Impact of Uncertainty Created by the US Post-QE Monetary Policy on Emerging Economies

Jae-Young Kim and Woong Yong Park

This research studies the impact of uncertainty generated by the US monetary policy in the post-quantitative easing period, particularly regarding the timing and pace of policy rate normalization by the Federal Reserve. We are specifically interested in the effects on emerging market economies such as South Korea. By using a news-based uncertainty index to measure the extent of monetary policy uncertainty in the US, we find that unexpected increased uncertainty with respect to the US monetary policy has significant adverse impact on the KRW/USD exchange rate, stock prices, and capital inflow to South Korea, but does not significantly affect the macroeconomic variables of the country, such as output and consumer prices. Therefore, we expect that heightened uncertainty regarding US monetary policy normalization would, at most, have temporary disruptions in financial markets but does not have a large impact on emerging market economies.

Keywords: Monetary policy uncertainty; quantitative easing; emerging market economies

JEL Classification: E44; E52; E58; F41

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I. Introduction

In the wake of the financial crisis in the US in 2008, the Federal Reserve aggressively lowered its conventional policy instrument (i.e., federal funds rate (FFR)) to boost aggregate demand but hit the zero lower bound (ZLB) in late 2008. With the FFR stuck at ZLB, the Federal Reserve had to rely on Years after maintaining FFR effectively at zero and implementing unconventional monetary policy, the economy of the US started to recover from the most severe recession in the post-World War II period. As the US economy recovered, the Federal Reserve started discussion on tapering and withdrawing its unconventional monetary policy measures and normalizing FFR to a positive value. However, undoing such unconventional monetary policy measures was as unprecedented as the actual unconventional monetary policy. Well-established and academically investigated strategies on how to revert to conventional monetary policy, particularly in terms of timing and pace, are lacking, thereby generating considerable uncertainty in the private sector.

This research studies the impact of uncertainty generated by the US monetary policy in the post-QE period, particularly the consequences of increased uncertainty regarding the path of policy rate normalization by the Federal Reserve after the withdrawal of QE. We are specifically interested in the effects on emerging market economies. Among the emerging market countries, we consider South Korea a representative example because of its trade and financial openness.

Our strategy aims to estimate the effects of fluctuations of US monetary policy uncertainty (MPU) on South Korea in the period leading to the QE withdrawal. Thereafter, we use estimates to compute the expected impact of heightened uncertainty regarding the US monetary policy actions during the normalization phase. To measure the extent of uncertainty perceived by the private sector regarding monetary policy in the US, we use MPU proposed by Husted, Rogers, and Sun (2016). MUP is a news-based uncertainty measure that shows the frequency that major US newspapers cover MPU-related topics. Structural vector autoregression (SVAR) is used to identify exogenous variations in this MPU index and estimate the effects of such exogenous variations.

We find that unexpectedly increased uncertainty regarding US monetary policy does not significantly affect the macroeconomy of the US and South Korea. However, uncertainty shock has significant adverse impact on the KRW/USD exchange rate, stock price, and capital inflow to South Korea. In response to a shock to the MPU index, the Korean Won depreciates against the US Dollar, stock price declines, and capital flows less into South Korea. Thus, the financial markets of South Korea are sensitive to increased uncertainty regarding US monetary policy. However, the impact is not persistent, which presumably explains that uncertainty shock does not propagate from the financial markets of South Korea to its macroeconomy. Exports and imports respond negatively to uncertainty shock despite insignificant responses of output in the US and South Korea. Evidently, this situation remains puzzling.

The remainder of this paper is organized as follows. Section 2 explains in detail the MPU index and presents the details of the estimation method. Section 3 reports the estimation results. Lastly, Section 4 concludes this research.

