model of Farhi and Gabaix (2016) predicts that a country with relatively higher exposure to disasters (i.e. a country that will experience a relatively greater reduction in productivity upon the occurrence of a disaster) will have depreciation in its currency compared with other countries as the probability of the rare disaster and its expected damage rises. We examine this prediction of the model by relating movements of South Korean exchange rates to North Korean actions that raise tensions in the region.

Since the ceasefire agreement was made in 1953, the political and military tension between the two Koreas has fluctuated. The level of tension has become higher recently because of repeated threatening actions from North Korea (e.g. intermediate-range ballistic missile tests, sixth nuclear test, etc. in 2017) and the application of greater pressure on North Korea by South Korea and its allies in response (e.g. UN sanctions against North Korea), attracting attention from the rest of the world. Although the probability that such high tension will result in disaster is low, investors facing news regarding the conflict in the Korean peninsula might re-evaluate the probability of the outbreak of another war and the possible damage caused by the war. For example, the completion of a long-range missile or an atomic bomb by North Korea raises the potential damage of a war far beyond that which would occur in a conventional war. As the exchange rate responds to the time-varying probability of a disaster and time-varying expected disastrous damages in Farhi and Gabaix (2016),[2] we investigate empirically whether the behavior of the South Korean exchange rate is consistent with the implications of Farhi and Gabaix (2016).

Our empirical exercise, relating South Korean exchange rates to North Korea's threatening actions, can be meaningful in the following two respects. First, existing empirical studies investigating the relevance of models with rare disasters focus on carry trade returns. Burnside et al. (2011) and Farhi et al. (2015) report that disaster risk is an important factor to explain the carry trade risk premium, while Jurek (2014) argues that it accounts for at most one third of carry trade returns. Unlike these studies, however, we directly relate movements of the South Korean exchange rate to significant threatening actions by North Korea that are likely to influence the probability of a disaster and its expected damage in the perception of investors (that is, the components of the resilience in Farhi and Gabaix (2016)). According to Farhi and Gabaix (2016), a higher probability of a disaster and/or greater expected damage will cause the depreciation of South Korean currency because South Korea would have greater damage in productivity compared with other countries if a war breaks out. We investigate this implication empirically instead of relying on the examination of carry trades,

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[2] Farhi and Gabaix (2016) refer to the product of the time-varying probability and time-varying expected damage as the 'resilience' and demonstrate that the resilience plays the role of a sufficient statistic for exchange rate movements.

which is expected to enrich the evidence for the literature.

Second, we apply different econometric methodologies in the empirical analysis compared with previous studies. The model in Farhi and Gabaix (2016) is flexible in the sense that the probability of a disaster and the expected relative damage of a disaster vary over time and the exchange rate responds to those time-varying factors even if a rare but extreme disaster has not occurred. Since the response of the exchange rate to time-varying resilience also varies in the model, we utilize the number of news articles covering North Korea's threatening actions (North Korea's military provocations, nuclear tests, and missile tests) as a proxy for an innovation to the time-varying resilience, and apply the nonparametric approach presented by Andrews (1991) in the estimation to capture the time-variability of the response of the exchange rate.[3] Since number of news articles covering North Korea's threatening actions may be a noisy proxy, we also conduct an event study utilizing five-minute high frequency exchange rate data to compare exchange rate movements immediately before and after the last five nuclear tests in North Korea. Employing the nonparametric regression approach and the event analysis with five minute high frequency data, we attempt to shed light on conflicting results in empirical studies about the effect of North Korean threats on the South Korean financial markets.[4]

Our results show that the South Korean exchange rate does depreciate in response to news about North Korea's threatening actions. Moreover, the magnitude and significance of

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[3] As more newspapers cover military provocations or the new development of weapons (missiles, atomic bombs, etc.) in North Korea, investors would expect higher probability and/or greater damages to South Korea once a war breaks out. The number of news articles covering North Korea's threatening actions is taken from bigkinds.or.kr managed by Korea Press Foundation.

[4] While Dibooglu and Cevi (2016) report that North Korean threats have a significant effect on the South Korean exchange rate, Kim and Roland (2014) and Huang and Woo (2017) are not able to find a significant impact from North Korean threats.

the depreciation vary over time. Since the timing of various North Korean military tests and verbal threats are not related with macroeconomic conditions in South Korea or the rest of the world, our result is another piece of evidence for the exchange rate disconnect puzzle reported in Meese and Rogoff (1983) and Obstfeld and Rogoff (2001), and is consistent with the implication in Farhi and Gabaix (2016). Although the impact of a disaster would last persistently once it really breaks out, the duration of the significant depreciation of the South Korean exchange rate in response to news on North Korea's threatening actions is short and the currency market in South Korea appears to stabilize quickly. This short duration is probably due to the fact that the real disaster (i.e. a war between the two Koreas) has not broken out during our sample period, although the tension in the Korean peninsula has fluctuated. Finally, we observe that the response of the exchange rate to news escalating the tension level in Korea varies over time and that the time-variability of the response is similar to the habituation learning process.

This paper is organized as follows. Section II presents briefly the model in Farhi and Gabaix (2016) and the strategy in our empirical analysis. Section III provides empirical results obtained by the application of nonparametric approach. The results of the event study with five-minute high frequency data are presented in Section IV. Concluding remarks are offered in Section V.

