Discussion Paper Series
No. 2102
September 2021

Monetary Policy and Exchange Rate Response : Evidence from Shock-based SVAR with Uncertainty Measures ▪

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Monetary Policy and Exchange Rate Response: Evidence from Shock-based SVAR with Uncertainty Measures*

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September 2021

Abstract: We examine the response of the exchange rate to monetary policy shocks using structural vector autoregression (SVAR). The SVAR approach employed in this study differs from the approaches used in previous studies in that we add uncertainty measures and employ shock-based identification constraints. Using structural shocks that are in accordance with the event and external variable constraints, we demonstrate that the US real effective exchange rate appreciates immediately in response to contractionary monetary policy shocks, with the maximum appreciation occurring within 1 to 2 quarters. We also provide evidence that recursive identification restrictions or the exclusion of any one of the two types of uncertainty measure can generate anomalous responses by the exchange rate. We further show via variance decomposition that monetary policy shocks explain a substantial portion of exchange rate variability, although they are not the most dominant driving force behind this variability.

Keywords: Exchange rate, Monetary policy, Structural vector autoregressive, Uncovered interest rate parity

JEL classification: C32, E52, F31, F41

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We thank conference and seminar participants at KERIC 2021, Bank of Korea, and Korea University for helpful comments and discussions. The usual disclaimers apply.

I. Introduction

According to the uncovered interest rate parity (UIP) hypothesis, the currency for a country with higher interest rates will appreciate immediately and then depreciate in the future. The UIP hypothesis is the cornerstone of a number of theoretical models in international economics because its failure indicates that there will be an arbitrage opportunity within the currency market. However, many empirical studies have reported that the UIP relationship does not conform with empirical data, which is known as the UIP puzzle.

The UIP puzzle is also observed when the response of the exchange rate to monetary policy is examined. The UIP hypothesis and international macroeconomic models based on the UIP, such as the Dornbusch (1976) model, predict that the exchange rate will appreciate instantaneously and depreciate gradually in response to a contractionary monetary policy shock. However, employing structural vector autoregression (SVAR) with recursive identification restrictions, Eichenbaum and Evans (1995) and subsequent studies have reported that instant appreciation is not clearly observed and, if appreciation occurs, it does so gradually, with its peak occurring a few years after the contractionary monetary policy shock. To resolve this anomalous response of the exchange rate, alternatives to recursive identification strategies have been proposed. For example, Kim and Roubini (2000) propose a non-recursive identification restriction, and Bjørnland (2009) applies a hybrid identification restriction combining recursive and long-run restrictions. In addition, Faust and Rogers (2003) and Scholl and Uhlig (2008) have explored sign restrictions. These studies have produced some successes, but a full explanation of the UIP puzzle has not yet been provided.[1] Because the puzzling phenomena in

[1] The non-recursive restriction in Kim and Roubini (2000) and the hybrid restriction in Bjørnland (2009) allow for the contemporaneous interaction between monetary policy and the exchange rate. Although Kim and Roubini (2000) report fewer puzzling cases in the response to non-US monetary policy shocks, the reaction of exchange

exchange rate responses have been observed in many studies, research employing the dynamic stochastic general equilibrium (DSGE), such as Smets and Wouters (2002) and Adolfson et al. (2008), have viewed the puzzle as a stylized fact that is associated with exchange rate behavior and has attempted to replicate it.

In this paper, we reconsider the response of the exchange rate to monetary policy employing SVAR. Although SVAR is a common methodology in this literature, our approach differs from previous studies in several respects. First, we add uncertainty measures to the SVAR system. Although many studies since Fama (1984) have highlighted the risk premium as a crucial reason for the failure of the UIP, few studies have included a variable to control for the risk premium in SVAR when examining the response of the exchange rate to monetary policy, which might have led to bias in impulse responses. The risk premium is not observable, but uncertainty measures may capture an important aspect of the risk premium because studies such as Bloom (2009) and Jurado, Ludvigson, and Ng (2015) have demonstrated that uncertainty measures rise sharply during a recession, as does the risk premium. Hence, we include uncertainty measures in our SVAR, although we do not attempt to argue that these uncertainty measures are a perfect proxy for the risk premium. We include both real and financial uncertainty in the SVAR because Ludvigson, Ma, and Ng (forthcoming) (LMN, hereafter) demonstrate that financial uncertainty and real uncertainty have distinct features over business cycles.

Second, in employing the SVAR approach, we impose a shock-based identification

rates to US monetary policy shocks remains unclear. Bjørnland (2009) applies the hybrid restriction to only small open economies such as Australia, Canada, New Zealand, and Sweden. Faust and Rogers (2003) and Scholl and Uhlig (2008) have identified non-unique structural shocks satisfying sign restrictions. As a result, it is difficult to draw a robust conclusion from those non-unique responses.

strategy to identify structural shocks instead of the contemporaneous or sign restrictions used in previous studies. Shock-based SVAR has been proposed by LMN, and Antolín-Díaz and Rubio-Ramírez (2018) also take a similar approach in a Bayesian setup. Our shock-based SVAR consists of event constraints and external variable constraints as in LMN. There exist infinitely many shock series that satisfy the reduced form relation from the data. Of these, we extract structural shock series that satisfy constraints imposed by important historical events (i.e., event constraints) and constraints on non-zero correlations between structural shocks and certain variables external to the SVAR (i.e., external variable constraints). It is not clear how to determine the ordering of the variables in SVAR or how to enter zeros into the contemporaneous relation between variables because no theoretical consensus has been established for the relation between macroeconomic variables and uncertainty measures. In this situation, unlike SVAR with recursive, sign, or long-term restrictions, shock-based SVAR overcomes these problems while identifying structural shocks.

Our investigation into the structural shock series that pass all of the event constraints and external variable constraints leads to a number of interesting findings. First, the US real effective exchange rate appreciates immediately in response to contractionary monetary policy shocks and maximum appreciation occurs within one to two quarters. Second, even when shock-based SVAR with event and external variable constraints is employed, we can observe immediate depreciation and/or delayed overshooting when uncertainty measures are excluded. This indicates that controlling for both uncertainty measures is important in analyzing exchange rate behavior. Third, if we impose recursive identification restrictions, we can observe immediate depreciation and/or delayed overshooting even with the inclusion of both uncertainty measures. Fourth, the contemporaneous restrictions imposed on our shock-based SVAR allow for the contemporaneous interaction between monetary policy and the exchange rate, but these restrictions remain distinct from the non-recursive identification restrictions employed in previous studies such as Kim and Roubini (2000) and Bjørnland (2009). Finally, our variance decomposition analysis shows that monetary policy shocks are not the most dominant driving force for exchange rate fluctuations but do explain a substantial portion of exchange rate variability.

This paper is organized as follows. Section II explains the shock-based identification strategy employed in this study, while Section III briefly discusses the data that are used. Section IV presents the responses of the exchange rate to contractionary monetary policy as estimated by the shock-based SVAR with both measures of uncertainty. In Section V, we investigate the responses of the exchange rate to monetary policy shocks by excluding either one of the uncertainty measures or imposing recursive identification resources to uncover the source of the puzzle associated with exchange rate behavior. We also compare the contemporaneous relation imposed on our shock-based SVAR with those reported in previous studies. Section VI then presents the results of variance decomposition analysis, and concluding remarks are provided in Section VII.

II. Shock-based SVAR Model

We consider the following structural relation between the variables of interest:

$$A_0 X_t = a + A_1 X_{t-1} + A_2 X_{t-2} + \cdots + A_p X_{t-p} + \varepsilon_t \tag{1}$$

where $X_t = (U_{R_t}, Y_t, U_{F_t}, \pi_t, i_t - i_t^*, q_t)'$, U_{R_t} is the real uncertainty index, Y_t is the detrended industrial production, U_{F_t} is the financial uncertainty index, π_t is the log inflation rate based on the consumer price index (CPI), i_t is the Federal Funds rate, i_t^* is the trade-weighted foreign interest rate, and q_t is the log US real effective exchange rate. The source of the data for each variable is explained in Section III. $\varepsilon_t = (\varepsilon_{R_t}, \varepsilon_{Y_t}, \varepsilon_{F_t}, \varepsilon_{\pi_t}, \varepsilon_{i_t}, \varepsilon_{q_t})'$ contains structural shocks that are serially uncorrelated and $\varepsilon_t \sim (0, I_k)$. They are structural shocks to the real uncertainty, output movements, financial uncertainty, inflation rate, monetary policy, and real effective exchange rate. The structural relation expressed in (1) is usually suggested by theoretical models and/or historical events but is not readily observable. However, the reduced form of (1) is readily observable and can be expressed as follows:

$$X_t = b + B_1 X_{t-1} + B_2 X_{t-2} + \cdots + B_p X_{t-p} + u_t \qquad (2)^2$$

From equations (1) and (2), $A_0^{-1}\varepsilon_t = u_t$, which implies $A_0^{-1}A_0^{-1\prime} = \Sigma_u$, where Σ_u is the covariance matrix of u_t. To understand the structural relation in (1), we need to determine k^2 elements in A_0^{-1}, but the symmetrical nature of Σ_u provides only $\frac{k(k+1)}{2}$ independent elements, which indicates that we need $\frac{k(k-1)}{2}$ restrictions to identify A_0^{-1}. Previous studies have solved this identification issue by putting $\frac{k(k-1)}{2}$ zeros at certain points in A_0^{-1} based on suggestions from theoretical models and historical experience.

Unlike previous studies, we take a shock-based SVAR approach and do not put zeros in A_0^{-1} *a priori* to identify A_0^{-1}. Instead, we select A_0^{-1} from infinitely many candidates when the corresponding ε_t is consistent with historical events and satisfies the correlation conditions with external variables. This shock-based SVAR approach is proposed by LMN, while Antolín-Díaz and Rubio-Ramírez (2018) have recently taken a similar approach. In order to put zeros in A_0^{-1} *a priori* as in previous studies, it is important to determine the order of

[2] Throughout this paper, we use a $p = 6$ lag in the VAR as in LMN.

variables in X_t based on careful consideration of the interactions between variables. However, we have included uncertainty measures in the system to determine the role of uncertainty in the exchange rate responses to monetary policy shocks. As emphasized by LMN, there is no consensus on the interacting relations between uncertainty and other variables; although many theoretical causal relations between uncertainty and output movements (or other variables) have been proposed, we still do not know which channel is dominant. In addition to uncertainty variables, the other variables could also interact contemporaneously with each other in a complicated manner. For example, Kim and Roubini (2000) and Bjørnland (2009) have emphasized the contemporaneous relation between monetary policy and the exchange rate. For these reasons, we take a shock-based SVAR approach to identify structural shocks rather than imposing contemporaneous zero restrictions.