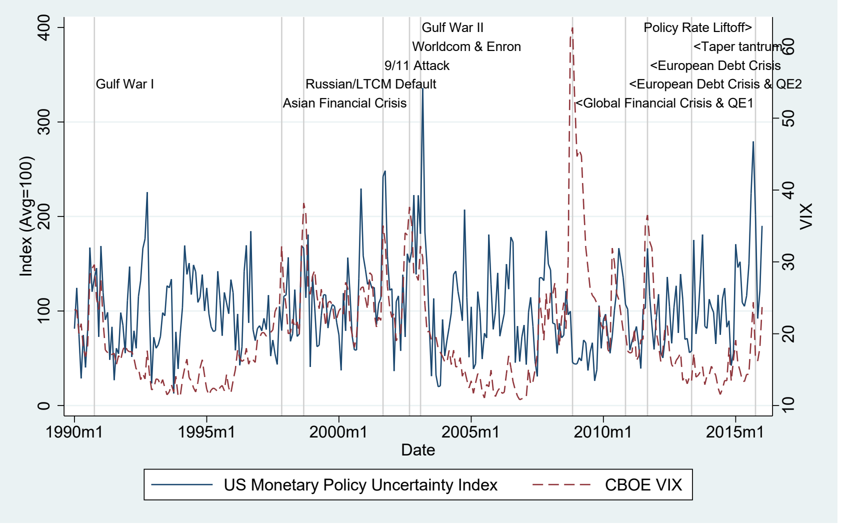
II. Empirical Method

This section explains the measure of US MPU and presents the details of the empirical analysis.

A. MPU Index

We use the MPU index computed by Husted, Rogers, and Sun (2016) as a measure of uncertainty that the private sector perceives regarding actions by the US Federal Reserve and their consequences. Husted, Rogers, and Sun (2016) follow the news-based search approach of Baker, Bloom, and Davis (2016) and track the frequency of MPU-related newspaper articles. That is, they construct an index by searching news articles for MPU-related keywords.[1]1 Figure 1 shows the MPU index with VIX, which is a common measure of general uncertainty in the US economy. The MPU index has frequent spikes and some of them can be associated with political and economic events, such as the Russian/

[1] Specifically, Husted, Rogers, and Sun (2016) search for news articles containing the triple of (i) “uncertainty or “uncertain; (ii) “monetary policy(ies) or “interest rate(s) or “Federal fund(s) rate or “Fed fund(s) rate; and (iii) “Federal Reserve or “the Fed or “Federal Open Market Committee or “FOMC.



Notes: The figure presents the MPU index (left axis) by Husted, Rogers and Sun (2016) and the VIX (right axis) with marks on important events. The MPU index is the baseline index by Husted, Rogers and Sun (2016).

Figure 1

US monetary policy uncertainty index and VIX

LTCM default, Gulf War II, and European debt crises. The MPU index specifically shows heightened uncertainty regarding the US monetary policy around the Taper tantrum in 2013 and the October 2015 Federal Open Market Committee (FOMC) meeting, in which a discussion of the policy rate liftoff was expected. The MPU index does not completely comove with VIX, which implies that it captures uncertainty that can be mostly associated to monetary policy actions but not to political or economic events.

Husted, Rogers, and Sun (2016) compare their MPU index with other measures of the US MPU, such as survey- and market-based measures, and conclude that it better captures uncertainty regarding the US monetary policy in the zero lower bound (ZLB) period compared with these measures. In the pre-ZLB period, it is highly correlated with these other measures. One of the alternatives to the MPU index of Husted, Rogers, and Sun (2016) is the monetary policy sub- index of the economic policy uncertainty index of Baker, Bloom, and Davis (2016). Owing to improved normalization of uncertainty index and specificity of search keywords, we prefer the MPU index of Husted, Rogers, and Sun (2016) over that of Baker, Bloom, and Davis (2016).

B. Empirical Model

a) Two-country VAR

In order to estimate the effects of increased uncertainty regarding the normalization of monetary policy or the lift-off of policy interest rates in the US, we use a two-country VAR with p lags. For notational simplicity, let us call the US country 1 and South Korea country 2. Then, collect the endogenous variables for country 1 and 2 in an $n_1 \times 1$ vector $y_{1,t}$ and an $n_2 \times 1$ vector $y_{2,t}$ respectively, and let $y_t = (y'_{1,t}, y'_{2,t})'$, which is an $n \times 1$ vector with $n = n_1 + n_2$. There might be some common exogenous variables that affect both countries so let us collect them in an $n_w \times 1$ vector w_t It also includes a constant term. The dynamics of $y_{1,t}$ and $y_{2,t}$ is represented as

$$\begin{bmatrix} y_{1,t} \\ y_{2,t} \end{bmatrix} = \begin{bmatrix} B_1^{11} & B_1^{12} \\ B_1^{21} & B_1^{22} \end{bmatrix} \begin{bmatrix} y_{1,t-1} \\ y_{2,t-1} \end{bmatrix} + \cdots + \begin{bmatrix} B_p^{11} & B_p^{12} \\ B_p^{21} & B_p^{22} \end{bmatrix} \begin{bmatrix} y_{1,t-p} \\ y_{2,t-p} \end{bmatrix} + \begin{bmatrix} B_w^{1} \\ B_w^{2} \end{bmatrix} w_t + \begin{bmatrix} u_{1,t} \\ u_{2,t} \end{bmatrix}, \quad (1)$$