II. Model and Strategy of Empirical Analysis

In the model of Farhi and Gabaix (2016), a disaster affects the world pricing kernel (denoted by M_t^*) and the productivity in an individual country (denoted by ω_{it}). Since consumption in the disastrous state will be substantially lower, the disaster risk is modeled as follows:

$$\frac{M^*_{t+1}}{M^*_t} = \exp(-R) \times 1 \qquad \text{if there is no disaster risk at } t\text{+1}$$

$$\frac{M^*_{t+1}}{M^*_t} = \exp(-R) \times B^{-\gamma}_{t+1} \qquad \text{if there is a disaster risk at } t\text{+1} \qquad (1)$$

Since a disaster also lowers the productivity of country i, the effect of a disaster on the productivity of an individual country is modeled as follows:

$$\frac{\omega_{i,t+1}}{\omega_{it}} = \exp(g_{\omega_i}) \times 1 \qquad \text{if there is no disaster risk at } t\text{+1}$$

$$\frac{\omega_{i,t+1}}{\omega_{it}} = \exp(g_{\omega_i}) \times F_{i,t+1} \qquad \text{if there is a disaster risk at } t\text{+1} \qquad (2)$$

B_{t+1} and $F_{i,t+1}$ capture the reduction in consumption and productivity under a disastrous state, respectively. In the model with those assumptions, Farhi and Gabaix (2016) demonstrate that the exchange rate of country *i* can be expressed as the present value of its future export productivity. Furthermore, movements of the exchange rate between country *i* (e.g. South Korea) and country j (e.g. the US) is tightly related with $H_{jt} - H_{it} = p_t E^D_t [B^{-\gamma}_{t+1}(F_{j,t+1} - F_{i,t+1})]$ where p_t denotes the probability of the occurrence of a disaster and E^D_t denotes the expectation conditional on the occurrence of a disaster at *t*+1. Farhi and Gabaix (2016) call $H_{jt} - H_{it}$ the difference in the resilience in those two countries, and show that as $H_{jt} - H_{it}$ increases, the currency of country *j* appreciates but the currency of country *i* depreciates.

Although $H_{jt} - H_{it}$ plays the role of a sufficient statistic in understanding appreciation/depreciation of exchange rates between two countries, $H_{jt} - H_{it}$ is an unobservable variable and its magnitude should be approximated by a proxy variable in an empirical analysis of the disaster hypothesis. In this regard, we utilize the number of South

Korean news articles covering North Korea's threatening actions within a month as a proxy variable to reflect an innovation to $H_{jt} - H_{it}$. For example, when news on the development of military weapons in North Korea is reported, investors would re-evaluate the probability of a war and the expected damage arising from a war as they read such news articles, which results in a new innovation to $H_{jt} - H_{it}$. We do not argue that the monthly number of news articles can capture innovations to $H_{jt} - H_{it}$ perfectly, but believe that as more and more news articles cover a threatening action by North Korea, that action is considered more serious and has a greater relative impact on South Korea than the US. Hence, more news articles can be considered as a greater innovation to $H_{jt} - H_{it}$, and our proxy variable shows innovations which cause the depreciation of the South Korean exchange rate against the US. Since the response of the exchange rate to an innovation of $H_{jt} - H_{it}$ varies in the model depending on which component of $H_{jt} - H_{it}$ (p_t, B_{t+1}, and $F_{j,t+1} - F_{i,t+1}$) is affected by the innovation, the response of South Korean exchange rate against the US to a proxy variable can vary over time. As a result, we apply the nonparametric approach in Andrews (1991) to capture this time-variability of the response of the exchange rate.[5]

Since the monthly number of news articles is not a perfect measure for an innovation to $H_{jt} - H_{it}$, we also examine movements of South Korean exchange rates in response to North Korea's nuclear tests. There have been six nuclear tests in North Korea, and they are testing more and more upgraded version of atomic bombs as they have conducted tests repeatedly. Hence, nuclear tests in North Korea imply disastrous costs to the world without a doubt, but particularly huge costs to South Korea, which suggests that a nuclear test in North

[5] Park (2010) apply the nonparametric approach to investigate the impact of demographic structure on stock prices.

Korea is a less arguable proxy to capture innovations to $H_{jt} - H_{it}$. In addition, since the exact times of nuclear tests are available, we are able to compare the response of South Korean exchange rates immediately before and immediately after the nuclear tests with five-minute high frequency data.[6] Thus, we also conduct an event study test for the South Korean exchange rate in response to North Korea's nuclear tests to examine the disaster hypothesis.

III. Empirical Evidence Based on Nonparametric Approach

1. Data

In the empirical analysis, we use the exchange rate between South Korea and the US. If a war breaks out in the Korean peninsula, countries such as China, Japan, Russia, and the US are likely to enter the war in addition to the two Koreas. However, the greatest war damages will be suffered by both Koreas. Hence, we assume that South Korea has relatively greater exposure to the disaster risk than the US once a war breaks out in the region. The monthly average bilateral exchange rate between South Korea and the US is obtained from the Economic Statistics System (ECOS) managed by the Bank of Korea. The nominal exchange rate is adjusted by the use of Consumer Price Indices (CPIs) in both countries to construct the real exchange rate because the Farhi and Gabaix (2016) model deals with the real exchange rate.

We utilize the monthly number of news articles covering North Korea's threatening actions to reflect innovations to relative resilience between South Korea and the US. The

[6] In case of missile tests, there is no clear borderline for what range of missile tests should be included in the analysis, and the exact times for some missile tests, especially for short-range missile tests, are not known.

Korea Press Foundation provides a website that can be used to analyze the big data of public news articles in South Korea.[7] We can obtain the monthly time series of the number of news articles covering North Korea's threatening actions by searching the website for news articles containing the (Korean) word pairs 'North Korea' & 'military provocations', 'North Korea' & 'nuclear tests' and 'North Korea' & 'missile tests'. Thus, our proxy variable covers comprehensive news articles about North Korean military provocations (e.g. small combat events around the demilitarized zone (DMZ), North Korea's shelling of a border island in 2010, etc.), nuclear tests (e.g. North Korea's second through sixth nuclear tests), and various missile tests (e.g. intermediate range ballistic missile tests, intercontinental ballistic missile tests, etc.)

The sample period is March 2008 – September 2017. The sample starts March 2008 because both Koreas reached temporary détente during the period of March 1998 – February 2008. During that period, South and North Koreas had two summit meetings and several meetings for separated families, and operated an economic cooperation complex in the Gaesung area and tours in certain areas of North Korea, although the first nuclear test was conducted on October 9, 2006 and some military conflicts did occur. Because of the different diplomatic policy stances in the Koreas before March 2008, we can observe many news articles that contain 'North Korea' & 'military provocations', 'North Korea' & 'nuclear tests' and 'North Korea' & 'missile tests' but are not necessarily related with a rise of tension in South Korea. If news reduces the tension between the two Koreas, then we need to put the negative sign to the number of those articles, which requires making arbitrary decisions and reading an enormous amount of articles. As a result, we limit the start of the sample period to

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[7] The address of the website is www.bigkinds.or.kr.