The identification strategy employed in our shock-based SVAR is as follows. Let $\hat{P}$ be the unique lower-triangular Cholesky factor of $\widehat{\Sigma_u}$. Hence, $\widehat{\Sigma_u} = \hat{P}\hat{P}'$. For a random orthonormal matrix Q, we also have $(\hat{P}Q)(\hat{P}Q)' = \hat{P}QQ'\hat{P}' = \widehat{\Sigma_u}$, which means that $\hat{P}Q$ satisfies the restrictions required for A_0^{-1}. We generate Q randomly and rotate $\hat{P}$ 2 million times and compute the corresponding $\hat{\varepsilon}_t = \left(\hat{P}Q\right)^{-1}\hat{u}_t$ for each generated Q. Of the 2 million series of $\hat{\varepsilon}_t$, we consider those $\hat{\varepsilon}_t$ that satisfy the conditions for a plausible structural shock and conduct our analysis using those $\hat{\varepsilon}_t$. Similar to LMN, the conditions for our shock-based SVAR approach consist of event and external variable constraints, which are summarized below.

Event constraints:

1. $\varepsilon_{F_{t_1}}(\hat{A}_0^{-1}) \geq \bar{k}_1$ at t_1 =1987:10 (Black Monday)

2. $\varepsilon_{R_{t_2}}(\hat{A}_0^{-1}) \geq \bar{k}_2$ or $\varepsilon_{F_{t_2}}(\hat{A}_0^{-1}) \geq \bar{k}_3$ at t_2 =2008:09 (Collapse of Lehman Brothers)

3. $\sum_{t_3} \varepsilon_{Y_{t_3}} (\hat{A}_0^{-1}) \leq 0$ for t_3 ∈[2007:12, 2009:06] (Great Recession)

4. $\varepsilon_{R_{t_4}}(\hat{A}_0^{-1}) \geq 0$ and $\varepsilon_{F_{t_4}}(\hat{A}_0^{-1}) \geq 0$ at t_4 ∈[2011:07, 2011:08] (Debt-ceiling Crisis)

5. $\sum_{t_5} \varepsilon_{q_{t_5}} (\hat{A}_0^{-1}) \leq 0$ for t_5 ∈[1985:09, 1987:01] (Plaza Accord)

The first constraint states that a plausible ε_{F_t} should be high when the stock market crashed in October 1987. The second constraint dictates that either ε_{F_t} or ε_{R_t} must be high in September 2008 when Lehman Brothers filed for bankruptcy. The third constraint requires that the sum of the real output shocks during the Great Recession must be below average.[3] The fourth constraint restricts both types of uncertainty shock (ε_{F_t} and ε_{R_t}) to a non-negative value during the debt-ceiling crisis in 2011. We set $\bar{k}_1$, $\bar{k}_2$, and $\bar{k}_3$ equal to the 50th percentile for ε_{F_t} and ε_{R_t} in the set of 2 million generated structural shocks for the event dates t_1 and t_2.[4] These four constraints are qualitatively identical to those considered by LMN.[5]

The last event constraint requires that the sum of the shocks to the US real effective exchange rate be non-positive, which reflects the depreciation of the US dollar, from the time of the agreement of the Plaza Accord until it was replaced by the Louvre Accord in 1987. The Plaza Accord was a joint agreement signed by five countries to depreciate the US dollar against

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[3] The period [2007:12, 2009:06] is taken from NBER recession dates.

[4] The results presented in the next section are robust even if the values for $\bar{k}_1$, $\bar{k}_2$, and $\bar{k}_3$ are set at a value between the 40th percentile and 65th percentile of ε_{F_t} and ε_{R_t} in the set of 2 million-generated structural shocks for the event dates t_1 and t_2. These results are available upon request.

[5] Because the sample period of this study is January 1985 to December 2019, the constraints in LMN for the high macro uncertainty shock at the end of 1970 due to the probable collapse of the Bretton Woods system and the positive shocks for macro uncertainty and financial uncertainty in October 1979 due to the Volker appointment are excluded.

the Japanese Yen and the Deutsche mark via intervention in currency markets.[6] The US real effective exchange rate depreciated by almost 21% during the Plaza Accord period due to the interventions of participating central banks (Figure 1). This final constraint requires that the sum of the real effective exchange rate shocks during the Plaza Accord period be below average to reflect this trend in the US exchange rate.

External Variable Constraints:

1. $corr(\varepsilon_{R_t}, S_{1t}) \leq 0$ and $corr(\varepsilon_{F_t}, S_{1t}) \leq 0$
2. $corr(\varepsilon_{R_t}, S_{2t}) \geq 0$ and $corr(\varepsilon_{F_t}, S_{2t}) \geq 0$
3. $corr(\varepsilon_{i_t}, S_{3t}) \geq 0.05$
4. $corr(\varepsilon_{q_t}, S_{2t}) \geq 0$
5. $corr(\varepsilon_{Y_t}, S_{4t}) \geq 0.1$

S_{1t} denotes the real return of the S&P 500 index, S_{2t} is the growth rate of the real gold price, S_{3t} represents the monetary policy news shock identified in Nakamura and Steinsson (2018), and S_{4t} is the growth rate of total factor productivity (TFP). All of these variables are external to the SVAR system described above. The first external variable constraint states that the structural shock to the real uncertainty and the structural shock to the financial uncertainty should be negatively correlated with the aggregate stock returns. That is, when ε_{R_t} or ε_{F_t} raises the real or financial uncertainty, the S&P 500 index returns tend to fall. The second constraint requires that, when both types of uncertainty in the US rise due to ε_{R_t} and ε_{F_t}, the

[6] The five countries that signed the Plaza Accord agreement were France, West Germany, Japan, the UK, and the US.

gold price also tends to rise. The third constraint means that the monetary policy shock ε_{i_t} identified in this study must be correlated with the monetary policy news shock identified using the different approach reported by Nakamura and Steinsson (2018). The fourth external variable constraint requires ε_{q_t} to be positively correlated with changes in the real gold price, meaning that the value of US currency tends to go in tandem with the real gold price. The final external variable constraint dictates that the output shock in our SVAR be correlated with the growth rate of TFP. The first two external variable constraints are identical to those in LMN while the third and the fifth constraints are consistent with those considered by Kang and Park (2020).

III. Data

The real and financial uncertainty measures used in this study are those proposed by Jurado, Ludvigson, and Ng (2015) and used in LMN and Kang and Park (2020). These uncertainty measures demonstrate the degree of the difficulty in forecasting real activity variables or financial variables, which can be formulated as follows:

$$U_{jt}^{C}(h) \equiv \sqrt{E[(y_{jt+h}^{C} - E(y_{jt+h}^{C}|I_t)^2|I_t]} \tag{3}$$

where y_j^C is a variable related to the real and financial variables, category indicator $C \in \{R, F\}$, and I_t represents all information available at time t. The real and financial uncertainty measures are the weighted average of these squared forecast errors and we use a one-month forecast horizon as in LMN.[7] We use real uncertainty instead of the macro uncertainty measure

[7] Refer to Jurado, Ludvigson, and Ng (2015) and LMN for a detailed discussion of the uncertainty measures. The uncertainty measures were downloaded from Ludvigson's website (https://www.sydneyludvigson.com/macro-

because the latter fluctuates due to both financial market and real activity variables. The real and financial uncertainty measures are presented in Figure 2. As shown in Figure 2, both uncertainty measures are countercyclical and are notably high during the Great Recession, while the financial uncertainty is also notable in October 1987.

We use the monthly industrial production index for the output data and apply the HP filter (Hodrick and Prescott (1997)) to detrend the industrial production index. The inflation rate is constructed by the log difference of the monthly CPI. Both industrial production and CPI data are taken from the website for the Federal Reserve Bank of St. Louis.[8]

Data for the US real effective exchange rate are obtained from the Bank for International Settlements (BIS).[9] The US Federal Funds rate and other countries' central bank policy rates are also extracted from the BIS website. We calculate US trade weights for the top 20 countries that the US trades with each year.[10] We then multiply the central bank policy rates with the relative trade weights for these countries to produce the trade-weighted foreign policy rate for the US.[11] The sum of the trade weights for the countries included in the construction of the trade-weighted foreign policy rate for the US covers most of the total trade for the US during the sample period. For example, the sum of trade weights for countries included in the construction of the trade-weighted foreign policy rate for the US is above 82% of the US total

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[8] The web address is https://fred.stlouisfed.org/.

[9] The web address is https://www.bis.org/statistics/full_data_sets.htm.

[10] The website from which the data for US exports and imports with other countries are taken is https://www.census.gov/foreign-trade/balance/index.html.

[11] In calculating the trade-weighted foreign policy rate for the US, we cannot include the policy rate for Taiwan for the entire sample period or the policy rates for Hong Kong, Israel, and Saudi Arabia for certain periods due to data limitations.

trades in 2019. The sample period of this study is January 1985–December 2019, which is dictated by the availability of trade weight data for the US. Figure 3 plots the detrended US industrial production, CPI inflation rate, and interest differential which is the gap between the US Federal Funds rate and trade-weighted foreign policy rate.