for $t = 1,2,\cdots,T$, given $y_0,\cdots,y_{-p+1}$, where

$$\begin{bmatrix} u_{1,t} \\ u_{2,t} \end{bmatrix} \Bigg| y_{t-1}, y_{t-2}, \cdots \sim \mathbb{N}\left(\begin{bmatrix} 0_{n_1\times 1} \\ 0_{n_2\times 1} \end{bmatrix}, \begin{bmatrix} \Sigma_{11} & \Sigma_{12} \\ \Sigma_{21} & \Sigma_{22} \end{bmatrix} \right).$$

Note that Σ_{11}, Σ_{22} and

$$\Sigma = \begin{bmatrix} \Sigma_{11} & \Sigma_{12} \\ \Sigma_{21} & \Sigma_{22} \end{bmatrix},$$

are positive definite. Also, the coefficient matrix B_i^{11} is an $n_1 \times n_1$ matrix, B_i^{12} $n_1 \times n_2$, B_i^{21} $n_2 \times n_1$ and B_i^{22} $n_2 \times n_2$ for $i = 1,2,\cdots,p$ and B_w^{1} is an $n_1 \times n_w$ vector and B_w^{2} $n_2 \times n_w$. We can compactly write (1) as

$$y_t = B_1 y_{t-1} + \cdots + B_p y_{t-p} + B_w w_t + u_t, \quad (2)$$

where $u_t = (u'_{1,t}, u'_{2,t})$, and

$$B_1 = \begin{bmatrix} B_1^{11} & B_1^{12} \\ B_1^{21} & B_1^{22} \end{bmatrix}, \cdots, B_p = \begin{bmatrix} B_p^{11} & B_p^{12} \\ B_p^{21} & B_p^{22} \end{bmatrix}, \text{ and } B_w = \begin{bmatrix} B_w^{1} \\ B_w^{2} \end{bmatrix}.$$

Now, rewrite (2) further as

$$y_t = BX_t + u_t, \tag{3}$$

where $B = [B_1 \cdots B_p\ B_w]$ and $X_t = [y'_{t-1} \cdots y'_{t-p}\ 1]'$ Note that B is an $n \times k$ matrix and X_t is an $k \times 1$ vector where $k = np + 1$. Lastly, vectorize (3) as

$$y_t = \left(X'_t \otimes I_m\right)\beta + u_t,$$

where $\beta = vec(\beta)$ is an $nk \times 1$ vector.

b) Block Exogeneity Assumption

We assume that country 2 is a small open economy compared to country 1 so any developments in country 2 do not influence country 1. That is, block exogeneity is imposed as follows: $B_i^{12} = 0_{n_1 \times n_2}$ for i = 1,2,$\cdots$,p. Let γ denote a $\gamma \times 1$ vector of unrestricted coefficients where $r = nk - n_1 n_2 p$. The restriction imposed by block exogeneity can be represented using the following equation

$$\beta = R\gamma,$$

where R is an $nk \times r$ matrix. Therefore,

$$\begin{aligned} y_t &= \left[\left(X'_t \otimes I_n\right)R\right]\gamma + u_t, \\ &= \tilde{X}_t \gamma + u_t, \end{aligned} \tag{4}$$

where $\tilde{X}_t = (X'_t \otimes I_n)R$ is an $n \times t$ vector.

Block exogeneity similar to the one imposed in (4) is often employed in the literature to study how external shocks affect a small open economy. For example, Cushman and Zha (1997) use a two-country VAR for the US and Canada, where the US affects Canada but not vice versa, and estimate the effects of conventional monetary policy shocks of the US on the Canadian economy. Mackowiak (2007) is another example where he uses a two-country VAR for two-country pairs of the US with emerging market countries, where the US affects an emerging market country but not vice versa, and investigates how external shocks including the US monetary policy shock affect these emerging market countries.

c) Estimation and Data

This paper estimates (4) using the Bayesian method. Therefore, we do not worry about potential non-stationarity of the data and use the raw data without any pre-processing except seasonal adjustment and log-transformations where necessary. The derivation of the posterior distribution of the parameters in (4) is presented in the appendix.