March 2008, which is consistent with the start of conservative government in South Korea.

The first panel of Figure 1 shows movements of the log real exchange rate between South Korea and the US during the sample period. The second panel of Figure 1 plots the monthly number of news articles on North Korea's threatening actions. As shown in the second panel, the number of news articles shows spikes around the time points of important military conflicts (e.g. the sinking of the South Korean warship Cheonan in March 2010, North Korea's shelling of a border island in November 2010, etc.), nuclear tests (see Table 1 for exact test times), and important missile tests (e.g. the submarine-launched ballistic missile test in August 2016, several intermediate range ballistic missile tests in 2017) in North Korea. Due to the recent high tension between North Korea and South Korea and its allies, the number of news articles has risen in 2016 and 2017.

2. Empirical Evidence

In order to examine the relevance of the Farhi and Gabaix (2016) model, we consider first the following constant-coefficient regression of the real exchange rate on the number of news articles escalating the tension between the two Koreas:

$$q_t = a + bX_t + e_t \tag{3}$$

where q_t is the log real exchange rate between South Korea and the US, and X_t denotes the number of news articles reporting North Korea's threatening actions. Since the number of news articles covering North Korea's military provocations, nuclear tests, and missile tests is likely to be independent of South Korean or world economic conditions, the impact of the number of news articles, a proxy for the innovations to relative resilience in the model, can be estimated consistently without other controlling variables.

The results are presented in Table 1. The coefficient of the number of news articles (denoted by b) is not significant and its magnitude is almost zero. Qualitatively the same pattern can be observed when we use the number of news articles covering North Korea's military provocations only, the number of news articles covering North Korea's nuclear tests only, or the number of news articles covering North Korea's missile tests only instead of the number of news articles covering all those incidents. If the number of articles escalating the tension between the two Koreas is a reasonable proxy for the innovation to the relative resilience in the Farhi and Gabaix (2016) model, the results in Table 1 are not supportive of the prediction of the model. Since the Farhi and Gabaix (2016) model predicts that the response of the real exchange rate to innovations varies over time depending on which component of $H_{jt} - H_{it}$ (p_t, B_{t+1}, and $F_{j,t+1} - F_{i,t+1}$) is affected by the innovation, however, the unfavorable results in Table 1 may arise from the use of constant-coefficient regression which cannot capture the time-variability of the response of the real exchange rate.

In order to check that possibility, we consider the following nonparametric regression allowing the time-variability of the coefficient:

$$q_t = a_t + b_t X_t + e_t \tag{4}$$

The nonparametric approach does not impose any process or functional form for time-varying parameters *a priori*, but we assume that the coefficients vary smoothly so that $b_t = b\left(\frac{t}{T}\right)$, where $b(\cdot)$ is a smooth function defined on [0, 1] and T is the sample size. Under the assumption that $b(\cdot)$ is a sufficiently smooth function that can be approximated by a series of polynomials and/or trigonometric functions, the regression in equation (4) can be written as follows:

$$q_t = a_t + b_t X_t + e_t$$

$$= a\left(\frac{t}{T}\right) + b\left(\frac{t}{T}\right) X_t + e_t$$

$$= a + \left[\sum_{i=1}^{n} \theta_i \varphi_i\left(\frac{t}{T}\right)\right] X_t + e_{nt}$$

$$= a + \chi'_{nt} a_n^b + e_{nt}, \qquad (5)$$

where $\chi_{nt} = \left[\varphi_1\left(\frac{t}{T}\right), \dots, \varphi_n\left(\frac{t}{T}\right)\right]' X_t$, $a_n^b = [\theta_1, \dots, \theta_n]'$, $b_n\left(\frac{t}{T}\right) = \sum_{i=1}^{n} \theta_i \varphi_i\left(\frac{t}{T}\right)$, and $e_{nt} = e_t + \left[a\left(\frac{t}{T}\right) - a\right] + \left[b\left(\frac{t}{T}\right) - b_n\left(\frac{t}{T}\right)\right] X_t$.

Once χ_{nt} is constructed, a_n^b can be estimated by the least squares approach. In this regard, Andrews (1991a) demonstrates desirable asymptotic results for the estimates of a_n^b. It is straightforward to recover $b_n\left(\frac{t}{T}\right)$ with the estimates of a_n^b. Note that possible time-variation of a_t will be reflected in the disturbance term of the regression. Since we cannot expand $b\left(\frac{t}{T}\right)$ with an infinite number of series functions, it is important to decide n (the number of series functions) in the empirical analysis to obtain a good approximation for $b\left(\frac{t}{T}\right)$. Regarding this issue, the modified h-block CV criteria, as suggested by Racine (1997), is utilized as a selection criterion for n.[8] The modified h-block CV criterion, motivated by cases where $\frac{n}{T}$ is not negligible, can be written as follows:

$$MCV = T^{-1} \sum_{t=h}^{T-h} (q_t - \hat{a}(t,h) - \chi'_{nt} \hat{a}_n^b(t,h))^2$$

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[8] The block size, h, is set as the integer nearest to $\frac{T}{6}$ following the suggestion by Burman, Chow, and Nolan (1994).

$$+T^{-2}\sum_{t=h}^{T-h}\sum_{i=1}^{T}(q_i-\hat{a}(t,h)-\chi'_{nt}\hat{a}_n^b(t,h))^2+T^{-1}\sum_{i=1}^{T}(q_i-\hat{a}-\chi'_{nt}\hat{a}_n^b)^2 \quad (6)$$

where $\hat{a}(t,h)$ and $\hat{a}_n^b(t,h)$ are estimators of the coefficients in equation (5) obtained by removing the *t*-th observation, and the h observations preceding and following the *t*-th observation in the dependent and independent variables in the regression. The n that minimizes MCV is selected.

As reported in Table 2, we test various forms of series functions. Among them, the MCV criterion is minimized when a quadratic function is used. When the number of news articles covering North Korea's threatening actions is replaced by the number of news articles covering North Korea's military provocations only, the number of articles covering North Korea's nuclear tests only, or the number of articles covering North Korea's missile tests only, a quadratic function continues to be chosen to approximate $b\left(\frac{t}{T}\right)$. Hence, we choose $1, m,$ and m^2 to approximate $b\left(\frac{t}{T}\right)$ in the empirical analysis.

