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# Do Uncertainty and Technology Drive Exchange Rates?

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**Abstract**

This paper investigates the extent to which technology and uncertainty contribute to fluctuations in real exchange rates. Using a structural VAR and bilateral exchange rates, I find that neutral technology shocks are important contributors to the dynamics of real exchange rates. Investment-specific and uncertainty shocks have a more restricted effect on international prices. All three disturbances cause short-run deviations from uncovered interest rate parity.

## 1 Introduction

A robust finding in international economics is that real exchange rates are substantially more volatile than other real variables such as output and consumption. Indeed, Rogoff (1996) refers to this excess variability and the large half-life of real exchange rates as the purchasing power parity (PPP) puzzle. Understanding the origins and consequences of this puzzle has been a central theme in the literature, with the recent debate focusing on whether dynamic stochastic general equilibrium (DSGE) models can capture the deviations from PPP found in the data. Chari et al. (2002), for example, argue that DSGE models entertaining price stickiness and monetary shocks fail to match the dynamics of real exchange rates. In contrast, Steinsson (2008) has shown that productivity shocks may be a way to reconcile sticky price models with the dynamics of exchange rates.[1] Hence, understanding the role of technology in exchange rates is of the uppermost importance because of its clear implications for the PPP puzzle.

At the heart of this controversy lies the issue of what disturbances drive real exchange rates. An informal introspection points toward the usual suspects: monetary and technology disturbances. The role of the former type of shocks has been extensively discussed in the literature (see Section 2 for a non-exhaustive list of related papers). Eichenbaum and Evans (1995), for example, report that monetary shocks explain between 23% and 43% of the variability of the US dollar against several currencies.[2] In

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[1] A second equally important controversy corresponds to properly measuring the half-life of the PPP deviations (Chen and Engel, 2004; Imbs et al., 2005).

[2] In particular, their results correspond to the relative price of the US dollar versus the currencies in Japan, Germany, Italy, France, and United Kingdom.

terms of technology shocks, there has been considerably less effort to study their relation to exchange rates. An early example of this line of research is Clarida and Gali (1994), who find that supply shocks (i.e., disturbances that affect output in the long run) explain around 10% of the variance of real exchange rates for several countries. This lack of investigation in the area is surprising given the significant attention that technology disturbances have received in the business cycle literature (Fernandez-Villaverde and Rubio-Ramirez, 2007; Justiniano and Primiceri, 2008).

Monetary and technology shocks are hardly the sole contributors to exchange rate variability. For instance, it seems plausible that exchange rates have reacted to the recent stock market volatility. This is because highly uncertain periods are typically associated with imprecise forecasts of macroeconomic variables (Stock and Watson, 2002). To the extent that exchange rates are asset prices, their dynamics reflect expectations about the future evolution of fundamentals (Engel et al., 2007). Therefore, forecast revisions arising from uncertainty should contribute to fluctuations in exchange rates. This intuition is readily confirmed in Figure 1, which plots the nominal yen-US dollar exchange rate (left axis) and the US implied stock market volatility (right axis) for the year 2008. Clearly, the dollar tends to depreciate as the volatility increases during the last months of the year (the correlation between those two variables during the last 4 months of 2008 is $-0.80$). Of course, there are plenty of potential explanations for a dollar depreciation (Engel and West, 2005), but it is still quite suggestive the co-movement of exchange rates and stock market volatility.

This paper takes on the task of assessing the contribution of uncertainty shocks as well as investment-specific and neutral technology shocks to the variability of exchange rates. To that end, I extend the identification schemes in Gali (1999) and Fisher (2006) for technology shocks, and Bloom (2008) for uncertainty disturbances, to incorporate the dynamics of international variables. Specifically, structural VARs and bilateral exchange rates for the US dollar vis-a-vis the Canadian dollar, the yen, and the British pound serve to understand how real exchange rates react to such shocks. A trade-weighted real exchange rate is also considered. The main results can be summarized as follows. First, following a jump in uncertainty in the US, measured as a positive one-standard-deviation shock to stock market volatility, the dollar depreciates against the other three currencies as well as a trade-weighted currency index. Furthermore, two years after the disturbance the dollar has lost on average 4% of its pre-shock value. This depreciation is robust to several VAR specifications. Second, the US dollar tends to appreciate following investment-specific shocks. Interestingly, the dollar's response is hump shaped, reaching its highest appreciation ($\approx 1.5\%$) between one and three years after the initial disturbance. The appreciation, however, is not statistically significant when measured against the yen.

Third, the US dollar appreciates in the aftermath of positive neutral technology shocks. Yet there is some heterogeneity regarding the shape of this appreciation. On one hand, the US dollar-Canadian dollar exchange rate unequivocally displays a hump-shaped response, reaching its peak about a year after the shock. On the other hand, that disturbance induces a monotonic response in the dollar-pound rate and a trade-weighted currency index. For the dollar-yen exchange rate, however, the shape of its impulse response is sensitive to the VAR specification. Taken at face value, these findings make it difficult to attribute the non-monotonic response of exchange rates uncovered from univariate analyses

(Chueng and Lai, 2000; Steinsson, 2008) to a unique shock. If anything, the data suggest that such a response most likely results from a convolution of the two types of technology disturbances, in particular, the investment-specific one.

Fourth, the results from a variance decomposition exercise vary substantially with the exchange rates and the forecasting horizon. For example, uncertainty and investment-specific disturbances each contributes to about 30% of the volatility in the real exchange rate between the US and Canada at the three-year horizon. In contrast, those same shocks have a mild effect on the volatility of the other two bilateral exchange rates. The only disturbance that has a similar impact on all bilateral exchange rates is a neutral technology shock. This shock explains about 16% and 20% of the variability of the US dollar against the Canadian dollar and the British pound, respectively, at all forecasting horizons. Finally, if one uses a trade-weighted exchange index, technology shocks in particular, the investment-specific one explain a larger fraction than the volatility disturbance.

There has been a renewed interest in studying the causes and consequences of the forward premium anomaly (a non-exhaustive list includes Sarno, 2005; Burnside et al., 2007; Ilut, 2008; Baccheta and van Wincoop, 2009). An advantage of using bilateral exchange rates is that one can precisely investigate the effects of structural shocks on uncovered interest rate parity (UIP). In this regard, the structural VARs reveal that investment-specific and uncertainty shocks induce significant deviations from the UIP. For instance, an excess return of a half percentage point to investing in Canadian dollars arises after an increase in uncertainty in the US. This premium is statistically significant and lasts for about eight months. This finding is quite suggestive given that current explanations of the forward premium puzzle solely consider nominal disturbances such as monetary shocks (Baccheta and van Wincoop, 2009) or exchange rate shocks (Burnside et al., 2007). The reason to favor nominal shocks is that the bulk of the empirical analysis has studied the effects of such disturbances only on the forward premium puzzle (Eichenbaum and Evans, 1995; Faust and Rogers, 2003; Scholl and Uhlig, 2008). In contrast, the results in this paper call for models of the UIP puzzle where uncertainty and technology play a role as important as that of nominal shocks.

This paper is closely related to the recent contributions of Corsetti et al. (2006, 2008), Bems et al. (2007), and Enders and Muller (2009). The first authors identify shocks to the US manufacturing sector to study the transmission mechanism behind those shocks and macroeconomic interdependence across countries. In accordance with my results, they find that a positive productivity disturbance to the tradable sector causes a real appreciation of the US dollar. The major difference between our studies is that I identify economy-wide technology rather than sector-specific shocks. This is because one of the objectives of this paper is to uncover the contribution of technology in the broad sense to the volatility of exchange rates. Bems et al. analyze the implications of investment-specific shocks for the current account in the US. These authors, however, do not explore the consequences of such shocks for the real exchange rate. Finally, Enders and Muller (2009) recover neutral technology shocks à la Gali (1999) to show that the terms of trade and the trade balance in the US have an S-shaped cross correlation function. These authors also report that the real exchange rate in the US appreciates after a positive technology shock. None of the above papers addresses the issue of the consequences of structural shocks on the forward premium.