IV. Dynamic Responses to Monetary Policy Shocks under Shock-based SVAR

This section provides empirical results from shock-based SVAR for six variables, $X_t = (U_{R_t}, Y_t, U_{F_t}, \pi_t, i_t - i_t^*, q_t)'$. With randomly generated 2 million orthonormal matrices Q, we rotate $\hat{P}$ (where $\widehat{\Sigma_u} = \hat{P}\hat{P}'$) and generate the same number of structural shocks $\hat{\varepsilon}_t$. Of the 2 million $\hat{\varepsilon}_t$, five satisfy the event and external variable constraints discussed in Section II. Figures 4 and 5 present the time series of the structural shocks $\varepsilon_t = (\varepsilon_{R_t}, \varepsilon_{Y_t}, \varepsilon_{F_t}, \varepsilon_{\pi_t}, \varepsilon_{i_t}, \varepsilon_{q_t})'$ for one solution satisfying all constraints. All identified shocks are negatively skewed and show excess kurtosis, which is similar to the results in LMN. Not only ε_{F_t} but also ε_{R_t} record large shocks in magnitude around October 1987. Large shocks are also noted for ε_{Y_t}, ε_{F_t}, and ε_{q_t} in September 2009 when Lehman Brothers filed for bankruptcy.

We focus on the responses of the variables in X_t to the five identified monetary policy shock series. Because the structural shocks identified by the shock-based SVAR approach are not unique, Figure 6 presents five impulse responses for each variable in the SVAR to contractionary monetary policy shocks. In general, contractionary monetary policy shocks are expected to raise the interest rate but lower output and the inflation rate. The impulse responses in the first row of Figure 6 are consistent with these predictions. Output declines immediately in response to a contractionary monetary policy shock, with the maximum reduction occurring within 5–9 months. Although the inflation rate rises in three cases and drops instantly in two cases, the response of the inflation rate becomes unanimously negative between 2 and 7 months after the shock occurs. The US interest rate relative to other economies rises immediately in response to a tighter US monetary policy stance but the initial impact disappears within 20 months, which indicates a temporary increase in the interest rate. The propagation of the effect of tightening monetary policy shown in the first row of Figure 6 is consistent with the predictions in the literature, which supports the validity of the identification strategy employed in this study.

The first two panels of the second row in Figure 6 present the dynamic effect of contractionary monetary policy shocks on real and financial uncertainty measures. There is a distinct difference in the responses of real and financial uncertainty to monetary policy shocks. Real uncertainty instantly rises with a tighter monetary policy and then declines gradually in four of the five cases. This response may be related to the delay in investment and consumption decisions caused by the temporarily higher interest rate accompanied by a contractionary monetary policy. The response of financial uncertainty to a tighter monetary policy is negative from 3 to 17 months after the shock in four of the five cases, although there is no clear trend in the immediate response of financial uncertainty. The decrease in financial uncertainty in response to a contractionary monetary policy may arise because the higher interest rate caused by a contractionary monetary policy prevents speculative behavior in the financial market. These responses of uncertainty measures to contractionary monetary policy shocks are generally similar to those reported in Kang and Park (2020).

The last panel of the second row in Figure 6 shows the response of the real effective exchange rate to contractionary monetary policy shocks. The US real effective exchange rate appreciates immediately in response to tighter monetary policies in all five cases. In contrast to previous studies that have reported that real appreciation peaks two to three years after a shock, the maximum appreciation in Figure 6 occurs almost immediately (i.e., within 2–6 months). Figure 7 magnifies the last panel of the second row in Figure 6 and shows the point-wise median response (the red dashed line) of the US real effective exchange rate to contractionary monetary policy shocks. From the median response, the US real effective exchange rate appreciates immediately, and appreciation peaks at six months. Figure 7 also shows the 60% credible set (the gray shaded area) that excludes the point-wise maximum and minimum responses. The credible set illustrates that the response is significant from the moment of impact until 15 months later, and the set only includes zero starting 16 months after the shock. After it peaks within 2–6 months, the real exchange rate gradually depreciates back to its initial level, which is generally consistent with other theories such as the Dornbusch (1976) model.

Overall, the dynamic response of the exchange rate to monetary policy in this study differs from the responses reported in previous studies in that there is clear instant appreciation and no delayed overshooting in the exchange rate response. It is thus important to determine whether this difference is because we include uncertainty measures in the SVAR or because the identification strategy employed in our shock-based SVAR differs from the restrictions imposed by existing studies. We address this in the following section.

V. Potential Sources of Anomalous Exchange Rate Response

The impulse responses presented in Figures 6 and 7 differ from those reported in many existing studies in that the figures show immediate appreciation and no delayed overshooting of the exchange rate in response to contractionary monetary policy. In this section, we investigate whether this difference arises from the use of novel uncertainty measures in the SVAR or from the identification strategy employed in the shock-based SVAR. We also examine features of $\hat{P}Q$ that satisfy all of the constraints discussed in Section II and compare those features with the restrictions imposed on the SVAR in previous studies.

1. Role of Uncertainty Measures

In this sub-section, we exclude either real uncertainty or financial uncertainty from the SVAR to determine whether immediate appreciation and no delayed overshooting are observed in their absence. This can potentially reveal the role of uncertainty measures in the dynamic response of the real effective exchange rate. Because real uncertainty, financial uncertainty, or both are excluded from the SVAR, the event constraints and external variable constraints imposed on these uncertainty measures must be modified or removed. The identification restrictions modified for the shock-based SVAR are summarized in Table 1.

Figure 8 presents the dynamic effects of contractionary monetary policy shocks on the real effective exchange rate when only financial uncertainty is excluded from the SVAR. i.e., $X_t = (U_{R_t}, Y_t, \pi_t, i_t - i_t^*, q_t)'$. We randomly generate 2 million structural shock candidates, and seven of them pass the modified constraints summarized in the first column of Table 1. The general pattern of the impulse responses of the real effective exchange rate in Figure 8 is similar to that in Figure 6. Maximum appreciation occurs within two to six months for all seven cases and the effect of a contractionary monetary policy shock slowly disappears as the horizon increases. However, it is worth noting that two of the seven cases show immediate depreciation in response to a contractionary monetary policy shock, although the size of this depreciation on impact is small. Figure 8 thus indicates that the absence of financial uncertainty may not cause the delayed overshooting problem but may lead to immediate depreciation or no significant response to contractionary monetary policy shocks at the moment of impact.

Figure 9 plots the impulse responses of the real effective exchange rate to contractionary monetary policy shocks when only real uncertainty is excluded from the SVAR, i.e., $X_t = (Y_t, U_{F_t}, \pi_t, i_t - i_t^*, q_t)'$. It is found that 107 of the 2 million candidates pass the modified constraints summarized in the second column of Table 1. As a result, the gray shaded area reports all impulse responses from these 107 cases. The gray shaded area includes both positive and negative values, which suggests that immediate appreciation and immediate depreciation are both possible when real uncertainty is excluded. In particular, 28 of the 107 cases exhibit instant depreciation in response to contractionary monetary policy shocks. We can also observe delayed overshooting when real uncertainty is eliminated from the SVAR, with the maximum appreciation occurring two years after the monetary policy shock in 9 of the 107 cases. These results suggest that both immediate depreciation and delayed overshooting are possible when only financial uncertainty is included in the SVAR.

Figure 10 displays the set of impulse responses of the real effective exchange rate to contractionary monetary policy shocks when both real and financial uncertainties are removed from the SVAR, i.e., $X_t = (Y_t, \pi_t, i_t - i_t^*, q_t)'$. In this case, the constraints associated with real or financial uncertainty become meaningless, thus the constraints listed in the third column of Table 1 are imposed to identify structural shocks. Because fewer constraints are imposed, more solutions are identified, leading to 4429 cases from the 2 million candidates. The gray shaded area in Figure 10 reports all of the impulse responses for these 4429 cases. Immediate depreciation and immediate appreciation are observed when both uncertainty measures are removed. More specifically, 1086 of the 4429 cases exhibit instant depreciation in response to a contractionary monetary policy shock, which is inconsistent with theoretical models. In addition, delayed overshooting is also common when both types of uncertainty are absent from the SVAR. In 303 of the 4429 cases, maximum appreciation occurs two years after the contractionary monetary policy shock.

Figures 8–10 suggest that both uncertainty measures play an important role in understanding the non-intuitive results reported in previous studies. With shock-based SVAR, both uncertainty measures are required to produce immediate appreciation and no delayed overshooting in the impulse response of the exchange rate to contractionary monetary policy. Without real or financial uncertainty in the SVAR, we can observe immediate depreciation and/or delayed overshooting in response to contractionary monetary policy shocks.

2. Recursive Identification Restrictions

The previous sub-section highlights the importance of uncertainty measures in understanding the responses of the exchange rate to a tighter monetary policy. In this sub-section, we examine the response of the real effective exchange rate to contractionary monetary policy shocks when the uncertainty measures are considered under recursive identification restrictions instead of constraints for the shock-based SVAR. For comparison purposes, we begin without any uncertainty measure to determine whether the well-established hump-shaped response can be obtained using $X_t = (Y_t, \pi_t, i_t - i_t^*, q_t)'$. The recursive identification restriction for $X_t = (Y_t, \pi_t, i_t - i_t^*, q_t)'$ assumes that the Fed considers output and inflation in setting its monetary policy, which has been a typical assumption employed in previous studies. Recursive identification restrictions also assume that the real effective exchange rate can respond immediately to a monetary policy shock, while monetary policy responds to the real effective exchange rate with a lag of at least one month. The response of the real effective exchange rate with the use of four-variable SVAR and recursive identification restrictions is indicated by the red solid line in Figure 11. Although instant appreciation is observed in response to a tighter monetary policy, appreciation peaks 28 months after the shock, which is consistent with the typical delayed overshooting reported in previous studies.

Following the recursive identification assumptions in Bloom (2009) and subsequent studies, we put each of the uncertainty measures ahead of the other variables and impose recursive constraints, i.e., $X_t = (U_{R_t}, Y_t, \pi_t, i_t - i_t^*, q_t)'$ or $X_t = (U_{F_t}, Y_t, \pi_t, i_t - i_t^*, q_t)'$. When one of the uncertainty measures is added to the SVAR, the impulse responses of the real exchange rate to contractionary monetary policy shocks are plotted with the black and blue dotted lines in Figure 11. Both responses exhibit instant appreciation but delayed overshooting. Maximum appreciation occurs after 25 months without financial uncertainty and 28 months without real uncertainty.[12]

Finally, we put both uncertainty measures ahead of the other variables in the SVAR and recursive restrictions. When $X_t = (U_{R_t}, U_{F_t}, Y_t, \pi_t, i_t - i_t^*, q_t)'$, the impulse responses of the real effective exchange rate to contractionary monetary policy shocks are plotted with the green dashed line in Figure 11. Delayed overshooting can be observed in the responses and maximum appreciation occurs 25 months after the shock. When we switch the order of real and financial uncertainty, the impulse response is almost indistinguishable from the green dashed one in Figure 11.