In the baseline specification, we include the following variables in the two-country VAR. Variable $y_{1,t}$ for country 1 or the US includes, in the following order, the log of the industrial production index as the measure of output, the log of consumer price levels as the measure of prices, the shadow federal funds rate (FFR) by Wu and Xia (2016) as the measure of conventional and unconventional monetary policy, and the US MPU index as the measure of monetary policy uncertainty. We use the shadow FFR by Wu and Xia (2016) to include in our sample the period where the FFR hits the zero lower bound (ZLB) in the US. As the FFR gets stuck at the ZLB in late 2008, the Federal Reserve of the US started to implement unconventional monetary policy such as the large scale asset purchase program (or QE) and forward guidance. The shadow FFR by Wu and Xia (2016) computes hypothetical values of the FFR during the ZLB period to measure macroeconomic impact of such unconventional policy as if the FFR were not bound by the ZLB. When the shadow FFR is at least 25 basis points or above, it is almost identical to the actual FFR.

Variable $y_{2,t}$ for country 2 or South Korea includes, in the following order, the log of the industrial production index as the measure of output, the log of consumer price levels as the measure of prices, the call rate as the measure of monetary policy in South Korea and the log of the KRW/USD exchange rate. The exchange rate is included to capture adjustment of the South Korean economy in response to external shocks. Because of the concern on the small sample size, trade flow and capital flow data are not included in the baseline specification. Instead, we estimate extended specifications by including additional variables including the stock price, the capital inflow to South Korea, exports and imports one at a time, and study how these variables respond to the US MPU shock. The stock price is the log of KOSPI in the Korea stock exchange. The capital flow is the log of the liabilities in the portfolio investment account of the balance of payments of South Korea. Exports and imports include trades of goods and services, receipt and payment of income, and transfers.

We do not include common exogenous variables in w_t except the constant term. The details of the data are presented in the appendix.

The sample covers the period from January 2000 through January 2016. The sample frequency is monthly. Because of the short sample period, we fix the lag length at 3. Our main results are robust to longer lag lengths like 4 and 5, which is not reported to conserve space.

d) Identification of US MPU Shocks

We use Choleski decomposition of the variance–covariance matrix Σ to isolate or identify exogenous variations in the US MPU index and estimate its effects on the US and South Korea. It is tantamount to imposing restrictions on the impact responses of the variables to shocks.

Imposed restrictions imply that a shock to the US MPU index contemporaneously affects the variables ordered in y_t after the US MPU index, whereas it does not contemporaneously affect the variables ordered in y_t before the US MPU index. That is, restrictions imply that the US MPU shock affects the actual US MPU index and all variables of South Korea on impact but does not affect the other variables of the US, such as industrial production, consumer prices, and shadow FFR on impact. After the impact period, all variables may respond as the effect propagates through lags of the variables in VAR.

We are convinced that such restrictions are plausible. Some of the variations in the US MPU index are likely to arise because the private sector becomes more uncertain or less uncertain about the future decision by the Federal Reserve following news on the economy. That is, the US MPU index is not completely exogenous to the developments of the US economy. However, the US MPU index is unlikely driven by the South Korean economy. The previously explained identification scheme based on recursive ordering reflects these considerations. Lastly, note that identification based on recursive ordering is consistent with the block exogeneity assumption that any developments in the economy of South Korea do not influence the US economy.

As a robustness check, we also try a recursive ordering that places the US MPU index before all variables of the US and South Korea. Our main results are robust to this change in the ordering of the variables.

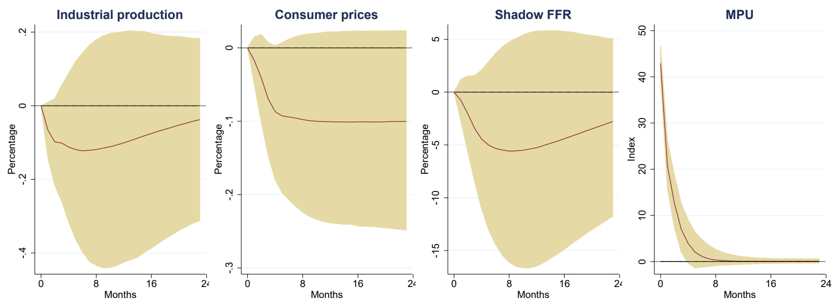
III. Empirical Results

This section reports the empirical results.