The asymmetric influence of structural shocks on exchange rates is not new to this paper. This feature has been carefully documented in the early work of Clarida and Gali (1994) and Corsetti et al. (2006). For instance, the first authors report that while nominal (monetary) shocks explain "more than one third of the variability of the dollar-yen real exchange rate at a horizon of 4 quarters," these same shocks explain a mere fraction (less than 1%) of the fluctuations observed in the relative prices between the US and Canada.

It is widely accepted among market participants that good news is typically associated with a strengthening of the US dollar, while bad news leads to its depreciation. In fact, one frequently reads newspaper articles along the lines of *dollar depreciates amid increasing uncertainty* and *dollar declines due to slowdown in productivity* (see the appendix for exact quotes). Taken at face value, this popular view (Corsetti et al., 2008) suggests that uncertainty and technology indeed affect exchange rates. As will become clear, the results in this paper garner some support for the notion that good shocks, say, advances in productivity, cause dollar appreciations.

The rest of the paper is organized as follows. A brief summary of the VAR methodologies pursued in this paper is in Section 2. Section 3 reports impulse response functions to uncover the effects of technology and uncertainty on exchange rates. Some sensitivity analysis is provided in Section 4. The last two sections provide variance decompositions and concluding remarks.

## 2 Some Reference VARs

This section discusses some methodologies that are relevant for understanding the implications, if any, of technology and uncertainty shocks on the time series of exchange rates. Specifically, three frameworks related to monetary, uncertainty, and technology shocks are reviewed.

The effects of monetary shocks are probably the most studied topic within the VAR literature. It is now widely agreed that a tightening of monetary policy entails a decline in inflation accompanied by a sustained contraction in economic activity (for a comprehensive review see, Christiano et al., 1999). The international dimension of monetary shocks has been studied at least since the contributions of Clarida and Gali (1994), Cushman and Zha (1997), and Eichenbaum and Evans (1995). In a nutshell, the last authors conduct their analysis using a parsimonious VAR composed of the following variables:

$$y_t = \left[\log(\textit{industrial production}), \log(CPI), \log(NBRX), R^{US} - R^{FOR}, \log(s^{FOR})\right],$$

where $s^{FOR}$ is the price of the foreign currency in terms of the domestic money; $R^{FOR}$ and $R^{US}$ are the foreign and domestic short-term interest rates, respectively; $NBRX$ is the ratio of non-borrowed to total reserves; and $CPI$ is the consumer price index.[3] As argued by Eichenbaum and Evans (1995), the inclusion of the difference between domestic and foreign interest rates captures the empirical and

[3] More recent papers on the international consequences of monetary policy include Faust and Rogers (2003), Kim and Roubini (2001), Kim (2003), and Scholl and Uhlig (2008). All these papers find that monetary shocks lead to short-term fluctuations of real exchange rates.

theoretical results outlined in Messe and Rogoff (1983). In this framework the authors show that a contractionary monetary shock, as captured by an orthogonalized shock to $NBRX$, leads to a significant and persistent, real and nominal, appreciation of the US dollar versus several foreign currencies. Additionally, the authors report conditional deviations from the uncovered interest rate parity.

### 2.1 Uncertainty Shocks and VARs

Understanding the consequences of volatility in the economy has been a very active area of research with important contributions by Cogley and Sargent (2005), Fernandez-Villaverde and Rubio-Ramirez (2007), and Justiniano and Primiceri (2008). Resorting to dynamic stochastic general equilibrium models, the last two papers find empirical evidence suggesting that stochastic volatility is a key ingredient in accounting for the so-called Great Moderation. Furthermore, Bloom (2008) shows that uncertainty shocks have sizable implications for industrial production and employment in the US, while Fernandez-Villaverde et al. (2008) show that those shocks have pervasive effects in emerging economies.

Relying on a VAR formulation and a stock market volatility indicator, Bloom (2008) identifies uncertainty shocks hitting the US. This volatility indicator takes a value of 1 for each of 17 crucial events that have buffeted the US economy in the past 40 years such as JFK's assassination, the Franklin National financial crisis in 1975, the 1987 stock market crash, gulf wars I and II, and the collapse of WorldCom and Enron (see Figure 1 in his paper). Bloom's reasoning is that uncertainty spikes during these periods of economic and political turmoil, and this increased uncertainty should induce firms to scale down production until things calm down. To demonstrate his argument, Bloom essentially estimates a VAR process for his volatility measure and the log of industrial production in the US. Using a Cholesky decomposition, he then shows that an orthogonalized shock to the volatility indicator, i.e., an increase in uncertainty, produces a marked decline in industrial production. The Wold ordering in the VAR does not influence his findings. His finding is robust to alternative measures of uncertainty and even after one controls for monetary policy, inflation, employment, and wages, which leads Bloom to conclude that uncertainty shocks have real contractionary effects on the economy.

In a theoretical context, uncertainty shocks can potentially affect international prices. To see this point, recall that exchange rates are typically viewed as asset prices whose dynamics are determined by expectations about macroeconomic fundamentals. Engel and West (2005), for example, show that a large class of open economy models imply that exchange rates obey

$$\log s^{For} = (1-\beta)\,\mathbb{E}_t \sum_{j=0}^{\infty} \beta^j \left(v_{t+j} - \left(ip_{t+j} - ip^*_{t+j}\right)\right), \tag{1}$$

where $\mathbb{E}_t$ is the expectation operator based on information at time $t$, $\beta \in (0,1)$ is the discount factor, $v_t$ is some stochastic process, and $ip_t$ and $ip^*_t$ stand for production at home and abroad, respectively. As suggested in Stock and Watson (2002), forecasting is done frequently and imprecisely during periods of high uncertainty. To the extent that uncertainty shocks induce households to revise downward their forecasts of future domestic production relative to foreign production, other things equal, Equation (1) indicates that a depreciation of the domestic currency should follow the increase in uncertainty. In the next sections, I use a modified version of Bloom's identification scheme to empirically establish whether volatility drives exchange rates as suggested by the previous argument.

## 2.2 Technology Shocks and VARs

Borrowing ideas from Greenwood et al. (1997) and Gali (1999), Fisher (2006) studies the implications of neutral and investment-specific technological disturbances. Fisher's approach relies on a structural VAR and the identification assumption that long-term changes in economy-wide labor productivity results from both neutral and investment-specific technology shocks, while the price of investment displays permanent changes only after the later shock. Using such a methodology, he concludes that technology disturbances can account for up to 38 % of hours' and 80 % of output's business cycle fluctuations.

Going into the details, Fisher (2006) resorts to a parsimonious VAR consisting of the following variables $y_t = [\Delta p_{i,t}, \Delta a_t, \log(h_t),\ \pi_t, R_t]$, where $p_{i,t}$ is the relative price of investment, $a_t$ is labor productivity, $h_t$ is labor, $\pi_t$ is inflation and $R_t$ is a measure of the short-term nominal interest rate. To understand his identification scheme, consider the following VAR:

$$y_t = A\left(L\right) y_{t-1} + \varepsilon_t, \tag{2}$$

where $A\left(L\right)$ is a polynomial of lag operators and $\varepsilon_t$ is the one-step-ahead forecast error. If one assumes that the VAR is invertible, then the corresponding Wold representation is $y_t = \left[I - A\left(L\right)\right]^{-1} \varepsilon_t$, where $I$ is the identity matrix.