[12] The hump-shaped response pattern remains when we switch the order of uncertainty and output.

In summary, all of the impulse responses in Figure 11 suggest that delayed overshooting remains under recursive identification restrictions even if uncertainty measures are included in the SVAR.

3. $\hat{P}Q$ Matrices Satisfying All Constraints for Shock-based SVAR

The results presented in previous sub-sections indicate that anomalies in the exchange rate responses to monetary policy shocks are an artifact arising from recursive identification restrictions and not controlling for uncertainty. However, some studies such as Kim and Roubini (2000) and Bjørnland (2009) have imposed non-recursive restrictions on A_0^{-1} rather than recursive restrictions to identify monetary policy shocks. Hence, we investigate elements in five $\hat{P}Q = A_0^{-1}$ matrices satisfying all of the constraints in Section II, although it is difficult to directly compare the present study with previous studies because of the different variables considered in the SVAR.

Table 2 presents the intervals for all elements in five $\hat{P}Q$ matrices satisfying the event constraints and external variable constraints in Section II. If recursive constraints are imposed, all of the elements above the diagonal must be zero. However, three of the intervals above the diagonal do not include zero: $(\hat{P}Q)_{2,5}$, $(\hat{P}Q)_{2,6}$, and $(\hat{P}Q)_{5,6}$. Imposing zero on these elements may be too strong even though recursive constraints produce a unique solution.

Even if the identification restrictions are not recursive, we need at least $\frac{6 \cdot 5}{2} = 15$ restrictions to identify a unique structural shock. According to the results in Table 2, however, we can find 10 intervals among the off-diagonal elements that do not include zero: $(\hat{P}Q)_{2,5}$, $(\hat{P}Q)_{2,6}$, $(\hat{P}Q)_{3,1}$, $(\hat{P}Q)_{4,1}$, $(\hat{P}Q)_{4,2}$, $(\hat{P}Q)_{5,3}$, $(\hat{P}Q)_{5,6}$, $(\hat{P}Q)_{6,1}$, $(\hat{P}Q)_{6,2}$, and $(\hat{P}Q)_{6,5}$.

This indicates that zero restrictions on these places in $\hat{P}Q = A_0^{-1}$ should be avoided. Kim and Roubini (2000) and Bjørnland (2009) have emphasized the contemporaneous interaction between monetary policy and the exchange rate in the identification strategy, which can be interpreted as non-zero for $(\hat{P}Q)_{5,6}$ in our SVAR. Interestingly, all of the elements for $(\hat{P}Q)_{5,6}$ in our exercise are positive, which is consistent with the assumption in these studies.[13] However, our approach is distinct from Kim and Roubini (2000) and Bjørnland (2009) in that we focus on identifying monetary policy shocks in the US, while they focus on identifying monetary policy shocks in non-US economies. In addition, $\hat{P}Q$ in this study differs from A_0^{-1} in Bjørnland (2009). For example, although Bjørnland (2009) assumes that the contemporaneous effect of an interest rate shock on output is zero when identifying structural shocks, the corresponding element $(\hat{P}Q)_{2,5}$ is always negative in our results. The unanimous non-zero elements $(\hat{P}Q)_{2,5}$ and $(\hat{P}Q)_{2,6}$ suggest that our identification strategy differs from that in Kim and Roubini (2000), who assume that real activity responds to interest rates and exchange rates with one period lag.

Finally, studies such as Faust and Rogers (2003) and Scholl and Uhlig (2008) have directly placed sign restrictions on impulse responses and obtained non-unique structural shocks satisfying these restrictions. However, our approach differs in that we do not impose any restrictions on the shape of an impulse response *a priori*. Our restrictions are imposed on the characteristics of structural shocks based on historical experience and correlations with variables that are external to our SVAR.

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[13] The contemporaneous interaction between monetary policy and the exchange rate arises because the exchange rate is affected by the current and future monetary policy stance and the Fed monitors the exchange rate and financial variables to control inflation and output.

VI. Variance Decomposition

In addition to the impulse response analysis, we conduct variance decomposition analyses to compute the quantitative importance of structural shocks in explaining the variability of the real effective exchange rate. Many empirical studies have quantified the importance of monetary policy shocks in exchange rate dynamics. The results differ greatly between studies depending on the methodologies employed and the structural shocks assumed. Of these, Clarida and Gali (1994), Faust and Rogers (2003), Juvenal (2011), and Kim and Park (2019) have reported a small contribution of monetary policy shocks to variation in the exchange rate, whereas Eichenbaum and Evans (1995), Rogers (1999), and Bergin (2006) have argued that monetary policy shocks account for a considerable portion of exchange rate movements. Hence, it would be interesting to investigate the relative contributions of structural shocks identified by the shock-based SVAR to fluctuations in the real effective exchange rate.

Table 3 presents fractions for the h-month-ahead forecast error variance of the real effective exchange rate attributable to each structural shock for various forecast horizons and h_{max}, where h_{max} is the horizon at which the fraction of the forecast error variance for a given structural shock is highest. Because multiple structural shocks pass the event and external variable constraints in Section II, we have a range of fractions for the forecast error variance. Though it is not easy to make a clear comparison, the empirical results in Table 3 suggest that real output shocks are most important factor in explaining the dynamics of the real effective exchange rate, explaining 24%–85% of the variation in the real effective exchange rate at h_{max}. Following output shocks, monetary policy shocks explain 7.7%–48% and real uncertainty shocks account for 3.3%–32% of the real effective exchange rate variation at h_{max}. The relative contribution of monetary policy shocks to the variability of the real effective exchange rate also declines gradually, as predicted by many theoretical models. However, monetary policy shocks still account for 4.2%–35% of the variation in the real effective exchange rate 100 months after the shock occurs.

We also report in Table 4 the variance decomposition results for the max-G solution to gain a clearer understanding of the relative importance of each structural shock.[14] Again, output shocks make the largest contribution to fluctuations in the real effective exchange rate, followed by financial uncertainty shocks and monetary policy shocks in the short run and by real uncertainty shocks and monetary policy shocks for the 100-month horizon.

As indicated by Tables 3 and 4, monetary policy shocks are not the most dominant factor in explaining the variability of the real effective exchange rate but do still account for a substantial fraction of this variability in the short run and at the 100-month horizon. It is also worth noting that the relative contribution of monetary policy shocks decreases gradually as the forecast horizon increases, while the relative contribution of real uncertainty increases.

VII. Conclusion

Previous studies have had difficulty explaining the discrepancy between the estimated responses of the exchange rate to monetary policy shocks reported in empirical studies and theoretical predictions of these responses. We revisit this issue employing the recently

[14] The max-G solution refers to a unique solution that collectively maximizes the inequalities pertaining to external variable constraints. Refer to LMN for a detailed definition of the max-G solution. The max-G solution for the response of the US real effective exchange rate is presented as the blue dashed line in Figure 3.

developed shock-based SVAR with real and financial uncertainty measures. We demonstrate that the US real effective exchange rate appreciates immediately and shows no delayed overshooting behavior using the shock-based SVAR with real and financial uncertainty measures. We also provide evidence that the use of recursive identification restrictions or the exclusion of either of the two uncertainty measures can result in the anomalous behavior of the exchange rate. We also show that monetary policy shocks account for a substantial portion of the fluctuation in the real effective exchange rate, although real output shocks are the largest contributor.

The results in this study suggest that the puzzling response of the exchange rate to contractionary monetary policy shocks observed in many studies may be the consequence of recursive identification restrictions and not controlling for uncertainty measures. These results also indicate that studies employing the DSGE approach should avoid replicating the delayed overshooting behavior of the exchange rate when the risk premium or uncertainty is considered in the model.