The estimate of b_t and the 90% confidence interval, based on the nonparametric regression with the selected n, are plotted in Figure 2. Unlike the results from the constant-coefficient regression, the real exchange rate responds significantly to the news articles about North Korea's threatening actions in Figure 2, and the estimated response varies over time. The South Korean exchange rate depreciated significantly in response to such news during the periods of March 2008 – August 2011 and around the end of the sample period (August 2017). If the number of news articles is a reasonable proxy for innovations to relative resilience between South Korea and the US, the plot in Figure 2 implies that as more articles cover threats from North Korea, investors would see a higher probability of the outbreak of a war in Korea and/or higher expected damage to South Korea due to a war, which results in a relatively greater decrease of resilience in South Korea than that in the US and eventually causes the depreciation of the South Korean exchange rate. Thus, Figure 2 can be interpreted as supportive evidence of the explanation of the disaster hypothesis on the exchange rate disconnect puzzle.

Although the response of the real exchange rate to news on North Korea's threatening actions varies over time consistently with the prediction of the Farhi and Gabaix (2016) model, the response is insignificant for a long period in the middle of the sample period. A possible reason for this is that the number of news articles is not a perfect measure for innovations to relative resilience in the Farhi and Gabaix (2016) model. As a result, the estimate of the response can have a bias toward zero, which results in the insignificant response in the estimation. Another explanation is that the insignificant response may show habituation in investors' perceptions while assessing news about North Korea's threats. Investors in the market may pay high attention initially to North Korea's military provocations, nuclear tests, and missile tests, but decrease their attention level after repeated presentations of such stimulations, similar to the habituation theory in psychology (see Thompson and Spencer (1966), Zimny and Miller (1966), Ziferstein (1967), and Mangelsdorff and Zuckerman (1975)). However, the abolishment of the Obama administration's strategic tolerance of North Korea's actions and the strong reaction to North Korea's threats –under the Trump administration might be considered as other types of stimulation to investors' perceptions, which might result in the rise of the response at the end of the sample period. Although Farhi and Gabaix (2016) assume a linearity-generating process for the resilience to manage the model, the results in Figure 2 imply that investors' perceptions or resilience process might be more complicated in the market.

In order to check the robustness of the results, we change the measure of innovation to relative resilience from the number of comprehensive news articles to the number of news articles covering North Korea's military provocations only, nuclear tests only, or missile tests only, and run the nonparametric regression. As the results presented in Figure 3 show, we can obtain qualitatively the same results. In all cases, we can observe a significant depreciation of the real exchange rate at the early part of the sample period, insignificant response in the middle, and the rise of the response at the end of the sample period.

IV. Empirical Evidence Based on Event Study

1. Data

The monthly number of news articles is an imperfect measure for innovations to relative resilience in the Farhi and Gabaix (2016) model, especially in terms of the timing of a shock within a given month. Some news articles might be analyzing North Korea's past actions. In addition, although news articles report small combat events around the DMZ, those relatively small conflicts may not have enough impact to be reflected in innovations to relative resilience. To overcome these shortcomings, this section focuses on the response of the South Korean exchange rate to North Korea's nuclear tests for which the exact timings are known. The chronology of nuclear tests from the first one through the sixth one is presented in Table 3. North Korea has conducted six nuclear tests so far. As North Korea carries out nuclear tests repeatedly, they appear to test more upgraded atomic bombs. Hence, North Korea's nuclear tests are likely to affect the expected damage of a possible war in the model, which ultimately impacts the relative resilience.

In order to investigate whether North Korean nuclear tests have affected movements of the exchange rate between South Korea and the US, we compare the behaviors of the exchange rate immediately before and immediately after a nuclear test. For this purpose, we use five-minute exchange rate data taken from Bloomberg and conduct an event study with those data and the exact timings of nuclear tests in North Korea. Since the five-minute exchange rate data from Bloomberg are not available around the period of the first nuclear test in 2006, our analysis focuses on the second to the sixth nuclear tests.

2. Empirical Evidence

An event study is a statistical approach in financial economics to evaluate the impact of an event on financial asset prices. Since North Korea's nuclear test can be considered as exogenous with respect to the South Korean or world economic state, we apply this approach to examine whether the South Korean exchange rate shows abnormal behavior immediately after a North Korean nuclear test compared with normal movements of the exchange rate immediately before the test. We set the estimation window as five trading days plus the time immediately before each nuclear test on the test day to estimate normal exchange rate behaviors which are not influenced by those tests. We also set the event window as the time immediately after each nuclear test on the test day plus five trading days. Thus, estimation windows and event windows do not overlap, and the differences of exchange rate movements during estimation windows and event windows are expected to reflect the impact of nuclear tests.

In order to model movements of the exchange rate at high frequency, we use the random walk model (i.e. the constant mean-return model in financial economics) which is known to have superior predictive ability to other macroeconomic models in the short run (see Rossi (2013)). Since high-frequency movements of the real exchange rate are influenced almost entirely by movements of the nominal exchange rate, we estimate the following random walk model with five-minute nominal bilateral exchange rate data between South Korea and the US during each estimation window:

$$\Delta s_t = \alpha_i + \varepsilon_t \tag{7}$$

where s_t denotes log nominal bilateral exchange rate data between South Korea and the US. Once α_i and σ_i^2 (the variance of ε_t in equation (7)) are estimated, then the abnormal exchange rate return vector and its covariance matrix are constructed as in Campbell, Lo, and MacKinlay (1997):