We are interested in identifying structural shocks, $\xi_t$, the first of which has permanent effects on $p_{i,t}$ and $a_t$, while the second one has only long-term implications for labor productivity. If we further assume that $V\left(\xi_t\right) = I$ and the structural and reduced shocks are related via the equation $\varepsilon_t = C\xi_t$, then identification requires that the first two rows of the matrix $B \equiv \left[I - A(1)\right]^{-1} C$ have the following structure

$$\begin{bmatrix} x & 0 & 0 & 0 & 0 \\ x & x & 0 & 0 & 0 \end{bmatrix},$$

where $x$ is a number different from zero. Fisher (2006) identifies the first shock as an investment-specific shock (IS shock) and the second one as a neutral technology disturbance (NT shock). There are no additional restrictions on the remaining rows because we are not interested in their associated shocks. As argued by Fisher, there is a family of matrix rotations satisfying the restriction on the matrix $B$. A convenient element of that family is the one corresponding to a Cholesky decomposition, i.e. $B = \widetilde{B}\widetilde{B}'$ where $\widetilde{B}$ is a lower triangular matrix.

Let $\widehat{A}(L)$ and $\widehat{\varepsilon}_t$ be the OLS estimates of the VAR Equation (2) and $\widehat{\Omega} = T^{-1} \sum_t \widehat{\varepsilon}_t \widehat{\varepsilon}_t'$ be the associated covariance matrix. Then recovering the matrix $\widetilde{B}$ involves pre-multiplying the Cholesky factor of $\left[I - A(1)\right]^{-1} \widehat{\Omega} \left[I - A'(1)\right]^{-1}$ by $\left[I - A(1)\right]$, which is precisely the identification variant proposed in Christiano et al. (2006) and Bems et al. (2007).

Previous empirical research (among others, Fisher, 2006; Gali, 1999) have established that technology does affect domestic variables. To the extent that technology disturbances drive fluctuations in current and future domestic production, as the empirical evidence suggests, models of exchange rate determination predict that exchange rates should also move after those shocks buffet the economy (see the discussion above and Equation 1). In other words, the developments in Fisher (2006) and Engel and West (2005) suggest that technology should influence the dynamics of exchange rates.

Note, however, that if the arguments above are found to be true in the data, they would establish only a causal relation between technology shocks and international prices. Furthermore, because Fisher's identification rests on overall labor productivity, the relation would be between exchange rates and economy-wide technology shocks. As argued in Corsetti et al. (2006 and 2008), studying aggregated shocks complicates learning the transmission mechanism behind movements of exchange rates. To improve on this dimension, Corsetti et al. (2006) favor the use of labor productivity in the manufacturing sector, which combined with existing theoretical models facilitates the analysis of the propagation mechanism.

But then why bother with more aggregated shocks? I choose to concentrate on economy-wide technology disturbances because by analyzing them one can establish whether technology as traditionally defined in the business cycle literature (Altig et al., 2005; Gali, 1999) drives real exchange rates. Given that productivity gains tend to be biased toward the tradable sector (Obstfeld and Rogoff, 1996), then one can use the results from aggregate productivity as a baseline scenario to study more disaggregated shocks. Finally, identifying aggregate technology shocks allows us to directly apply the theoretical results from the closed economy literature (Fisher, 2006). Such a direct application is not straightforward if one were to rely on sector-specific disturbances.

## 3 Uncertainty, Technology, and Exchange Rates

In this section, I discuss the consequences of uncertainty and technology shocks for exchange rates as well as the uncovered interest rate parity. The approach consists of blending the ideas in Bloom (2008) and Fisher (2006) with those in Eichenbaum and Evans (1995). In the discussion that follows, the term domestic refers to the US economy.

### 3.1 Effects of Uncertainty Shocks

To understand the implications of uncertainty for exchange rates, I propose to study the properties of a VAR whose elements are given by

$$y_t = \left[ Volatility, \log(industrial\ production), \log(CPI), R^{US} - R^{FOR}, \log(s^{FOR}) \right]. \qquad \text{(VAR \#1)}$$

This vector obeys the AR process $y_t = A(L)y_{t-1} + \varepsilon_t$, where $A(L)$ is a $p^{th}$-ordered polynomial in the lag operator $L$. Following Bloom's benchmark formulation, the ordering in $y_t$ reflects the assumption that all variables react to a volatility shock (alternative ordering did not change the results). Volatility corresponds to Bloom's volatility indicator (see Section 2.1). Moreover, the inclusion of the last three variables follows Eichenbaum and Evans' (1995) VAR. As previously discussed, using the difference between domestic and foreign nominal interest rates accommodates the theoretical arguments in, among others, Dornbusch (1976), Messe and Rogoff (1983) and Gali and Monacelli (2005).

Data correspond to monthly observations spanning the period 1982.10 - 2005.12. As will become clear momentarily, this sample facilitates the discussion and comparison of the consequences of uncertainty and technology shocks. Details on the data sources are provided in the appendix. As in Bloom (2008), a value of $p$ equal to 12 is large enough to adequately capture the dynamics of the data.[4] Following his approach, industrial production and the consumer price index are HP-filtered prior to the estimation. I report the properties of the US dollar against the Canadian dollar, the yen, and the British Pound (the case of the trade-weighted currency index is discussed in Section 4.5). These currencies have received substantial attention in the empirical literature (Clarida and Gali, 1994; Eichenbaum and Evans,1995) and they correspond to the historically major trading partners of the US. Except for $R^{FOR}$, all variables are for the US. In the rest of the paper, $R^{For}$ corresponds to the short-term interest rate either in Canada, Japan, or the United Kingdom. Additionally, $s^{For}$ is the domestic price of the foreign currency in real terms. Consequently, an increase in $s^{For}$ corresponds to a real depreciation of the local currency.

The impulse responses following a one-standard-deviation increase in volatility are reported in Figure 2. This shock is meant to capture an increase in the level of uncertainty surrounding the economy (Bloom, 2008). From top to bottom, the rows portray the results when the foreign interest rate and currency come from Canada, Japan, and the UK, respectively. A solid line corresponds to the point estimates while dashed lines represent plus- and minus-one-standard-deviation error bands.[5] All variables are expressed as percentage deviations from their pre-shock levels except for interest rates, which are plotted as basis point deviations from their initial value.

The results from the Canadian case reveal some interesting patterns. To begin with, there is a sharp decline in US industrial production following the volatility shock, but it quickly bounces back. Indeed, the economy reaches its lowest production ($-0.75\%$) about 5 months after the shock, with production fully recovered after 1 year. Hence, the first important lesson from this exercise is that Bloom's findings are robust to the inclusion of foreign variables.

Upon impact, the interest rate differential, $R^{US} - R^{FOR}$, displays an insignificant decline. This result, though, teaches us nothing about the individual dynamic responses. In fact, it is consistent with both rates going up or down simultaneously. Later on, an alternative VAR formulation will help us to disentangle the dynamic properties of each interest rate. It suffices for now to note that the interest rate differential quickly becomes negative and statistically significant, reaching its lowest level about 15 months after the shock.

One may suspect that following the mute response of the interest rate differential, investors' demand for the domestic currency remains unchanged. The nil initial response of the US dollar confirm our suspicion. Note, however, that the Canadian dollar quickly gains ground. Indeed, two years after

[4] Using a different number of lags has no substantial impact on the results. Similarly, using differences rather than levels in the exchange rates has minimal impact on the findings.

[5] These bands are computed using the Monte Carlo method suggested in Sims and Zha (1999). A total of 500 replications were used to obtain the error bands for each impulse response.

the disturbance, the US dollar has depreciated in real terms by roughly 5%.[6] Furthermore, the nominal exchange rate displays qualitatively similar dynamic paths (for space considerations, they are not reported here but they are available upon request). Abusing Dornbusch's (1976) terminology, we can argue that the real exchange rate displays an undershooting profile; i.e., the medium term depreciation results from a smooth sequence of monthly depreciations. More important, the drop in domestic output and the subsequent dollar depreciation is perfectly consistent with the simple exchange rate model outlined in Section 2.1.