A. Baseline Results

We first report the estimation results of the baseline specification. Figure 2 presents the impulse responses of the US variables to a one-standard-deviation shock to the US MPU index, which show how the US economy responds when uncertainty regarding US monetary policy unexpectedly increases. The magnitude of the shock is the average size of fluctuations of the MPU index over the sample period.

The US economy is estimated to not respond significantly to MPU shock. Although the median responses of industrial production are negative, the 90% error band is wide. Hence, statistical evidence is not sufficiently strong to conclude that MPU shock adversely affects the US output. Median responses of consumer prices are also negative, which implies that MPU shock works similar to a supply shock even though monetary policy often drives aggregate demand. Shadow FFR also responds negatively on average but not significantly. Insignificant responses of output, consumer prices, and interest rates in the US



Notes: The figure presents impulse responses of each variable to a one-standard-deviation shock to the US MPU index. The shock is identified by recursive ordering in the order as given in the figure. The red line is the posterior median responses, while the shaded area represents the error band with the 5% and 95% quantile in the posterior distribution of impulse responses at each point in time.

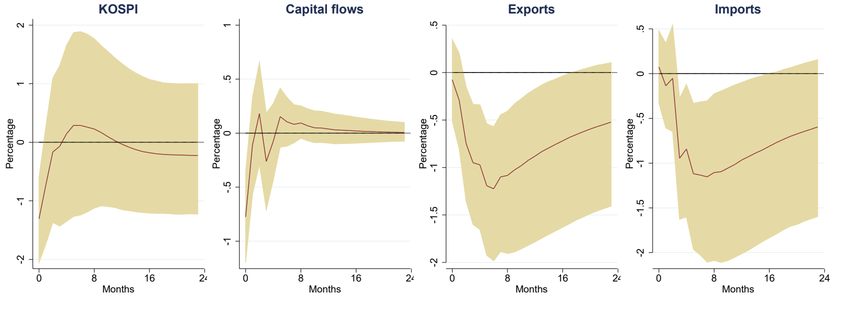
Figure 2

Impulse responses of the US to a shock to US monetary policy uncertainty

Notes: The figure presents impulse responses of each variable to a one-standard-deviation shock to the US MPU index. The red line is the posterior median responses, while the shaded area represents the error band with the 5% and 95% quantile in the posterior distribution of impulse responses at each point in time. Exchange rate is KRW units of a unit of USD. Hence, an increase in exchange rate means depreciation of KRW.

Figure 3

Impulse responses of South Korea to a shock to US monetary policy uncertainty: Baseline variables



Notes: The figure presents impulse responses of each variable to a one-standard deviation shock to the US MPU index. The red line is the posterior median responses while the shaded area represents the error band with the 5% and 95% quantile in the posterior distribution of impulse responses at each point in time. Impulse responses of each variable are estimated by including the same variable in the baseline model one by one.

Figure 4

Impulse responses of South Korea to a shock to US monetary policy uncertainty: Additional variables suggest that fluctuations of uncertainty regarding the US monetary policy lack sufficient strength to generally drive the US macroeconomy.

MPU index increases sharply on impact in response to a shock to itself and reverts back to zero immediately. This result implies that MPU shock is not persistent, which is consistent with the dynamics of the MPU index shown in Figure 1. The private sector of the US may become markedly uncertain about monetary policy actions by the Federal Reserve from time to time but increased uncertainty does not persist and dissipate immediately.

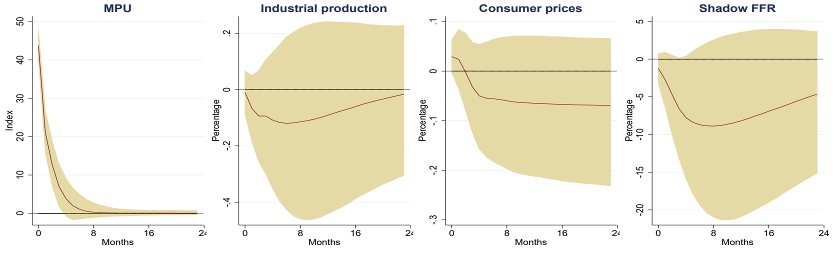
Let us turn to the impulse responses of South Korea to the same shock in Figure 3. Similar to the US, the median responses of industrial production and interest rates are negative but their responses are not significant. Consumer prices respond negatively. However, the response of consumer prices is not significant except for a month after the impact. By contrast, the local currency of South Korea (KRW) significantly depreciates for the first two months against the US Dollar in response to the MPU shock in the US. The size of the depreciation is approximately 0.5% at the peak.