$$\hat{\varepsilon}_i^* = \begin{bmatrix} \Delta s_{t_{0,i}+1} \\ \Delta s_{t_{0,i}+2} \\ \vdots \\ \Delta s_{t_{0,i}+n_{2,i}} \end{bmatrix} - \begin{bmatrix} \hat{\alpha}_i \\ \hat{\alpha}_i \\ \vdots \\ \hat{\alpha}_i \end{bmatrix} \text{ and } \hat{V}_i = \begin{bmatrix} \left(1+\frac{1}{n_{1,i}}\right) & \frac{1}{n_{1,i}} & \cdots \frac{1}{n_{1,i}} \\ \frac{1}{n_{1,i}} & \left(1+\frac{1}{n_{1,i}}\right) & \cdots \frac{1}{n_{1,i}} \\ & \vdots & \\ \frac{1}{n_{1,i}} & \frac{1}{n_{1,i}} & \cdots \left(1+\frac{1}{n_{1,i}}\right) \end{bmatrix} \hat{\sigma}_i^2 \tag{8}$$

where $t_{0,i}$ denotes the *i*-th nuclear test time point, and $n_{1,i}$ and $n_{2,i}$ are the number of observations during the *i*-th estimation window and event window, respectively. Then the cumulative abnormal movements of the exchange rate from $t_{0,i}+1$ to $t_{0,i}+\tau$ and its variance can be estimated as follows:

$$\widehat{CAR}_i(1,\tau) = \gamma' \hat{\varepsilon}_i^* \tag{9}$$

$$\text{Var}\left[\widehat{CAR}_i(1,\tau)\right] = \gamma' \hat{V}_i \gamma \tag{10}$$

where γ is a $\tau \times 1$ vector with ones.

Using (9) and (10), the average cumulative abnormal movements of the exchange rate across N nuclear tests can be constructed as follows:

$$\overline{CAR}(1,\tau) = \frac{1}{N}\sum \widehat{CAR}_i(1,\tau) \tag{11}$$

$$\mathrm{Var}[\overline{CAR}(1,\tau)] = \frac{1}{N^2}\sum \mathrm{Var}\left[\widehat{CAR}_i(1,\tau)\right] \tag{12}$$

where N denotes the number of events, which is the number of North Korea's nuclear tests in the analysis.

The average cumulative abnormal exchange rate returns across the second through the sixth nuclear test in North Korea ($\overline{CAR}(1,\tau)$) is presented along with its 90% confidence interval in Figure 4. North Korea's nuclear tests cause artificial earthquakes, which are immediately reported in South Korean and world news articles together with assessment articles about the performance of atomic bombs in North Korea. The Farhi and Gabaix (2016) model would predict that upon facing such news, investors immediately re-evaluate possible damage of a war between the two Koreas, the probability of a war breaking out, and other consequences of the test, which impacts the relative resilience between South Korea and the US and results in the significant depreciation of South Korean exchange rate. As Figure 4 clearly presents, the South Korean exchange rate jumps up significantly following North Korean nuclear tests and the significant depreciation ($\overline{CAR}(1,\tau)$) lasts for approximately two hours (= 5 minute × 25 periods). This finding is consistent with the implication of the Farhi and Gabaix (2016) model and can be another piece of evidence for the exchange rate disconnect puzzle.[9]

[9] We check whether an FOMC meeting, which can influence the exchange rate between South Korea and the US, was held during the estimation windows and event windows and find that that has not happened in our

We also investigate the response of the exchange rate to each of those nuclear tests separately because individual responses could differ across tests similarly to the time-varying response found in figures 2 and 3. As shown in Figure 5, the cumulative abnormal exchange rate returns ($\widehat{CAR_\iota}(1,\tau)$) differ greatly across North Korea's nuclear tests. Significant $\widehat{CAR_\iota}(1,\tau)$ shows up approximately 50 minutes later after the second nuclear test and $\widehat{CAR_\iota}(1,\tau)$ remains significant for approximately the next 50 minutes, while significant $\widehat{CAR_\iota}(1,\tau)$ first appears approximately 15 minutes after the third nuclear test and $\widehat{CAR_\iota}(1,\tau)$ remains significant for approximately 5 minutes only. However, we cannot find significant $\widehat{CAR_\iota}(1,\tau)$ at all for the third and fourth nuclear tests.[10] The sixth nuclear test was conducted on a Sunday, and significant $\widehat{CAR_\iota}(1,\tau)$ was observed upon the opening of the currency market the next day and lasted for approximately two-and-a-half hours. The significant $\widehat{CAR_\iota}(1,\tau)$ found in the sixth nuclear test may be due to the high tension level caused by a series of North Korean military provocations and missile tests and the strong reaction from South Korea and the US in the summer of 2017. The different patterns of separate $\widehat{CAR_\iota}(1,\tau)$ are consistent with the pattern of time-varying response of the real exchange rate to the number of news articles in the previous section and may be related with the habituation learning process.

V. Conclusion

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sample period.

[10] Regarding the fourth nuclear test, the significant $\widehat{CAR_\iota}(1,\tau)$ appearing four trading days after the fourth test seems to be related with the Chuseok holidays in South Korea from September 14 to 18, 2016. During the long holidays, the demand for foreign currencies from South Koreans going abroad over the holidays is likely to be a more dominant factor in the depreciation.

We investigated the implication of the disaster hypothesis proposed by Farhi and Gabaix (2016) that changes in the probability of the outbreak of a rare disaster and/or expected damage caused by a rare disaster will be reflected in exchange rate fluctuations. Assuming that news articles reporting North Korea's actions affect the probability and expected damage of a disastrous war in the region, we found that the South Korean exchange rate depreciates significantly in response to the number of such news articles with the application of the nonparametric approach. After narrowing North Korea's actions to the last five nuclear tests, we also showed through the event study that the South Korean exchange rate depreciates significantly immediately after nuclear tests, although the duration of the significant depreciation does not last long. These findings are consistent with the implication of the Farhi and Gabaix (2016) model, and can be considered as another piece of evidence that exchange rate behaviors are disconnected from macroeconomic fundamentals. Finally, we observed that the response of the exchange rate to news escalating the tension level in Korea varies over time: the response was significant initially, became insignificant in the middle of the sample period, and became significant again at the end of the sample. If North Korea's actions under the strategic tolerance of the Obama administration and those under the strong reaction of the Trump administration can be considered as different types of stimulations to investors' evaluations, then the pattern of the time-varying response is similar to the habituation learning process.