The sharp weakening of the US dollar coupled with the initial mute response of the interest rate differential signals potential deviations from the uncovered interest rate parity. To formally assess this possibility, I follow Eichenbaum and Evans (1995) and Faust and Rogers (2003) in defining $\Psi_t$ as the ex post difference in the return between investing \$1 in $j$-period foreign bonds and investing \$1 in $j$-period US bonds.[7] Measured in US dollars, this excess return is given by

$$\Psi_t^j = R_{t,j}^{For} - R_{t,j}^{US} + (\mathfrak{s}_{t+j}^{For} - \mathfrak{s}_t^{For}) \tag{3}$$

where $R_{t,j}^{For}$ is the return on a $j$-period bond and $\mathfrak{s}_t^{For}$ is the log nominal exchange rate. If the uncovered parity condition holds, investors expect zero excess returns on average, i.e., $\mathbb{E}_t\Psi_t^j = 0$, where the expectation operator uses information available up to time $t$. Since the empirical exercise relies on short-term interest rates, I consider the case $j = 3$.

The last column in Figure 1 displays the dynamic response of $\mathbb{E}_t\Psi_t^{j=3}$ expressed in annual terms. Following the uncertainty shock, there is an excess return of a half percentage point to investments in foreign currency; i.e., it is better to borrow in US dollars and invest in Canadian dollars. Moreover, this excess return is above 1% even eight months after the shock but tends to vanish after one year. This evidence complements the results in Eichenbaum and Evans (1995), Faust and Rogers (2003), and Scholl and Uhlig (2008), who find UIP violations following monetary shocks. The results, however, are inconsistent with theoretical models as in Dornbusch (1976), Gali and Monacelli (2005), Kollmann (2001) and Monacelli (2004), where UIP holds by assumption.

The Japanese and British cases share some similarities with the Canadian one but there are also some important differences. US industrial production contracts after the shock but recovers relatively fast, which is consistent with the results from the Canadian data. Furthermore, the interest rate differential between the US and Japan declines after the shock and remains below its steady state value for about a year and half. The difference between interest rates in the US and the UK is slightly positive upon impact but quickly becomes statistically insignificant. Unlike with the Canadian data, the depreciation of the US dollar against the yen starts immediately after the shock, which is largely consistent with the dynamics of this exchange rate portrayed in Figure 1. The depreciation persists in the medium term, with the dollar losing about 4% of its initial value against either currency. Finally, the deviations from UIP are substantially different from those reported for the Canadian dollar. In particular, note that it is profitable to invest in the US dollar rather than in British pounds or yen. The excess return equals

[6] Expanding the impulse responses, I find that the real depreciation of the US dollar remains even after 4 years.
[7] Lewis (1995) and Sarno and Taylor (2001) provide excellent reviews of the forward premium puzzle.

almost two percentage points and is statistically significant 4 months after the shock.

A recurrent finding in this section is that the US dollar depreciates in real terms following an increase in uncertainty. Interestingly, this association between uncertainty and exchange rates is consistent with the dynamics of the dollar/yen rate during the last quarter of 2008 (see Figure 1). Section 2 provides some intuition as to why a depreciation follows an uncertainty shock based on the notion that such a shock induces downward revisions on industrial production forecasts. An alternative interpretation is as follows. An increase in the volatility of the domestic stock market induces a sustained recession in the domestic economy (Bloom, 2008). Fearing that the recession may bring future negative returns, risk-adverse investors may opt to liquidate their portfolios in the domestic market. Ultimately, this liquidation reduces the demand for the domestic currency, which leads to its depreciation.

### 3.2 Effects of Technology Shocks

To understand the implications of technology on exchange rates, let us combine Fisher's (2006) approach with that of Eichenbaum and Evans (1995). In particular, consider a VAR specification containing the following variables:

$$y_t = \left[\Delta p_{i,t}, \Delta a_t, \log(h_t), \pi_t, R_t^{US} - R_t^{FOR}, \log(s^{FOR})\right]. \qquad \text{(VAR \#2)}$$

To facilitate the identification of technology shocks, the VAR specification preserves the ordering and variables in Fisher (2006). It also includes the interest rate differential and the real exchange rate for the reasons discussed in Sections 1 and 2.[8]

Data on the price of investment, $p_{i,t}$, and labor productivity, $a_t$, are available only on a quarterly basis. Additionally, Fisher (2006) finds a statistically significant break in the price of investment series in the third quarter of 1982. Hence, the data correspond to quarterly observations spanning the period 1982.3 - 2005.4. Details on the data and sources are discussed in the appendix. Following Fisher, the number of lags in the VAR is set to 4. As before, I report the dynamics of the US dollar against the Canadian dollar, the yen, and the British pound.

Figure 3 displays the responses to a positive one-standard-deviation investment-specific technology shock. The first row corresponds to the case when Canadian data are used for the foreign variables. As in Fisher (2006) and Altig et al. (2005), such a disturbance leads to a permanent decline in the relative price of investment (about 0.6% after 5 years). The shock also permanently raises labor productivity while producing a non-monotonic increase in hours worked. In addition, the interest rate differential rises upon impact by 9 basis points. This result is similar to the initial rise in the feds fund rate reported in Altig et al. (2005). These authors further report that interest rates in the US display a persistent response peaking about three quarters after the shock. Unlike with their results, I find that the interest rate differential decays exponentially, which suggests that the foreign interest rate may have a significant response interacting with the dynamics of the domestic interest rates. We will confirm this observation resorting to an alternative VAR implementation to be discussed momentarily.

[8] Bems et al. (2007) rely on a related VAR specification to analyze US imbalances. Instead of the interest rate differential and exchange rates, they use interest rates and the net trade-to-GDP ratio in the US as the last two variables in the VAR.

In terms of real exchange rates, there is an initial and statistically significant depreciation of the US dollar. This depreciation, however, quickly turns into a highly persistent appreciation.[9] In fact, the US dollar exhibits a hump-shaped profile, which reaches its highest value (1.5%) about 3 years following the shock. Furthermore, it remains appreciated by 1.2% even after five years. To put these numbers in context, note that Eichenbaum and Evans (1995) report that the US dollar reaches its highest appreciation (2%) roughly 3 years after a contractionary monetary shock. Hence, the results here suggest that investment-specific shocks can possibly explain a fraction of the variability in exchange rates comparable to that captured by monetary disturbances. This possibility is explored in more detail in Section 5.

Without a theory of IS shocks and exchange rates, explaining the dynamics of the dollar is akin to navigating in uncharted waters. Yet if one is willing to speculate a little bit, a plausible interpretation is as follows. Let us consider the time path of productivity and Equation (1). Following the investment-specific shock, productivity in the US initially declines, which, other things equal, implies a contraction in domestic production. According to Equation (1), this decline induces a depreciation of the domestic currency. Furthermore, as productivity improves, the dollar strengthens.[10]

Interestingly, the dynamics of the exchange rates are consistent with two widespread views. First, they confirm the observation that favorable disturbances in the US lead to a real appreciation of its currency (Engel et al., 2007). As noted in the previous paragraph, the real exchange rate appreciates as productivity rises over time. Second, Bems et al. (2007) report a worsening of the US trade account following an investment-specific shock. Hence, their findings and the dollar appreciation in Figure 3 lend support to the textbook view that the strengthening of a country's currency typically leads to a decline in its trade balance.

The initial spike in the interest rate differential may result from a compensation due to future dollar depreciations. In contrast, the empirical evidence shows that the US dollar actually appreciates, thus signaling potential excess returns from trading bonds denominated in US and Canadian dollars. The last column in Figure 3 reveals the violation of the uncovered interest parity condition (this figure plots equation (3) with $j = 1$, which corresponds to three-month contracts when using quarterly data). Clearly, borrowing in Canadian dollars and then investing in the US dollars delivers a significant profit of 0.5% upon impact. This excess return results from the relatively higher interest rate in US coupled with the sharp depreciation of the Canadian dollar. Furthermore, the UIP violation persists over the next two years after the disturbance.