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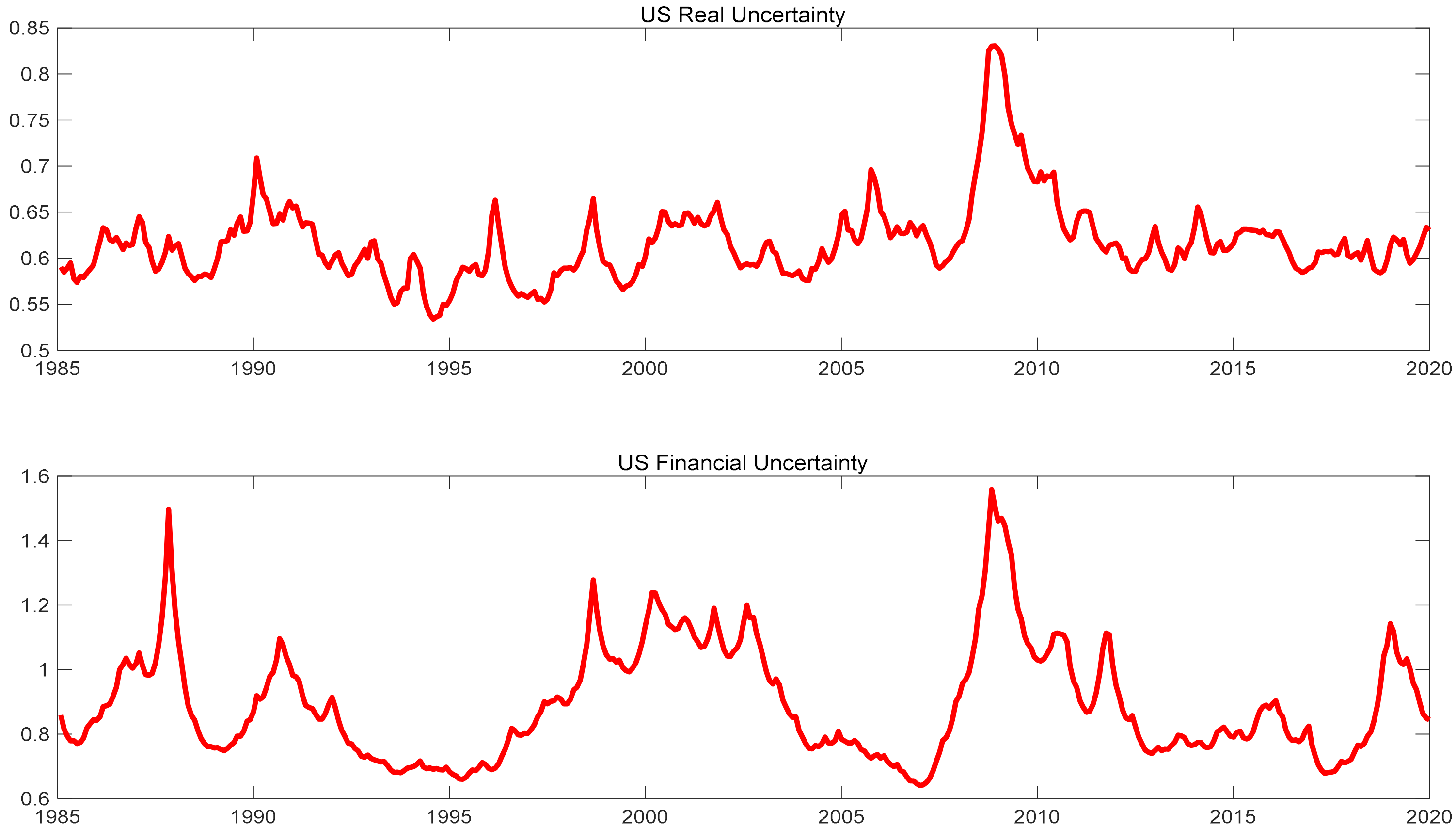
Figure 1. Movement in the Log US Real Effective Exchange Rate

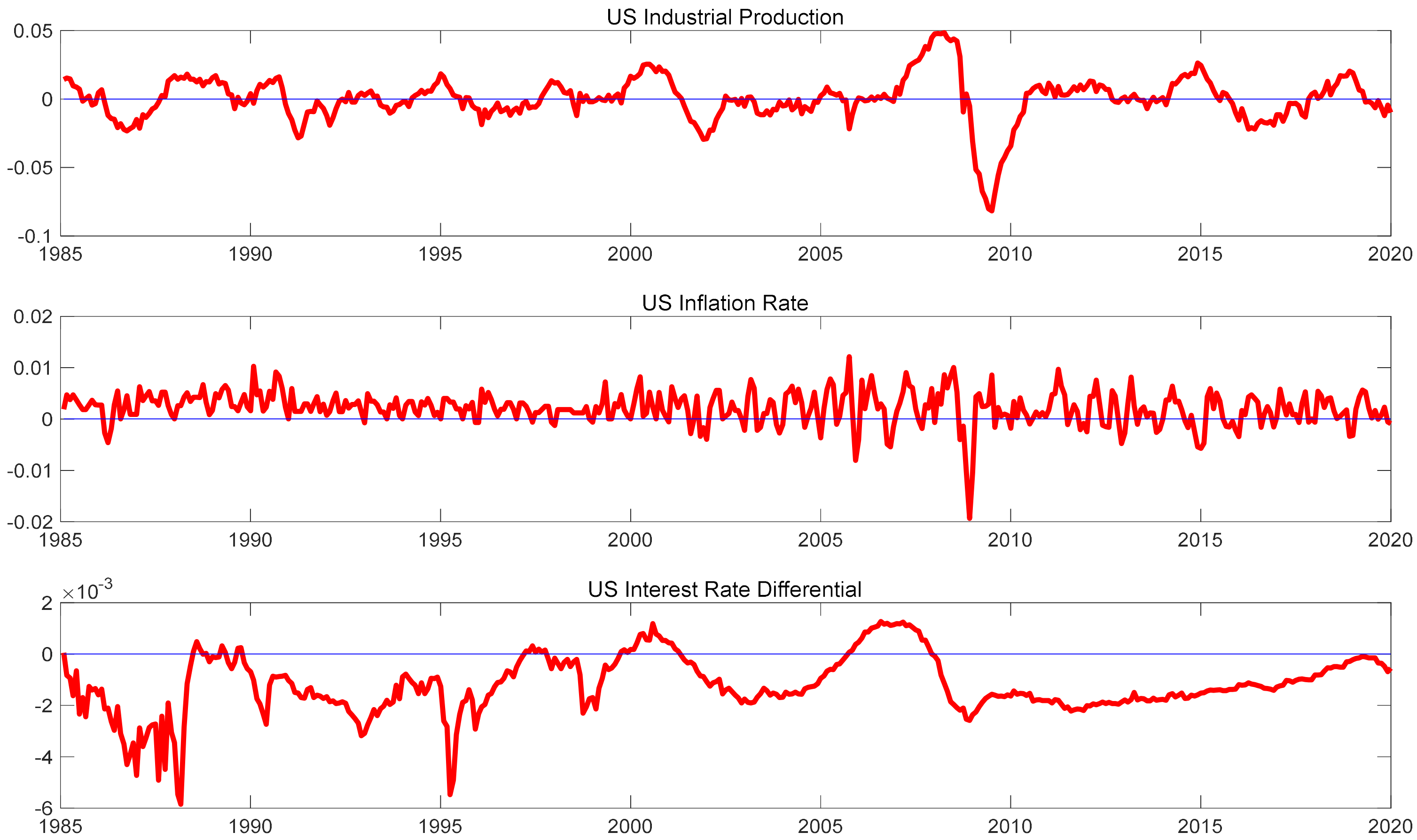
Notes: Figure 1 shows the movement in the log US real effective exchange rate between January 1985 and December 2019. Data are obtained from the BIS.

Figure 2. Movements of Uncertainty Measures



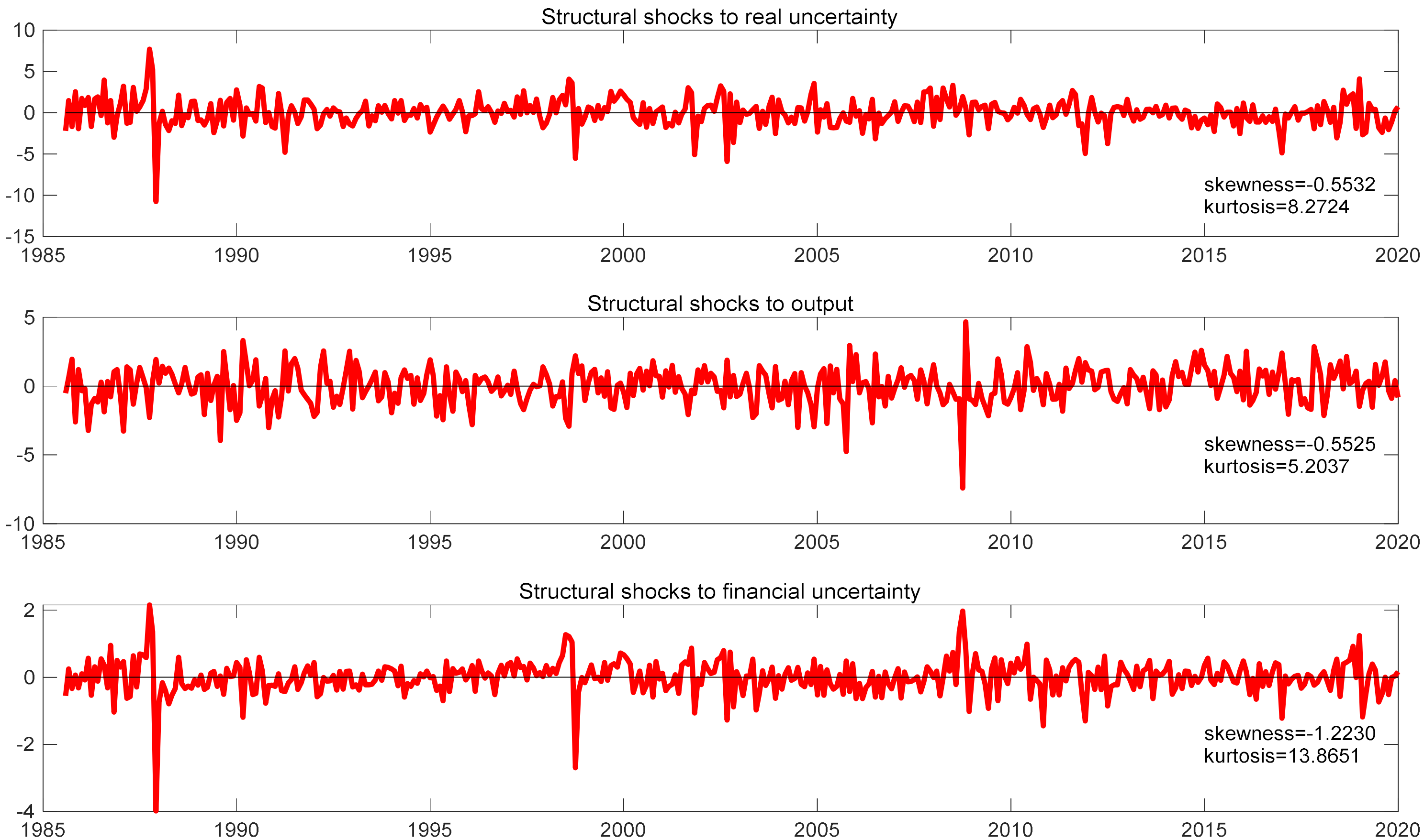
Notes: Figure 2 shows the movement in uncertainty measures between January 1985 and December 2019. Data are obtained from Ludvigson's website.