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Table 1. Estimated Impact of the Number of News Articles on the Real Exchange Rate: Constant-Coefficient Regression

	a	b
News articles covering North Korea's military provocations, nuclear bomb tests, missile tests	7.9010*** (397.5111)	0.0000 (1.0414)
News articles covering North Korea's military provocations	7.9064*** (369.3697)	0.0000 (0.1507)
News articles covering North Korea's nuclear bomb tests	7.9039*** (424.2452)	0.0000 (0.7743)
News articles covering North Korea's missile tests	7.9009*** (426.1594)	0.0000 (1.1293)

Note: The constant-coefficient regression, $q_t = a + bX_t + e_t$, is run where q_t is the log real exchange rate between South Korea and the US, and X_t denotes the number of news articles escalating the tension between the two Koreas. Numbers in parentheses are t-statistics constructed from Newey-West standard errors. '*', '**', and '***' denote the significance level at the 10%, 5%, and 1% level, respectively.

Table 2. Modified *h*-block Cross-Validation Criteria

	Modified h-block CV			
	Comprehensive News Articles	News Articles Covering North Korea's Military Provocations Only	News Articles Covering North Korea's Nuclear Bomb Tests Only	News Articles Covering North Korea's Missile Tests Only
$1, m, m^2$	2.273×10^{13}	4.758×10^{10}	6.614×10^{11}	2.621×10^{12}
$1, m, m^2, m^3$	3.285×10^{13}	6.337×10^{10}	8.262×10^{11}	4.114×10^{12}
$1, m, m^2, m^3, m^4$	4.334×10^{13}	7.866×10^{10}	9.585×10^{11}	5.809×10^{12}
$1, m, m^2, \ldots, m^5$	5.409×10^{13}	9.355×10^{10}	1.066×10^{12}	7.678×10^{12}
$1, m, m^2, \cos(m), \sin(m)$	3.056×10^{13}	4.978×10^{10}	7.595×10^{11}	4.043×10^{12}
$1, m, m^2, \cos(m), \sin(m),$ $\cos(2m), \sin(2m)$	3.813×10^{13}	5.459×10^{10}	9.331×10^{11}	5.382×10^{12}
$1, m, m^2, \cos(m), \sin(m),$ $\ldots$ $, \cos(3m), \sin(3m)$	4.208×10^{13}	5.041×10^{10}	15.31×10^{11}	5.952×10^{12}
$1, m, m^2, \cos(m), \sin(m),$ $\ldots$ $, \cos(4m), \sin(4m)$	4.270×10^{13}	7.974×10^{10}	17.27×10^{11}	6.297×10^{12}

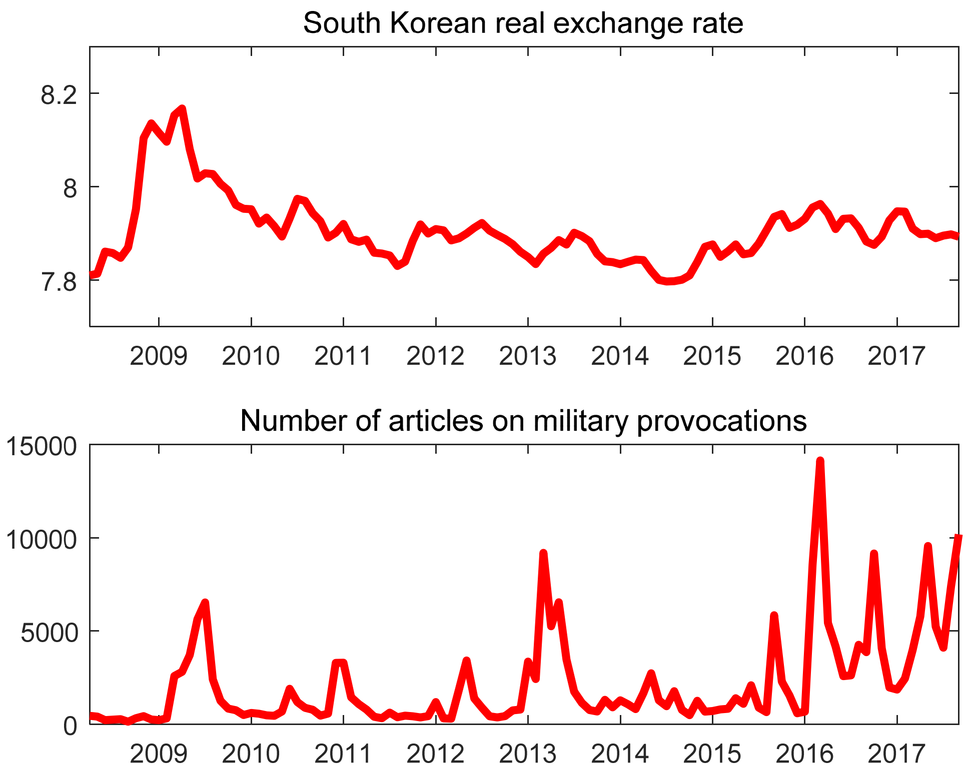
Notes: Modified *h*-block cross-validation is a data-dependent criterion for the selection of the optimal number of series functions. Statistics for modified *h*-block cross-validation are computed from equation (6). The n that minimizes the modified *h*-block CV criteria is selected. See Racine (1997) for further discussion.

Table 3. Chronology of North Korea's Nuclear Tests

Trials	Time
First Test	10:35 AM, October 9, 2006 (Monday)
Second Test	09:54 AM, May 25, 2009 (Monday)
Third Test	11:57 AM, February 12, 2013 (Tuesday)
Fourth Test	09:30 AM, January 6, 2016 (Wednesday)
Fifth Test	10:30 AM, September 9, 2016 (Friday)
Sixth Test	12:29 PM, September 3, 2017 (Sunday)