The last two rows in Figure 3 present the IRFs when the foreign variables correspond to Japan and the UK. The responses with British data are substantially similar to those obtain using Canadian data. For example, the price of investment displays a permanent contraction following the shock. Furthermore, the real exchange rate initially depreciates but it tends to improve over time with the highest appreciation (1.1%) happening two years after the shock. This appreciation, however, is only statistically significant in the short run. Indeed, after 5 years we cannot reject the hypothesis that the

[9] Under incomplete markets and persistent technology improvements, the initial depreciation possibly results from an initial decline in the terms of trade due to a low trade elasticity (see Corsetti et al., 2006).

[10] The decline in productivity is so strong that overcomes the expansionary effect on output due to higher labor supply.

IS disturbance has no effect on the dollar-pound rate. There is also evidence of deviations from the UIP in favor of investing in US dollars, albeit marginally significant and smaller than that found against the Canadian dollar. When we turn to the yen, note that this currency immediately depreciates after the disturbance.[11] The maximal depreciation happens about 5 quarters earlier than with the Canadian dollar and the British pound. In terms of the excess return to investing in dollars or yens, there is a positive profit from doing it in bonds denominated in the former currency. The return, however, is significant only for a couple of quarters after the shock.

The dynamic consequences of a one-standard-deviation neutral technology shock are displayed in Figure (4). As before, I concentrate on the Canadian case. Extending the number of periods in the simulations, we would observe that productivity rises permanently by about 0.2%. Hours worked displays a hump-shaped profile, reaching its highest level four years after the shock. The initial decline in labor is consistent with the evidence summarized in Gali and Rabanal (2004). The significant rise in the interest differential in favor of the US is consistent with Altig et al.'s (2005) finding that interest rates in the US increase in the aftermath of a neutral technology shock. Here, however, the increase is also consistent with a scenario in which the domestic interest rate remains unchanged while its foreign counterpart contracts (more on this in the next section).

More interesting, there is a significant and hump-shaped real appreciation of the US dollar. At its peak, the domestic currency has strengthened by 1%, which favorably compares with the values reported after an IS disturbance (Figure 3). Such a finding highlights the importance of investment-specific as well as neutral technology shocks in generating high frequency fluctuations in the real exchange rate. The results reported here are broadly consistent with those presented in Corsetti et al. (2008) and Enders and Muller (2009). The first authors, for example, find that the US dollar appreciates in real terms following a rise in manufacturing productivity. Indeed, the exchange rate dynamics look remarkably similar in our studies (see Figures 3 and 4 in their paper). One plausible interpretation of our results is that an economy-wide productivity disturbance has biased sectoral effects, with the bulk of the shock falling on the manufacturing sector. Obstfeld and Rogoff (1996) endorse this interpretation by noting that "the scope for [total] productivity gain is more limited in non-tradables than in tradables." Enders and Muller report that the real exchange rate of the US dollar against a basket of currencies appreciates after a positive technology shock identified à la Gali (1999). The appreciation reaches its highest level (2%) about 5 quarters after the disturbance.

Figure 4 also shows an excess return to borrowing in Canada and then investing the funds in US dollars. Upon impact, the profits from following such a strategy equals 0.2%. Unlike in the case of investment-specific shocks, the deviations from the uncovered interest parity condition are short-lived and marginally significant. Furthermore, the initial excess return is substantially smaller in absolute value than that found after an uncertainty disturbance.

The last two rows in Figure 4 show the consequences of NT shocks when data from Japan and the UK are used. Broadly speaking the impulse responses display characteristics resembling those from the

[11] The immediate appreciation of the US dollar is quite possible if the trade elasticity between Japanese and US goods is large to begin with (see previous footnote and Corsetti et al., 2006).

Canadian data, but there are some important differences as well. As before, productivity in the US rises between 0.2% and 0.3% five years after the shock. Furthermore, there is a significant and persistent increase in the interest rates in the US relative to those in Japan and the UK. A crucial distinction relative to the Canadian data is that upon impact the US dollar sharply appreciates against the yen and pound by 3% and 1.8%, respectively. This initial appreciation tends to vanish in a monotonic fashion with a brief interruption about a year after the shock. The subsequent weakening of the US dollar is strong enough to generate a short-lived excess return in favor of investing in either yen or pounds. This is so even though the interest rate in the US is relatively larger than abroad.

### 3.3 Summary of Results

To wrap up this section, it is worth emphasizing the effects of the different shocks on real exchange rates. To begin with, uncertainty, investment-specific, and neutral technology disturbances generate persistent and significant deviations away from purchasing power parity. Uncertainty and IS disturbances induce hump-shaped responses in all three bilateral exchange rates. Except for the US dollar-Canadian dollar exchange rate, the other two international prices display a monotonic response following a neutral technology shock. This last finding challenges the theoretical arguments in Steinsson (2008), who argues that such technology shocks induce a delayed response in real exchange rates.

Investment-specific and uncertainty shocks, and to a lesser degree neutral technology disturbances, are important contributors to violations of the uncovered interest rate parity. This suggestive evidence calls for a revision of the current theoretical explanations of the forward premium puzzle. This is because they have entertained models with nominal shocks as the sole source of fluctuations in the economy. For instance, the driving force in Baccheta and van Wincoop (2009) is a monetary disturbance, which combined with infrequent currency portfolio re-balancing gives rise to UIP deviations. Ilut (2008) explains the forward premium anomaly relying on a model with shocks to the nominal interest rate differential between the home and foreign countries and where agents have distorted beliefs. Finally, Burnside et al. (2007) allow for a richer structure of shocks buffeting nominal exchange rates but none of these disturbances can be linked to uncertainty or technology.

## 4 Sensitivity Analysis

The results in the previous section lend support to the view that technology and uncertainty do indeed contribute to the dynamics of exchange rates. This conclusion, however, is reached based on very parsimonious VAR representations. In this section, I analyze whether the results are robust to alternative specifications.

### 4.1 Uncertainty

Although theoretical arguments (e.g. Dornbusch, 1976; Gali and Monacelli, 2005) point to the use of the difference between the foreign and the domestic interest rate, it may well be that such a specification is too restrictive from an empirical point of view. Therefore, it seems desirable to assess the implications of relaxing that assumption. To this end, the next VAR formulation incorporates each interest rate separately; i.e., the vector $y_t$ now contains

$$y_t = \left[Volatility, \log(industrial\ production), \log(CPI), R^{US}, R^{FOR}, \log(s^{FOR})\right]. \qquad \text{(VAR \#3)}$$

The results in Figure 5 indicate that the dynamic paths of production, exchange rates, and the excess return are unaffected by the inclusion of foreign interest rates as a separate element in the VAR. For example, the US dollar still depreciates in real terms by an amount consistent with that reported in Figure 2.

A key element in the new results is that we now observe the impulse responses of the interest rates separately. For the Canadian case (first row), note that interest rates display a U-shaped response, which mimics that of industrial production. Indeed, interest rates and production reach their lowest levels around the fifth month following the uncertainty shock. Moreover, the initial drop of the interest rate differential previously reported (Figure 2) results from a sharp decline in interest rates in the US.