Figure 3. Movements of Macroeconomic Variables



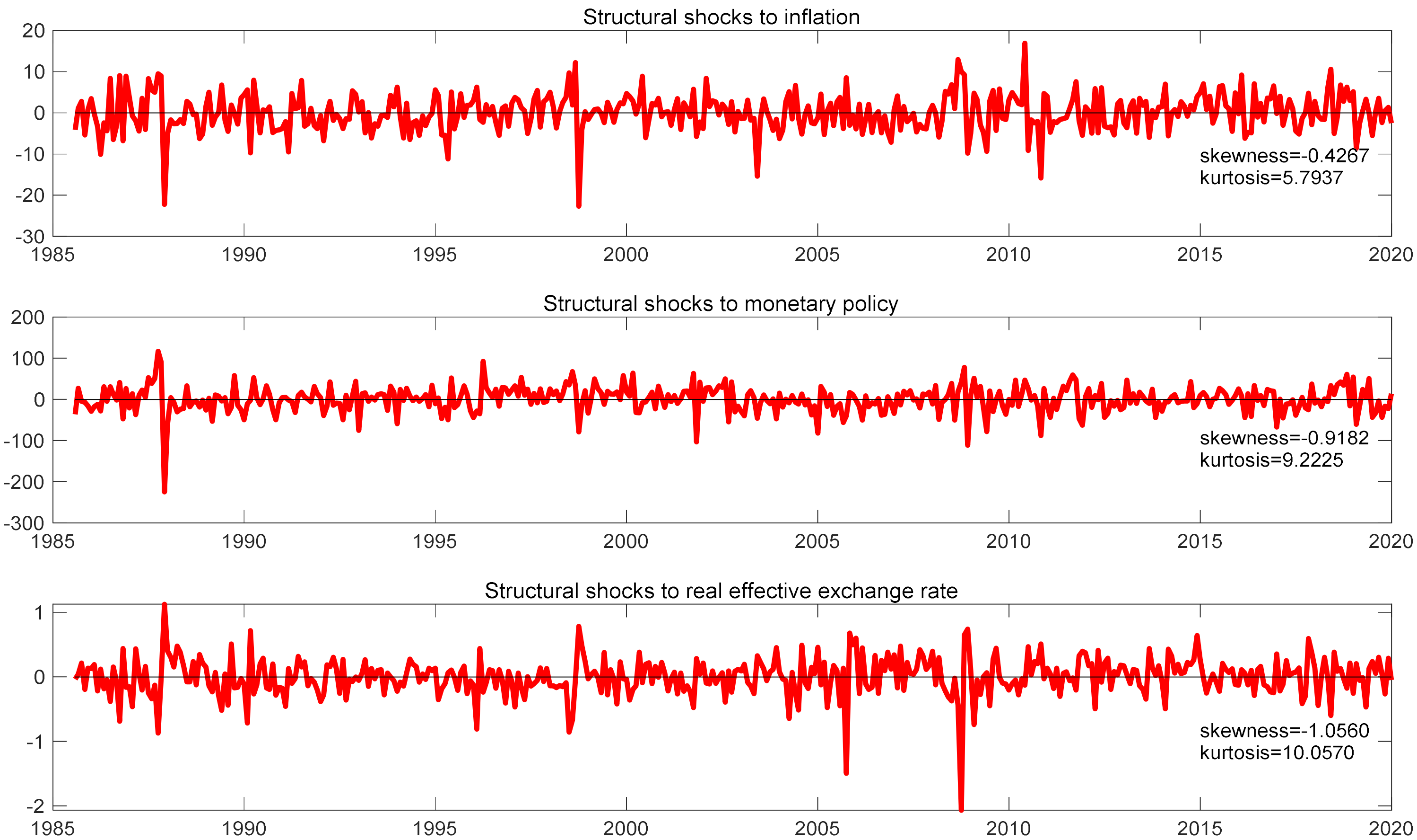
Notes: Figure 3 shows the movement of macroeconomic variables in the SVAR between January 1985 and December 2019.

Figure 4. One Solution of Structural Shocks to Real Uncertainty, Output, and Financial Uncertainty



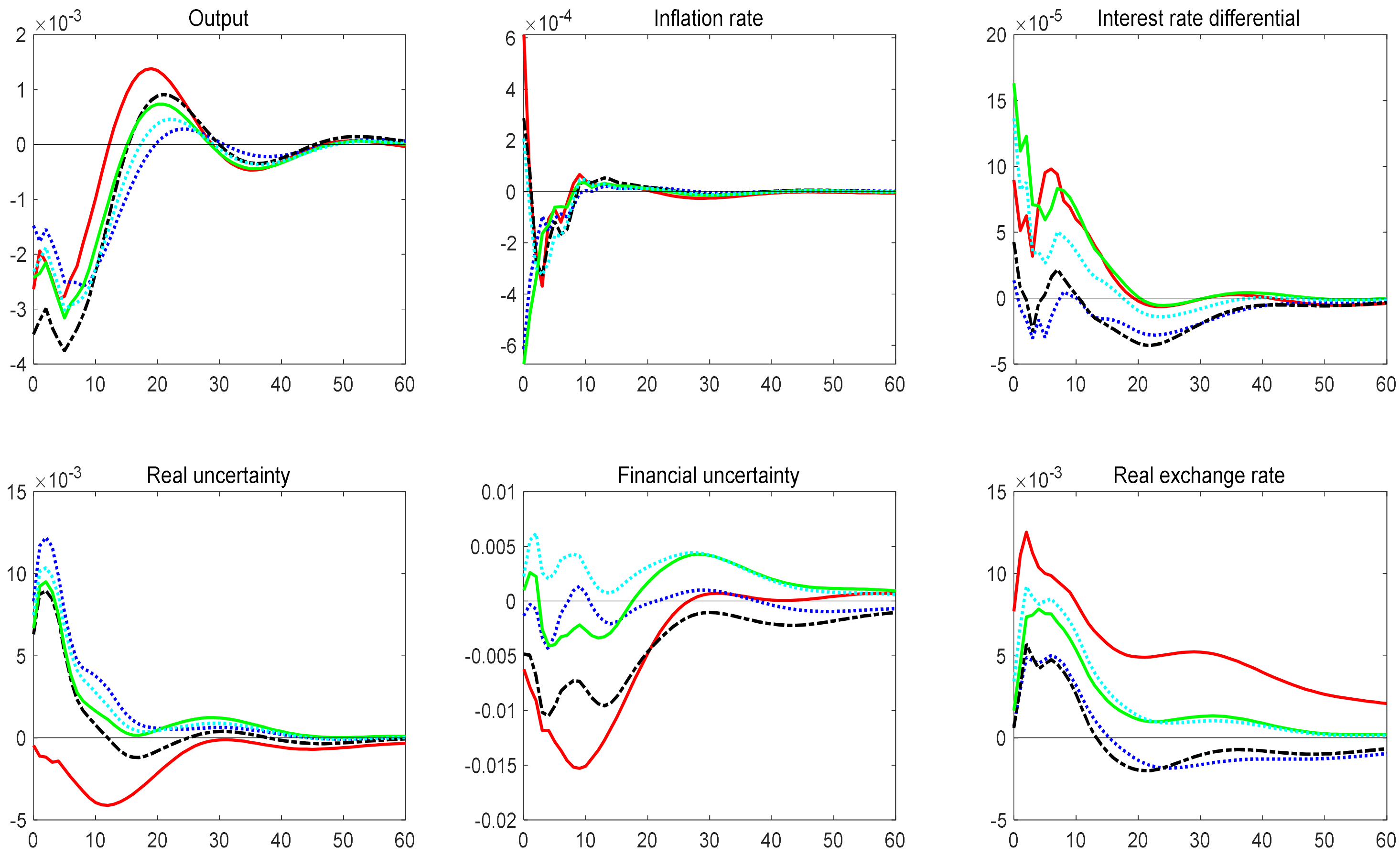
Notes: Figure 4 reports the time series of ε_{R_t}, ε_{Y_t}, and ε_{F_t} for one solution from the set of five solutions satisfying all constraints.

Figure 5. One Solution of Structural Shocks to Inflation Rate, Monetary Policy, and Real Exchange Rate



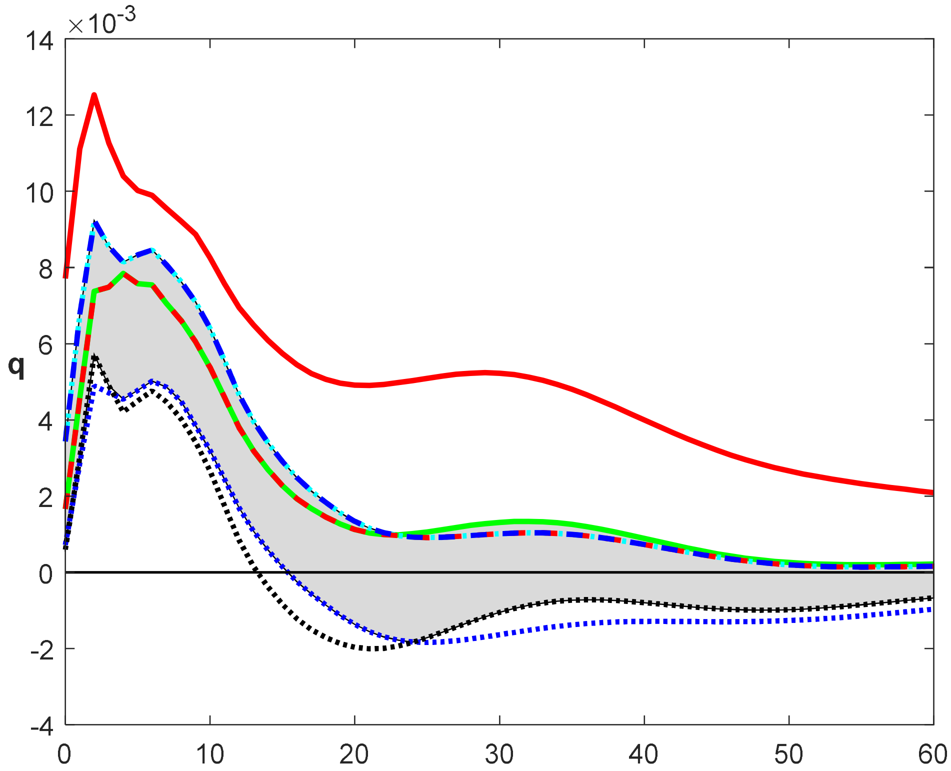
Notes: Figure 4 reports the time series of ε_{π_t}, ε_{i_t}, and ε_{q_t} for one solution from the set of five solutions satisfying all constraints.