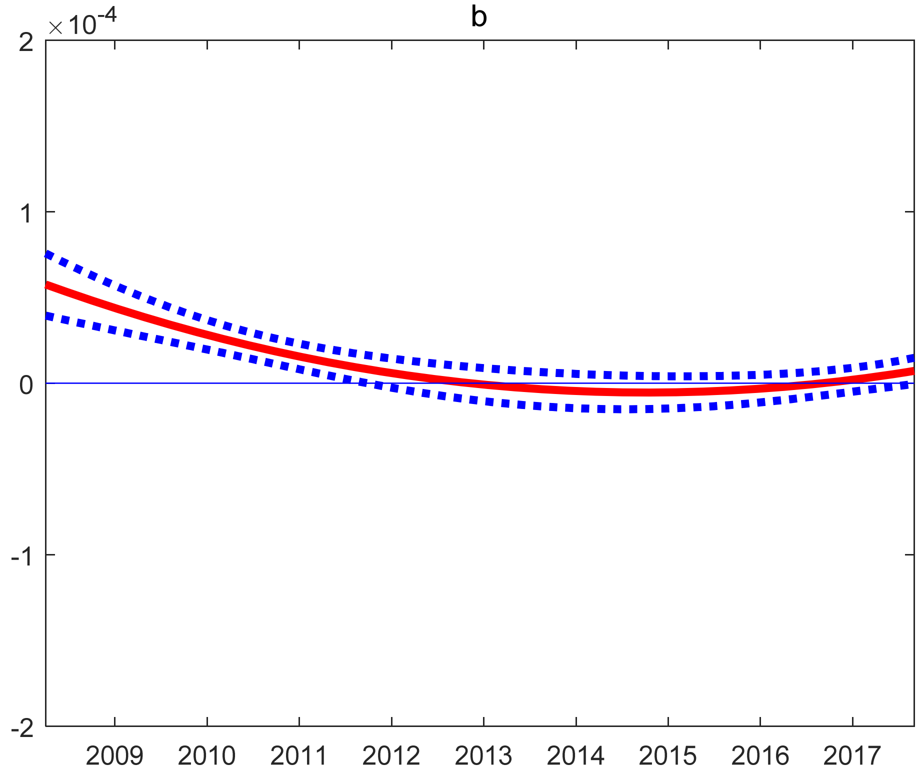
Notes: The times of North Korean nuclear tests are based on South Korean local time.

Figure 1. Movements of Real Exchange Rate and the Number of News Articles Reporting North Korea's Military Provocations, Nuclear Tests and Missile Tests



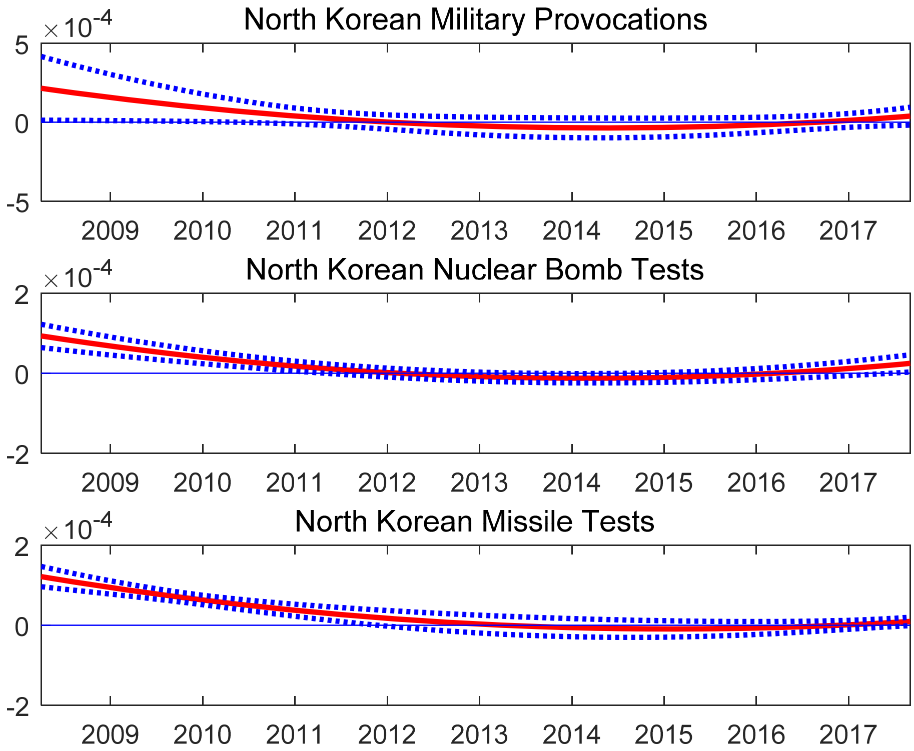
Note: The first panel shows the movements of the log real exchange rate between South Korea and the US. The second panel shows the monthly number of news articles on North Korean threatening actions (North Korea's military provocations, nuclear tests, and missile tests).

Figure 2. Estimated Impact of the Number of News Articles on the Real Exchange Rate: Nonparametric Regression



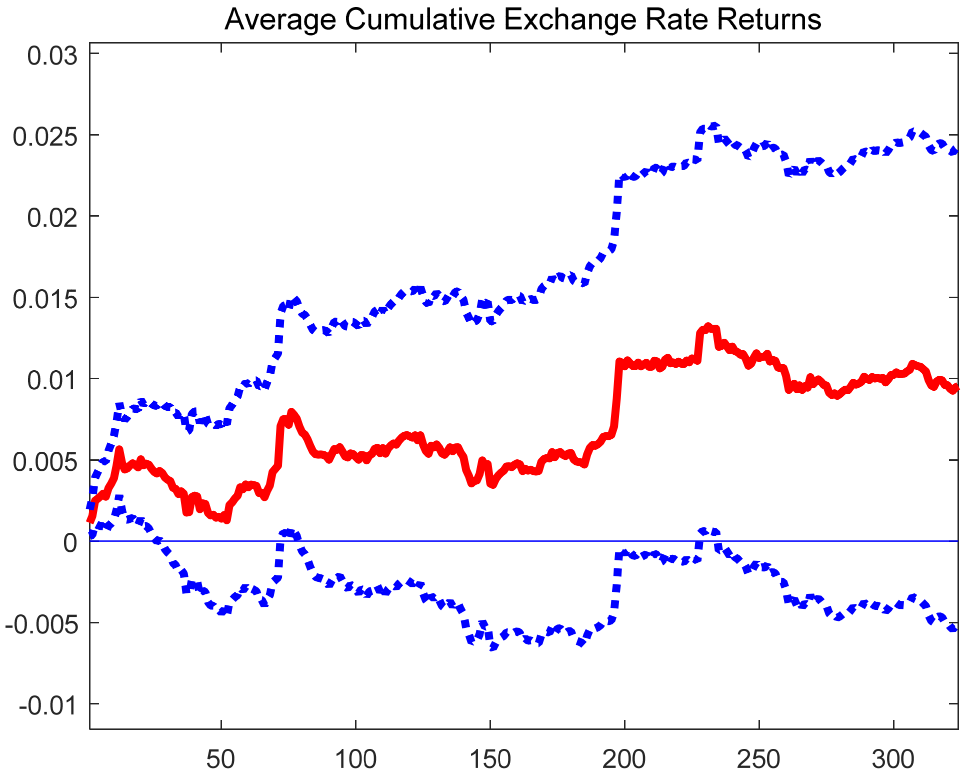
Notes: Nonparametric regression $q_t = a_t + b_t X_t + e_t$ is run where q_t is the log real exchange rate between South Korea and the US, and X_t denotes the number of news articles covering North Korea's threatening actions. Point estimates for b_t (solid curve) and the 90% confidence interval (dotted curves) are plotted. Newey-West standard errors are used to construct the 90% confidence interval.