From VAR specifications 1 and 3, we consistently find a marked and significant decline in industrial production following a volatility shock. In a globalized economy, this contraction should be associated with a drop in domestic imports and hence a slowdown in production abroad. To the extent that the foreign output decline is expected to last, Equation (1) suggests that omitting foreign production may be biasing the response of exchange rates. If we want to ameliorate this bias, industrial activity abroad must be included in the estimation. One way to incorporate such information is to use the difference between domestic and foreign production as the relevant variable in the VAR (Clarida and Gali, 1994). This approach, however, imposes the rather strong assumption of symmetry between the domestic and foreign economies (Corsetti et al., 2008). While the symmetry premise seems plausible for the US and Japan, it is difficult to swallow such an assumption when comparing the US with the UK and Canada. Hence, following Eichenbaum and Evans (1995) and Faust and Rogers (2003), I opt for a more general formulation, which allows for industrial production at home and abroad to enter separately into the VAR. In particular, let us consider the following variant

$$y_t = \left[\begin{array}{c} Volatility, \log(industrial\ production), \\ \log(foreign\ industrial\ production), \log(CPI), R^{US}, R^{FOR}, \log(s^{FOR}) \end{array}\right]. \qquad \text{(VAR \#4)}$$

The new findings indicate that adding foreign production does not change the results significantly (Figure 6). We still observe a real depreciation of the US dollar and deviations from the UIP. In fact, two years after the shock, the Canadian dollar has appreciated by more than 4%, a value consistent with our previous findings. This forward premium for the US-Canada exchange rate is statistically significant and short-lived, vanishing one year after the shock. For the other two exchange rates, the excess return is only statistically significant for a brief period about 8 months following the initial disturbance.

Foreign industrial production contracts for all countries after the volatility shock, but it is only statistically significant in Japan. Furthermore, the temporary appreciation of the US dollar against the yen is consistent with the relatively strong decline in Japanese production during the first year. The simple exchange rate determination model (Equation 1) suggests a dollar appreciation when production at home is expected to be stronger than it is abroad.

## 4.2 Technology

As previously discussed, using the difference between the foreign and the domestic interest rate may be too strong from an empirical point of view. The next VAR specification relaxes such an assumption by considering the following specification:

$$y_t = \left[\Delta p_{i,t}, \Delta a_t, \log(h_t), \pi_t, R_t^{US}, R_t^{FOR}, \log(s^{FOR})\right]. \qquad \text{(VAR \#5)}$$

For space considerations, I concentrate on the effects of technology shocks on the Canadian-based VAR. The resulting impulse responses in Figure 7 display significant similarities to those from the benchmark VAR. For instance, the price of investment declines permanently following the capital embodied shock. Introducing the interest rates separately into the VAR reveals that the surge in the interest rate differential in Figure 3 arises from a combination of an increase in the domestic rate and a contraction in its foreign counterpart. Note that interest rates in the US display a hump-shaped response. This last finding corroborates Altig et al.'s (2005) results regarding interest rates and IS shocks. More interesting, we still find an initial depreciation of the US dollar that subsequently switches to a persistent appreciation. Furthermore, the domestic currency reaches its peak of 2% about 3 years after the initial disturbance. In fact, even after 5 years the dollar remains appreciated by 1.5%. The main difference relative to the baseline VAR #2 is that the response of the dollar/yen exchange rate is not statistically significant, albeit hump shaped.

When we turn to the UIP response, note that borrowing in Canadian dollars and investing in US dollars is profitable for two reasons: 1) the lower interest rate abroad and 2) the strong appreciation of the US dollar. This excess return is statistically significant and persists even two years after the investment-specific shock.

The implications of a positive neutral technology shock are reported in Figure 8. Note how introducing the foreign interest rate as an independent element in the VAR does not alter the previous findings for Canada. For example, there is a significant and persistent real appreciation of the US dollar (a similar situation arises with the other currencies). The decline in the domestic interest rate is consistent with the empirical results reported in Altig et al. (2005). There is some evidence of deviations from UIP, albeit marginally significant.

A closer look at Figure 8 reveals that the dollar/yen rate now displays a non-monotonic profile, which differs from the results under the VAR formulation #2. This finding shows that the response of exchange rates to neutral technology shocks is very sensitive to the currency of reference as well as the VAR specification. Consequently, one cannot unequivocally attribute the hump shaped response of exchange rates found in univariate regression (Chueng and Lai, 2000) to neutral technology shocks. The empirical results provide only inconclusive evidence to sustain that connection.

An important drawback with the VAR formulations 2 and 5 is that they ignore potential spillovers abroad arising from technology shocks at home. Indeed, Backus et al. (1992) report a correlation of 0.43 between the Solow residuals in the US and Canada. Hence, it seems logical to expect that a positive technology shock at home also raises productivity abroad. But the increase in foreign productivity, via a boost to foreign production, is likely to influence the domestic price of the foreign currency (Equation (1)). Therefore, the results previously displayed may provide a biased view of the true dynamics of the US dollar following technology disturbances.

To control for potential international productivity diffusion, information about technology progress abroad, i.e., foreign labor productivity and the price of investment, should be incorporated into the analysis. Doing so, however, presents some important challenges. To begin with, there are no available measures of the relative price of investment for any of the foreign countries in this study. Second, even with foreign labor productivity data in hand, we still need to decide how to introduce that variable in the VAR. As in Section 4.1, I treat the domestic and foreign countries differently in an attempt to avoid the curse of dimensionality. Specifically, domestic and foreign productivity enter separately in the VAR. As argued in the previous section, such a premise has the additional benefit of relaxing the assumption of symmetric countries (Corsetti et al., 2008). With these considerations in mind, I propose the following variant

$$y_t = \left[\Delta p_{i,t}, \Delta a_t, \Delta a_t^*, \log(h_t), \pi_t, R_t^{US}, R_t^{FOR}, \log(s^{FOR})\right], \qquad \text{(VAR \#6)}$$

where $\Delta a^*$ corresponds to foreign labor productivity.[12] Figure 9 displays the implications of a positive investment-specific shock. The second and third columns confirm our suspicion that improvements at home ultimately translate into productivity changes abroad. Broadly speaking, the inclusion of foreign productivity leaves unchanged the conclusions we drew from the more parsimonious VARs. For instance, interest rates and labor in US rise in response to a capital-embodied shock. More important, the real appreciation of the US dollar displays substantial similarities to that reported in Figures 3 and 7. That is, the dollar reaches its highest appreciation ($\approx 2\%$) around 3 years after the economy is buffeted by the IS shock. The exception once again is the yen, which appreciates after the investment-specific disturbance, albeit statistically insignificant.

Figure 10 presents the dynamic responses to a positive neutral technology shock. Note that foreign labor productivity benefits from the technology disturbance at home, although to a lesser degree than the initial rise in domestic productivity. This observation, therefore, provides further confirmation to Backus et al.'s (1992) findings of international spillovers. By comparing Figures 4 and 10, we observe that the US dollar-Canadian dollar exchange rate preserves its hump-shaped response even after controlling for foreign productivity. Its response, however, is smaller than in the absence of technology spillovers. The peak of the US dollar appreciation is about 0.85% while it is 1.2% in the baseline scenario. Similar to the benchmark case, there is an excess return from investing in US dollars.

[12] One potential interpretation of omitting $\Delta a_t^*$ from the VAR is that the effects of foreign shocks on domestic variables are small relative to those from shocks to $\Delta a_t$ and $\Delta p_t^I$. In fact, that is the implicit assumption on the VAR formulations of Blanchard and Quah (1989) and Fisher (2006). By incorporating $\Delta a_t^*$ we ameliorate the consequences of such an assumption.

In sum, the real appreciations in the US dollar following investment-specific and neutral technology shocks are robust to the inclusion of foreign variables such as interest rates and productivity. The response of exchange rates after the NT shock are somehow smaller but the appreciation is present and statistically significant.