Figure 6. Impulse Response to Contractionary Monetary Policy Shocks



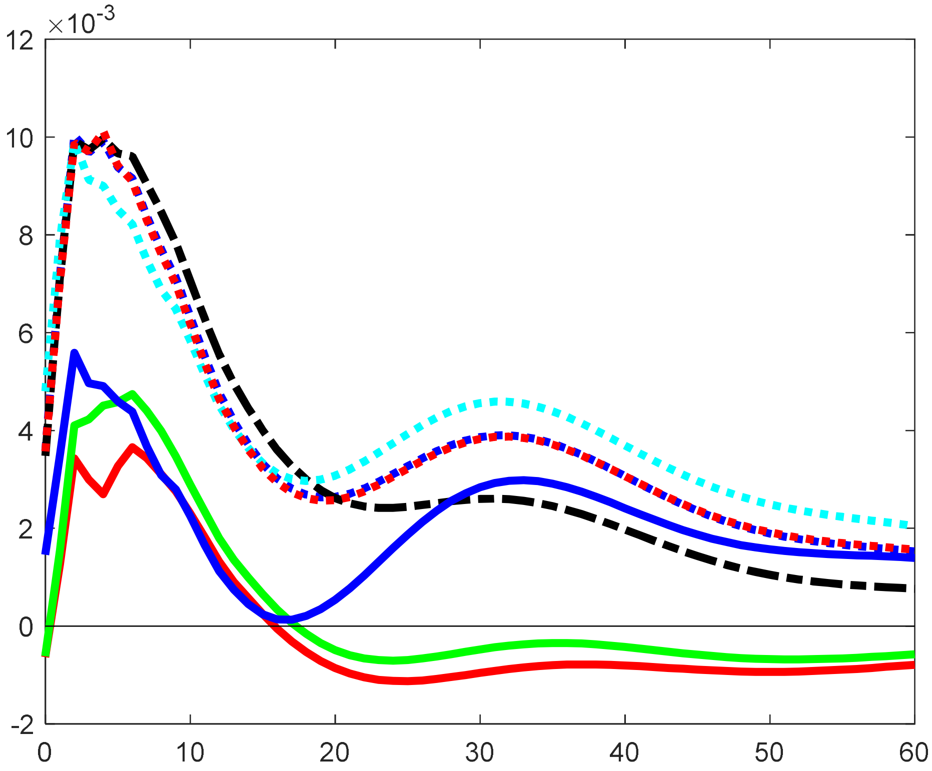
Notes: Figure 6 shows the impulse response to contractionary monetary policy shocks identified using the shock-based SVAR.

Figure 7. Impulse Response of the US Real Effective Exchange Rate to Contractionary Monetary Policy Shocks



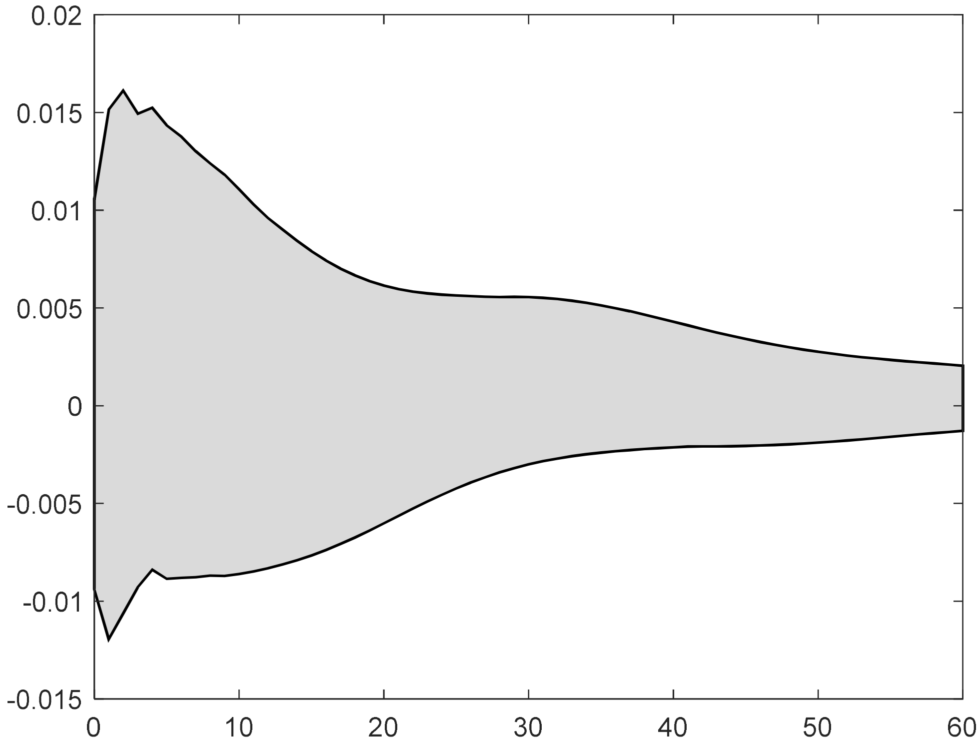
Notes: Figure 7 shows the point-wise median response (red dashed line) of the US real effective exchange rate to contractionary monetary policy shocks and the 60% credible set, which excludes the point-wise maximum and minimum responses (gray shaded area). Figure 3 also shows the max-G solution (blue dashed line) for the response of the exchange rate.

Figure 8. Response of the Real Effective Exchange Rate to Contractionary Monetary Policy Shocks without Financial Uncertainty



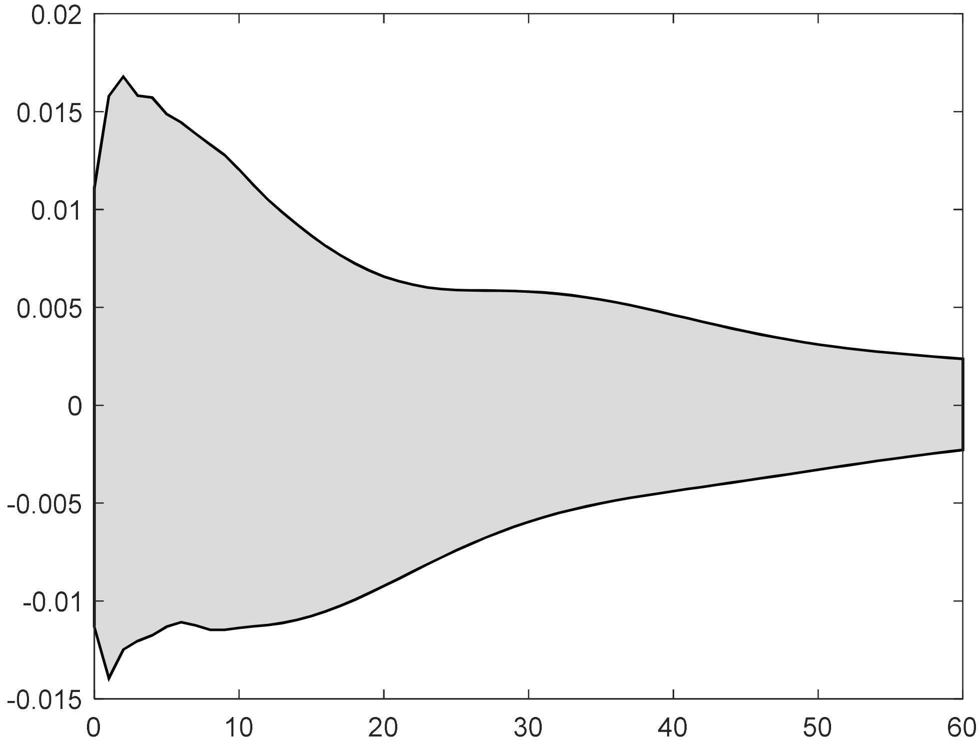
Notes: Figure 8 shows the dynamic effects of contractionary monetary policy shocks on the real effective exchange rate when financial uncertainty is excluded from the SVAR, i.e., $X_t = (U_{R_t}, Y_t, \pi_t, i_t - i_t^*, q_t)'$.

Figure 9. Response of the Real Effective Exchange Rate to Contractionary Monetary Policy Shocks without Real Uncertainty



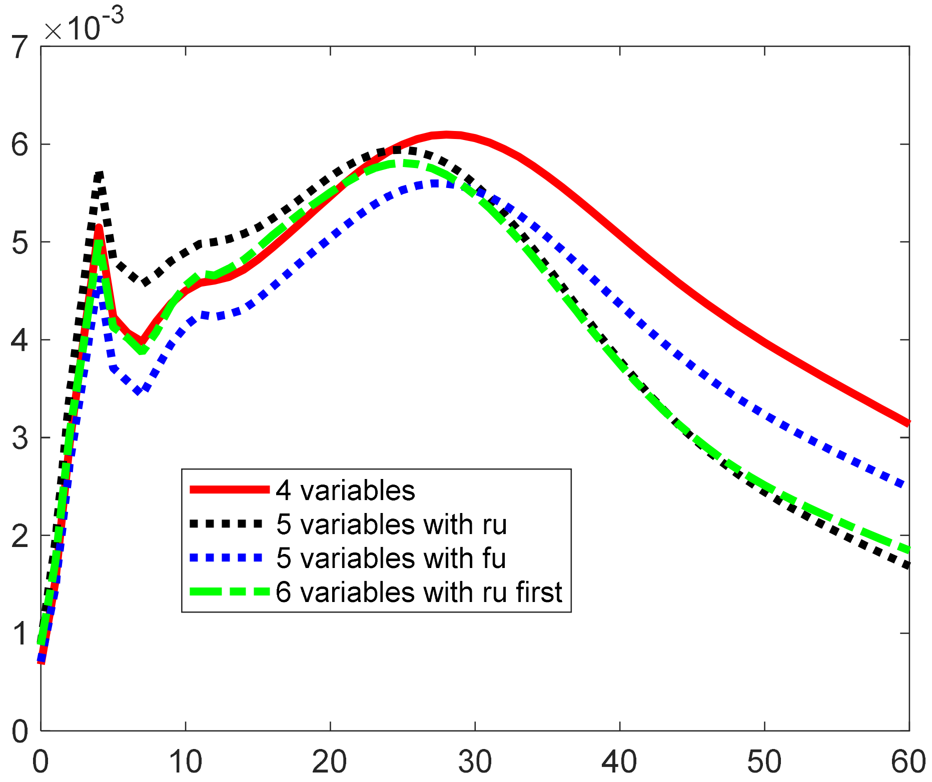
Notes: Figure 9 shows the dynamic effects of contractionary monetary policy shocks on the real effective exchange rate when real uncertainty is excluded from the SVAR, i.e., $X_t = (\ Y_t, U_{F_t}, \pi_t, i_t - i_t^*, q_t)'$.