Figure 3. Robustness Checks: Estimated Impact of the Number of News Articles on the Real Exchange Rate with Alternative Measures for Innovations to Relative Resilience



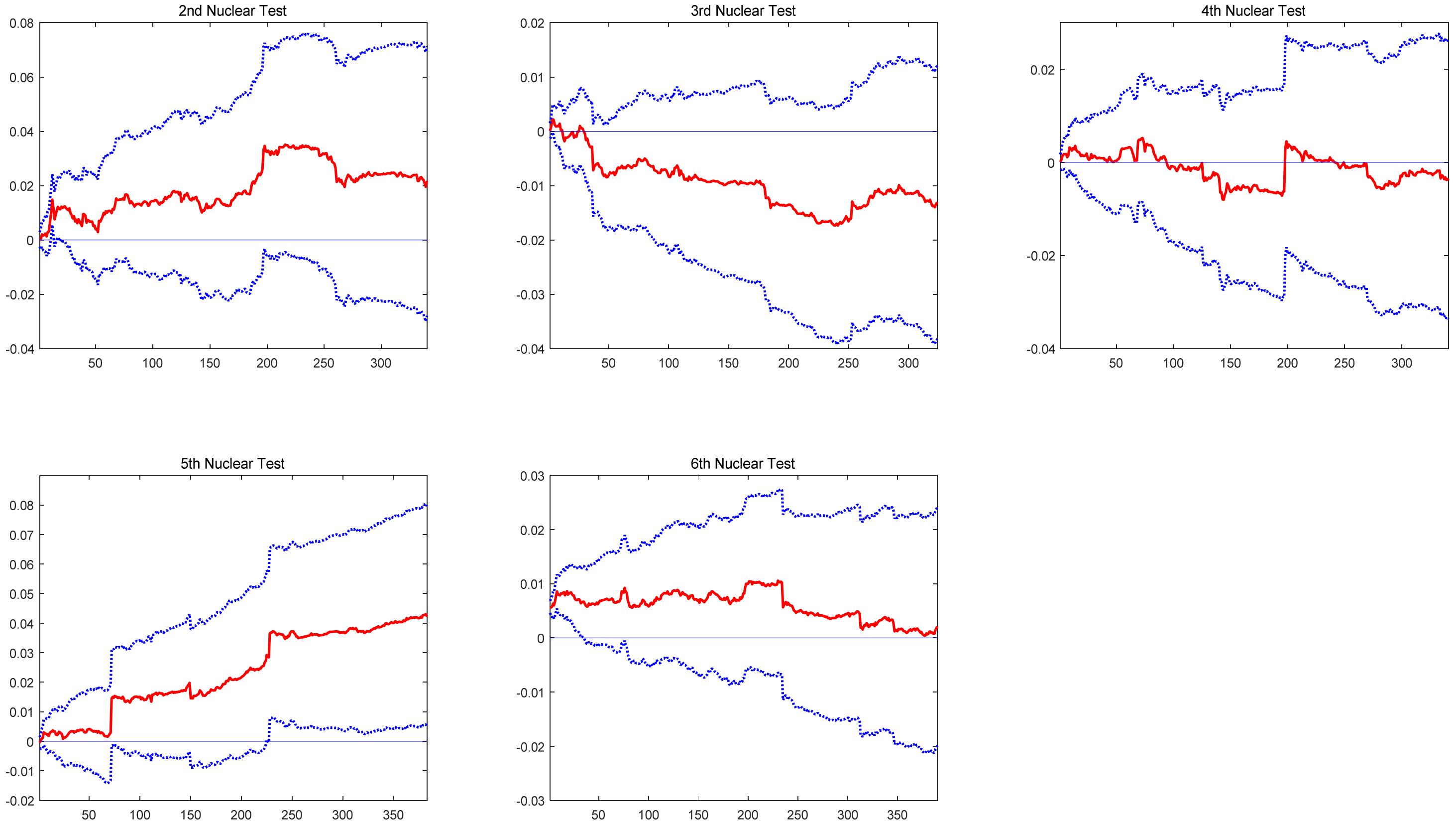
Notes: Nonparametric regression $q_t = a_t + b_t X_t + e_t$ is run where q_t is the log real exchange rate between South Korea and the US, and X_t denotes the number of news articles covering North Korea's military provocations, nuclear tests and missile tests in the first, second and third panel, respectively. Point estimates for b_t (solid curve) and the 90% confidence interval (dotted curves) are plotted. Newey-West standard errors are used to construct the 90% confidence interval.

Figure 4. Average Cumulative Abnormal Exchange Rate Returns across Nuclear Tests



Note: The average cumulative abnormal exchange rate returns across the second through the sixth nuclear tests in North Korea is plotted along with its 90% confidence interval.

Figure 5. Cumulative Abnormal Exchange Rate Returns



Notes: Cumulative abnormal exchange rate returns in response to each of North Korea's nuclear tests and their 90% confidence intervals are plotted.