### 4.3 Alternative Interest Rate

The domestic and foreign interest rates in the previous exercises correspond to the effective fed funds rate and the 3-month Treasury bill, respectively. I opt to use the fed funds rate to respect the original constructs in Eichenbaum and Evans (1995), Fisher (2006), and Bloom (2008). This choice, however, may create a maturity mismatch between domestic and foreign securities and therefore bias the estimates. Such a bias is potentially worrisome for the uncovered interest rate parity. To explore this possibility, I repeat the estimation of the VAR specifications 1 and 2 using the US 3-month Treasury bill rate as a measure for $R^{US}$.

The new impulse responses are displayed in Figures 11, 12, and 13 for the uncertainty, investment-specific, and neutral technology shocks, respectively. A quick look at the new results shows that the responses look qualitatively and quantitatively similar to those from the benchmark VARs. For example, the US dollar still depreciates in real terms relative to the Canadian dollar after an increase in uncertainty. This depreciation is statistically significant and present even after 2 years. More interesting, the excess returns following the volatility shock are remarkably similar to those uncovered using the fed funds rate.

When we turn to the technology shocks, note that the price of investment significantly declines following a positive capital-embodied shock. Borrowing in Canadian dollars and then investing in US dollars delivers a significant excess return, which is consistent with the results reported in Figure 3. Finally, a similar picture emerges from the impulse responses following a neutral technology shock. The US dollar, for instance, depreciates vis-a-vis the other three currencies. Moreover, the shape of the impulse responses is again similar to those found in Figure 4. As far as the UIP response, they agree with our previous findings. In summary, using the US 3-month T-bill rate as an alternate interest rate measure has no significant impact on the consequences of uncertainty and technology on exchange rates and the forward premium puzzle.

### 4.4 Relative Volatility

Stock markets have become more integrated worldwide thanks to the widespread use of electronic trading. As a consequence, uncertainty shocks at home quickly affect financial markets abroad. But by the same logic in Section 2, one should expect a contraction in foreign output followed by a depreciation of the foreign currency, which in turn should restrain the decline in the value of the domestic currency. Hence, it seems necessary to control for changes in foreign stock market volatility. Figure 14 displays the impulse responses after a volatility shock at home under two scenarios. The first row shows the results when the difference between the home and foreign volatilities are used in the VAR #1 (see the appendix for the data description)

$$y_t = \left[Volatility - Volatility^{FOR}, \log(industrial\ production), \log(CPI), R^{US} - R^{FOR}, \log(s^{FOR})\right].$$

The second row in turn presents the impulse responses when the volatility measures at home and abroad enter separately into the VAR

$$y_t = \left[Volatility, Volatility^{FOR}, \log(industrial\ production), \log(CPI), R^{US} - R^{FOR}, \log(s^{FOR})\right].$$

The ordering reflects the assumption that the uncertainty shock originates at home and then spreads to foreign markets. Due to data availability, the foreign uncertainty measure corresponds to the stock market volatility in Canada.

The new impulse responses show significant similarities, both qualitatively and quantitatively, to those reported in previous sections. The most noticeable effect is that two years after the volatility shock the US dollar depreciation is about 1 percentage point smaller than that reported in Figure 2. More important, the depreciation is statistically significant and highly persistent. Interestingly, the way the foreign volatility measure enters into the VAR affects only the statistical significance of the initial UIP deviation.

### 4.5 Trade-Weighted Exchange Rate

As a final sensitivity test, this section reports the results when a trade-weighted exchange rate (major currencies) for the US replaces the bilateral ones. Figure 15 presents the impulse responses when using the VAR specifications #1 and #2. The foreign interest rate is a weighted average of the countries' interest rates in the basket of currencies (see appendix). Broadly speaking, the main qualitative conclusions carry over from the previous sections. For example, the real exchange rate depreciates by about 2% after an uncertainty shock. Similarly, technology shocks induce a real appreciation of the US dollar. The new impulse responses are similar to those of Canada for investment-specific shocks or those of Japan for the other two shocks. This finding is not completely unexpected because these countries are the largest trading partners of the US, which implies that their currencies heavily influence the dynamics of the trade-weighted exchange rate.

What is interesting to note is that following a neutral technology disturbance the largest appreciation happens upon impact (1.2%). More important, the dollar's response is not hump shaped, although it is highly persistent. This finding and those from the sections above suggest that neutral technology shocks are not necessarily the source of the non-monotonic response of exchange rates found in univariate reduced-form studies (Chueng and Lai, 2000; Steinsson, 2008). Moreover, looking at Figure 15 it is clear that investment-specific shocks generate non-monotonic responses in real exchange rates. But this finding is troublesome because Martinez-Garcia and Sondergaard (2008) show that DSGE models entertaining investment-specific disturbances are unable to replicate the persistence and volatility of exchange rates found in the data.

## 5 Variance Decomposition

The overall contribution (in percentage points) of each shock to the variability of real exchange rates is displayed in Table 1. Specifically, it reports the percent of the variance of the $k$-step forecast error due to each structural disturbance, for $k = 1, 2$, and 3 years. To facilitate the discussion, let us concentrate momentarily on the US dollar-Canadian dollar exchange rate. At first glance, the variance decomposition exercise reveals that all three shocks are important contributors to the variability of real exchange rates. Take, for example, uncertainty shocks. Under the baseline scenario (VAR #1), these shocks explain about 13% of the volatility of the real exchange rate one year following the disturbance. More important, their contribution tends to grow with the length of the forecasting horizon (the IRFs in Figure 1 already alerted us to the increasing role of uncertainty in explaining the medium-term dynamics of exchange rates). Indeed, uncertainty explains roughly 32% of the exchange rate variability three years after the initial disturbance. Interestingly, adding more variables to the VAR specification has little impact on the contribution of uncertainty shocks. Depending on the VAR formulation, uncertainty roughly captures between 22% and 31% of the variability of exchange rates at the two-year horizon.

When we turn to the link between the US dollar-Canadian dollar exchange rate and technology shocks, three important features surface. First, the individual contributions of technology disturbances are generally smaller than those found for the uncertainty shock (except for the one-year-ahead decomposition under NT shocks). For example, under the formulation VAR #2 investment-specific shocks explain only half of the variability captured by uncertainty at the one- and two-year horizons (compare 7% with 13% and 15% with 28%). Second, the NT disturbance is relatively more important in the short run than its IS counterpart. According to the benchmark specification VAR #2, the former shock explains 16%, while the later shock captures 7% of the one-year-ahead forecast errors. Finally, the contribution of the IS shocks rises with the forecasting horizon while that of NT shocks tend to be stable at about 16%.

The picture looks substantially different when we study the yen-dollar relationship. Indeed, the NT shock explains a significantly large fraction of the fluctuations of the relative prices between Japan and the US. Under the benchmark specifications, whereas uncertainty explain only a mere 2% (VAR #1), neutral technology shocks capture 29% (VAR #2) of the exchange rate variability at the one-year horizon. Interestingly, the variance decompositions in Table 1 reveal that the importance of technology shocks is robust to the inclusion of foreign productivity (VAR #6). The results also indicate that uncertainty and IS disturbances roughly explain the same fraction of the forecast errors in the yen-dollar exchange rate.

The importance of technology shocks is also apparent for the bilateral exchange rate between the UK and the US. Among the two technology disturbances, it is the NT shock that contributes more to the fluctuations of the pound-dollar rate. For the benchmark scenario (VAR #2), such a disturbance explains around 20% of the exchange rate variability at all horizons. On the other hand, uncertainty shocks explain only a modest 1% of the short-term fluctuations of the bilateral exchange rate between the US and the UK. Similar to the case with Japan, the relevance of technology shocks in explaining the dynamics of the pound-dollar rate is robust to the inclusion of foreign variables. In fact, the contribution of NT and IS shocks tend to rise as we introduce interest rates separately (VAR # 5) or include foreign productivity (VAR #6). For instance, IS disturbances explain an additional 16% at the one-year horizon when foreign productivity is included relative to the benchmark case.