Figure 10. Response of the Real Effective Exchange Rate to Contractionary Monetary Policy Shocks without Real Uncertainty or Financial Uncertainty



Notes: Figure 10 shows the dynamic effects of contractionary monetary policy shocks on the real effective exchange rate when real uncertainty and financial uncertainty are excluded from the SVAR, i.e., $X_t = (Y_t, \pi_t, i_t - i_t^*, q_t)'$.

Figure 11. Response of the Real Effective Exchange Rate to Contractionary Monetary Policy Shocks under Recursive Identification Restrictions



Notes: Figure 11 shows the dynamic effects of contractionary monetary policy shocks on the real effective exchange rate for various recursive restrictions imposed on the SVAR.

Table 1. Modified Identification Restrictions

	Without Financial Uncertainty $X_t = (U_{R_t}, Y_t, \pi_t, i_t - i_t^*, q_t)'$.		Without Real Uncertainty $X_t = (Y_t, U_{F_t}, \pi_t, i_t - i_t^*, q_t)'$.		Without Any Uncertainty Measures $X_t = (Y_t, \pi_t, i_t - i_t^*, q_t)'$.	
	Restrictions	Notes	Restrictions	Notes	Restrictions	Notes
Event Constraints	$\varepsilon_{R_{t_2}}(\hat{A}_0^{-1}) \geq \bar{k}_2$ at t_2 =2008:09	Collapse of Lehman Brothers	$\varepsilon_{F_{t_1}}(\hat{A}_0^{-1}) \geq \bar{k}_1$ at t_1 =1987:10	Black Monday	$\sum_{t_3} \varepsilon_{Y_{t_3}}(\hat{A}_0^{-1}) \leq 0$ for t_3 ∈[2007:12, 2009:06]	Great Recession
	$\sum_{t_3} \varepsilon_{Y_{t_3}}(\hat{A}_0^{-1}) \leq 0$ for t_3 ∈[2007:12, 2009:06]	Great Recession	$\varepsilon_{F_{t_2}}(\hat{A}_0^{-1}) \geq \bar{k}_3$ at t_2 =2008:09	Collapse of Lehman Brothers	$\sum_{t_5} \varepsilon_{q_{t_5}}(\hat{A}_0^{-1}) \leq 0$ for t_5 ∈ [1985:09, 1987:01]	Plaza Accord
	$\varepsilon_{R_{t_4}}(\hat{A}_0^{-1}) \geq 0$ at t_4 ∈[2011:07, 2011:08]	Debt Ceiling	$\sum_{t_3} \varepsilon_{Y_{t_3}}(\hat{A}_0^{-1}) \leq 0$ for t_3 ∈ [2007:12, 2009:06]	Great Recession		
	$\sum_{t_5} \varepsilon_{q_{t_5}}(\hat{A}_0^{-1}) \leq 0$ for t_5 ∈ [1985:09, 1987:01]	Plaza Accord	$\varepsilon_{F_{t_4}}(\hat{A}_0^{-1}) \geq 0$ at t_4 ∈ [2011:07, 2011:08]	Debt Ceiling		
			$\sum_{t_5} \varepsilon_{q_{t_5}}(\hat{A}_0^{-1}) \leq 0$ for t_5 ∈ [1985:09, 1987:01]	Plaza Accord		
External Variable Constraints	$corr(\varepsilon_{R_t}, S_{1t}) \leq 0$	Stock Returns	$corr(\varepsilon_{F_t}, S_{1t}) \leq 0$	Stock Returns	$corr(\varepsilon_{i_t}, S_{3t}) \geq 0.05$	Monetary Policy Shock
	$corr(\varepsilon_{R_t}, S_{2t}) \geq 0$	Gold Price	$corr(\varepsilon_{F_t}, S_{2t}) \geq 0$	Gold Price	$corr(\varepsilon_{q_t}, S_{2t}) \geq 0$	Gold Price
	$corr(\varepsilon_{i_t}, S_{3t}) \geq 0.05$	Monetary Policy Shock	$corr(\varepsilon_{i_t}, S_{3t}) \geq 0.05$	Monetary Policy Shock	$corr(\varepsilon_{Y_t}, S_{4t}) \geq 0.1$	TFP
	$corr(\varepsilon_{q_t}, S_{2t}) \geq 0$	Gold Price	$corr(\varepsilon_{q_t}, S_{2t}) \geq 0$	Gold Price		
	$corr(\varepsilon_{Y_t}, S_{4t}) \geq 0.1$	TFP	$corr(\varepsilon_{Y_t}, S_{4t}) \geq 0.1$	TFP		

Notes: Table 1 shows the modified identification restrictions that are compared for the event and external variable constraints in Section II.

Table 2. $(\hat{P}Q)$ Matrices Satisfying All Constraints for Shock-based SVAR

u_{R_t}		[0.0009, 0.0044]	[-0.0019, 0.0031]	[-0.0004, 0.0064]	[-0.0027, 0.0018]	[-0.0005, 0.0083]	[-0.0054, 0.0042]	ε_{R_t}
u_{Y_t}		[-0.0025, 0.0011]	[0.0011, 0.0029]	[-0.0015, 0.0042]	[-0.0008, 0.0013]	**[-0.0035, -0.0015]**	**[0.0001, 0.0040]**	ε_{Y_t}
u_{F_t}	=	**[0.0007, 0.0199]**	[-0.0030, 0.0055]	[0.0004, 0.0173]	[-0.0236, 0.0165]	[-0.0062, 0.0022]	[-0.0180, 0.0035]	ε_{F_t}
u_{π_t}		**[0.0010, 0.0023]**	**[0.0004, 0.0013]**	[-0.0013, 0.0018]	[0.0002, 0.0014]	[-0.0007, 0.0006]	[-0.0007, 0.0016]	ε_{π_t}
u_{i_t}		[-0.0003, 0.0001]	[-0.0001, 0.0001]	**[0.0000, 0.0002]**	[-0.0001, 0.0003]	[0.0000, 0.0002]	**[0.0001, 0.0004]**	ε_{i_t}
u_{q_t}		**[-0.0032, -0.0012]**	**[0.0061, 0.0114]**	[-0.0053, 0.0005]	[-0.0071, 0.0033]	**[0.0006, 0.0077]**	[0.0000, 0.0008]	ε_{q_t}

Notes: Table 2 shows intervals for each element in the $(\hat{P}Q)$ matrices satisfying the event constraints and external variable constraints in Section II. Bold fonts represent intervals that do not include zero in the off-diagonal positions.

Table 3. Variance Decomposition of the Real Effective Exchange Rate

	Real Uncertainty Shock	Output Shock	Financial Uncertainty Shock	Inflation Shock	Monetary Policy Shock	Real Exchange Rate Shock
h_1	[0.0051,0.0604]	[0.1997,0.8142]	[0.0022,0.1745]	[0.0696,0.3200]	[0.0203,0.4280]	[0.0002,0.0061]
h_6	[0.0101,0.1315]	[0.0970,0.6355]	[0.0065,0.1654]	[0.0953,0.3066]	[0.0722,0.4523]	[0.0015,0.0371]
h_{12}	[0.0137,0.1411]	[0.1060,0.6379]	[0.0061,0.1537]	[0.0902,0.2828]	[0.0664,0.4298]	[0.0039,0.0435]
h_{24}	[0.0299,0.2058]	[0.1028,0.6066]	[0.0227,0.1222]	[0.0775,0.2789]	[0.0509,0.3641]	[0.0291,0.0946]
h_{100}	[0.0323,0.3203]	[0.0728,0.5274]	[0.0197,0.1221]	[0.0592,0.2662]	[0.0421,0.3542]	[0.0364,0.1505]
h_{max}	[0.0325,0.3203]	[0.2441,0.8510]	[0.0242,0.1816]	[0.0964,0.3275]	[0.0769,0.4756]	[0.0426,0.1505]

Notes: Table 3 presents the results of forecast error variance decomposition for structural shocks satisfying all of the constraints in Section II.

Table 4. Variance Decomposition of the Real Effective Exchange Rate for the max-G Solution

	Real Uncertainty Shock	Output Shock	Financial Uncertainty Shock	Inflation Shock	Monetary Policy Shock	Real Exchange Rate Shock
h_1	0.0604	0.5502	0.1745	0.0789	0.1346	0.0015
h_6	0.1315	0.3576	0.1654	0.0964	0.2476	0.0015
h_{12}	0.1411	0.3582	0.1537	0.0902	0.2469	0.0099
h_{24}	0.2058	0.3764	0.1222	0.0775	0.1766	0.0415
h_{100}	0.3203	0.3604	0.0976	0.0592	0.1262	0.0364
h_{max}	0.3203	0.6171	0.1816	0.0964	0.2587	0.0426

Notes: Table 4 presents the results of forecast error variance decomposition for the max-G solution of the shock-based SVAR considered in this study. The max-G solution refers to a unique solution that satisfies all of the constraints in Section II and collectively maximizes the inequalities pertaining to the external variable constraints.