Figure 4 presents the impulse responses of other interesting variables of South Korea, including stock price, capital flows, exports, and imports, to the MPU shock in the US. Although the effect is short-lived, the US MPU shock significantly decreases the stock price in South Korea and the capital inflow to the country. They decrease approximately 1.3% and 0.08%, respectively, on impact. Exports and imports persistently decrease by a similar magnitude in response to the MPU shock in the US. Hence, net exports do not significantly change.

For South Korea, macro variables, including output, consumer prices, and interest rates, do not respond significantly to the US MPU shock. Meanwhile, asset prices, such as the KRW/USD exchange rate and stock price, significantly respond. An argument frequently observed in the news media in emerging market countries (*e.g.*, South Korea) is that uncertainty generated by the US monetary policy is often blamed for disruptions in their economy. The empirical results in Figures 3 and 4 suggest that this argument is partially right and wrong. The financial market is markedly susceptible to fluctuations in uncertainty regarding the US monetary policy, while the macro economy is relatively robust. However, exports and imports respond persistently in spite of insignificant response of output and price levels in the US and South Korea, as well as a weak depreciation of the Korean Won. This aspect calls for further investigation.

B. Robustness Exercise

We redo the empirical analysis using an alternative ordering for identification of the US MPU shock. Unlike the baseline specification, we place the MPU index in first place in y_t of VAR, thereby implying that the MPU index is not driven by any other shocks in the US economy on impact. As shown in Figures 5 to 7, our main results are robust to this change in the MPU index ordering. The robustness of the main results implies that the MPU index is likely not driven substantially by any other shocks in the US economy.



Notes: The figure presents impulse responses of each variable to a one-standard-deviation shock to the US MPU index. The shock is identified by recursive ordering in the order given in the figure. That is, unlike the baseline model, MPU is ordered in the first place. The red line is the posterior median responses, while the shaded area represents the error band with the 5% and 95% quantile in the posterior distribution of impulse responses at each point in time.

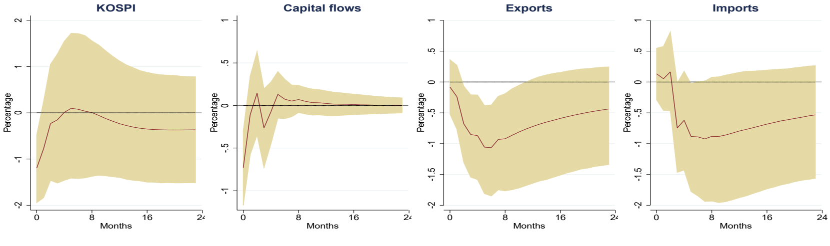
Figure 5

Impulse responses of the US to a shock to US monetary policy uncertainty (MPU is placed first)

Notes: The figure presents impulse responses of each variable to a one-standard-deviation shock to the US MPU index. Unlike the baseline model, MPU is ordered in the first place. The red line is the posterior median responses, while the shaded area represents the error band with the 5% and 95% quantile in the posterior distribution of impulse responses at each point in time. Exchange rate is KRW units of a unit of USD. Thus, an increase in exchange rate means depreciation of KRW.

Figure 6

Impulse responses of South Korea to a shock to US monetary policy uncertainty: baseline variables (MPU is placed first)



Notes: The figure presents impulse responses of each variable to a one-standard-deviation shock to the US MPU index. Unlike the baseline model, MPU is ordered in the first place. The red line is the posterior median responses, while the shaded area represents the error band with the 5% and 95% quantile in the posterior distribution of impulse responses at each point in time. Impulse responses of each variable are estimated by including the same variable in the baseline model one by one.

Figure 7

Impulse responses of South Korea to a shock to US monetary policy uncertainty: Additional variables (MPU is placed first)

IV. Conclusion

This research studies how increased uncertainty regarding the US monetary policy affects emerging market countries, such as South Korea, after QE by the Federal Reserve is withdrawn and it starts to normalize its policy rate. Using the MPU index in Husted, Rogers, and Sun (2016) as a proxy for uncertainty regarding US monetary policy, we estimate that a shock to the US monetary policy uncertainty negatively affects the KRW/USD exchange rate, stock price and capital inflow to South Korea, while it does not have significant effects on the macroeconomic variables of the country. Exports and imports respond negatively to uncertainty shock even though output does not significantly respond in South Korea, which is puzzling. This aspect calls for further investigation in future research.

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Appendix A: Data Descriptions

All the data are monthly. The sample period is from January 2000 to January 2016. Data for the US except for the shadow FFR and the monetary policy uncertainty index was downloaded from the FRED database maintained by the Federal Reserve Bank of St Louis. The Wu–Xia shadow FFR was collected at the Federal Reserve Bank of Atlanta website and the monetary policy uncertainty index was obtained at the Federal Reserve Board website. Data for South Korea was downloaded from the ECOS database provided by the Bank of Korea. All data except the MPU index are seasonally adjusted by X11, unless the raw data are already seasonally adjusted.

Table 1
Data descriptions

Country	Variable	Description
US	Industrial production	Index 2012=100
	Consumer prices	Consumer Price Index for All Urban Consumers: All Items Index 1982-1984=100
	Shadow FFR	Wu and Xia (2016)
	M2	M2 money stock
	MPU index	Husted, Rogers and Sun (2016)
South Korea	Industrial production	Of all industry production (excluding Agriculture, Forestry and Fishing) Index 2010=100
	Consumer prices	Index 2015=100
	Call rates	Overnight call rates. Percent per annum / 100
	KRW/USD exchange rates	Units of KRW per unit of USD
	Stock prices	KOSPI composite index
	Capital flows	Portfolio investment liabilities in the financial account of the balance of payments
	Exports	Goods, services, income receipts and transfers
	Imports	Goods, services, income payments and transfers
	Net exports	Exports - imports

Appendix B: Posterior Distribution of the Two-country VAR

This section lays out the posterior distribution of the parameters of the two-country model.
Consider

$$y_t = \tilde{X}_t \gamma + u_t. \tag{5}$$

The likelihood function of (5) is given by

$$p\left(\{y_t\}_{t=1}^{T} \middle| \gamma, \Sigma, \{y_t\}_{t=-p+1}^{0}\right) = (2\pi)^{-Tn/2} |\Sigma|^{-T/2} \exp\left[-\frac{1}{2}\sum_{t=1}^{T}(y_t - \tilde{X}_t\gamma)'\Sigma^{-1}(y_t - \tilde{X}_t\gamma)\right].$$

We use the Minesota-type prior in addition to the standard Normal-Inverted Wishart prior distribution. The Normal-Inverted Wishart distribution is given by

$$\gamma \left| \Sigma \sim \mathbb{N}\left(\gamma, \Sigma_{\gamma}\right), \right.$$
$$\Sigma^{-1} \sim \mathbb{W}(\upsilon, S^{-1}),$$

where $\upsilon = n + 2$ to set a very loose prior for Σ^{-1}. Given the prior distribution, the posterior distribution is given as

$$\gamma \left| \Sigma, \{y_t\}_{t=1}^{T}, \{y_t\}_{t=-p+1}^{0} \sim \mathbb{N}\left[\tilde{\gamma}, \left(\sum_{t=1}^{T} \tilde{X}_t' \Sigma^{-1} \tilde{X}_t + \Sigma_{\gamma}^{-1}\right)^{-1}\right], \right.$$
$$\Sigma^{-1} \left| \{y_t\}_{t=1}^{T}, \{y_t\}_{t=-p+1}^{0} \sim \mathbb{W}\left(T + \upsilon, \tilde{S}^{-1}\right), \right.$$

where

$$\tilde{\gamma} = \left(\sum_{t=1}^{T} \tilde{X}_t' \Sigma^{-1} \tilde{X}_t + \Sigma_{\gamma}^{-1}\right)^{-1} \left[\left(\sum_{t=1}^{T} \tilde{X}_t' \Sigma^{-1} \tilde{X}_t\right) \hat{\gamma} + \Sigma_{\gamma}^{-1} \gamma\right],$$

with

$$\hat{\gamma} = \left(\sum_{t=1}^{T} \tilde{X}_t' \Sigma^{-1} \tilde{X}_t\right)^{-1} \left(\tilde{X}' \Sigma^{-1} y_t\right)^{-1},$$

and

$$\tilde{S} = \sum_{t=1}^{T} (y_t - \tilde{X}_t \gamma)(y_t - \tilde{X}_t \gamma)' + S.$$

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