Roughly speaking, the sum of the individual variance decompositions provides an upper bound to the combined contribution of the three shocks. This sum is a ceiling because uncertainty and technology shocks are identified using separate VARs, which is a consequence of the lack of monthly data for the price of investment and labor productivity. With this caveat in mind, the most conservative scenario reveals that the three shocks can potentially explain up to 30%, 52%, and 61% of the Cd-US dollar exchange rate at one-, two-, and three-year horizons, respectively.[13] For the same forecasting horizons, these shocks account for up to 30%, 41% and 44% for the yen-dollar exchange rate and 18%, 29%, and 31% for the pound-dollar exchange rate.

The variance decomposition results when using the US 3-month T-bill rate rather than the fed funds rate are reported under the label VAR #7. Overall, the results agree with those from the benchmark VARs #1 and #2. An exception is that the explanatory power of uncertainty and neutral technology shocks for the US dollar-Canadian exchange dollar rate tend to be smaller than that reported for the baseline scenario. However, given the large standard errors, we cannot rule out the hypothesis that the variance decompositions are the same under the benchmark VARs and the alternative specification with the US T-bill rate.

When foreign volatility is introduced into the analysis (Section 4.4), the contribution of the uncertainty shock to the one-, two-, and three-year-ahead forecast errors are $\{7\%, 15\%, 16\%\}$ for the VAR with the difference in volatilities. These contributions are smaller than those from the baseline case. However, the gap between the two sets of estimates is not significant after taking into account sampling errors. If the volatilities enter separately into the VAR, the contributions are $\{10\%, 22\%, 25\%\}$, which are close to those obtained from the VAR #1.

For the trade-weighted exchange index, the variance decomposition exercise attributes $\{2\%, 6\%, 8\%\}$ to uncertainty shocks, $\{5\%, 20\%, 28\%\}$ to investment-specific shocks, and $\{11\%, 8\%, 7\%\}$ to neutral technology disturbances. Similar to the dollar/pound and dollar/yen cases, technology shocks explain a larger fraction of the fluctuations in the real exchange rate. Yet the investment-specific disturbance tends to capture more of the variability at the two- and three-year horizons.

Do technology and uncertainty drive exchange rates? Based on the variance decomposition exercise, the answer is yes but to a lesser extent than one could have initially guessed from the works of Fisher (2006) and Bloom (2008). Yet the relatively low explanatory power of those disturbances should not be that surprising. After all, it is just another manifestation of the celebrated exchange rate disconnect puzzle (Obstfeld and Rogoff, 2000), i.e., the disconnection between real exchange rates and macoeconomic fundamentals.

Finally, the empirical evidence suggests that uncertainty shocks have localized effects, while tech-

[13] The first number results from summing up the contribution of the uncertainty shock (13% under VAR #1), the IS disturbance (6% under VAR #6) and the NT shock (11% under VAR #6). The other numbers are obtained in a similar fashion. The information from VAR #7 is not considered, since it is an alternative specification to VAR #1 (see Section 4.3).

nology disturbances seem to have far-reaching consequences for exchange rates. This conclusion results from the following observations. To begin with, whereas uncertainty shocks explain a disproportionately large portion of the variability of the US dollar-Canadian dollar exchange rate, this shock explains only a modest fraction of the other exchange rates (this point was already apparent from the impulse responses reported in Figures 1 and 2). Second, NT shocks explain comparable fractions of the variability in the three bilateral exchange rates (see the last four rows in Table 1). Additionally, IS disturbances capture a sizable portion of the fluctuations in the US dollar/Canadian dollar and trade-weighted exchange rates. Interestingly, the last two points lend some empirical support to Steinsson's (2008) view that technology is an essential ingredient in explaining the dynamics of the real exchange rate.

## 6 Concluding Remarks

Uncertainty and technology disturbances have received a lot of attention in the recent business cycle literature. This paper has explored the role of those shocks in accounting for the volatility of real exchange rates as well as deviations from uncovered interest rate parity. Impulse responses and a variance decomposition exercise reveal that neutral technology shocks contribute to the volatility of the three exchange rates under study. In contrast, the empirical analysis shows that investment-specific are more relevant for the US dollar - Canadian dollar and a trade-weighted exchange index, while uncertainty shocks are important for the former exchange rate.

A puzzling finding is that uncertainty shocks mostly affect the US-Canada exchange rate. In principle, one would expect that given the relatively large amount of trade between these two countries, Canadian production should decline due to smaller exports to the US after an increase in volatility. As a consequence, the Canadian dollar would be less attractive and hence the depreciation of the US dollar should be small. Yet the variance decomposition as well as the impulse responses indicate exactly the opposite. Without a sound theory of exchange rates and uncertainty, it is impossible to provide a sound answer to this intriguing result.

Regarding the forward premium anomaly, the results in this paper make some interesting points. For example, I show that uncertainty and technology shocks induce UIP violations and the sign of these deviations is currency specific. From a theoretical point of view, these results call for extensions to existing models of the forward premium anomaly (Burnside et al., 2007; Baccheta and van Wincoop, 2009). Indeed, future developments should impart an important role to uncertainty and technology and also allow for asymmetric excess returns. Having this country-specific flavor of the UIP puzzle is probably the biggest challenge, since one must first identify the source of the heterogeneity. Is it geographical factors, different financial markets, or monetary policy?

One of the recent debates on the PPP puzzle centers on whether DSGE models entertaining neutral technology shocks can account for the volatility and persistence of real exchange rates. A central argument in this debate is that such shocks induce a delayed response in international prices (Steinsson, 2008). My results contribute to this literature with two insightful findings. First, it is shown that neutral technology disturbances indeed contribute to the volatility of exchange rates. More important, the results here provide inconclusive evidence as to whether neutral technology disturbances induce hump-shaped profiles in real exchange rates.

Table1: Variance Decomposition

Real Exchange Rates

| | 1 year ahead | | | 2 years ahead | | | 3 years ahead | | |
|---|---|---|---|---|---|---|---|---|---|
| | Cd | Jp | UK | Cd | Jp | UK | Cd | Jp | UK |
| | Uncertainty Shocks | | | | | | | | |
| VAR #1 | 13 | 2 | 1 | 28 | 5 | 8 | 32 | 8 | 10 |
| | [4,19] | [1,8] | [1,6] | [6,29] | [2,11] | [2,11] | [6,39] | [2,12] | [2,12] |
| VAR #3 | 13 | 2 | 1 | 27 | 9 | 6 | 28 | 12 | 8 |
| | [4,22] | [1,8] | [1,7] | [6,30] | [3,12] | [2,11] | [5,30] | [3,12] | [2,12] |
| VAR #4 | 13 | 2 | 1 | 31 | 6 | 3 | 32 | 8 | 4 |
| | [5,22] | [1,9] | [1,6] | [7,35] | [2,12] | [1,9] | [6,33] | [2,12] | [2,9] |
| VAR #7 | 13 | 2 | 1 | 22 | 4 | 7 | 23 | 6 | 9 |
| | [4,18] | [1,8] | [1,6] | [4,27] | [2,9] | [2,11] | [3,29] | [2,9] | [2,12] |
| | Investment-Specific (IS) Shocks | | | | | | | | |
| VAR #2 | 7 | 2 | 2 | 15 | 7 | 4 | 26 | 7 | 6 |
| | [6,36] | [2,26] | [2,24] | [11,43] | [5,42] | [4,27] | [11,53] | [6,43] | [5,31] |
| VAR #5 | 6 | 2 | 12 | 17 | 10 | 11 | 31 | 11 | 14 |
| | [3,34] | [2,26] | [5,42] | [7,49] | [4,41] | [9,36] | [9,60] | [5,42] | [10,37] |
| VAR #6 | 6 | 14 | 18 | 19 | 10 | 12 | 37 | 10 | 13 |
| | [4,30] | [2,26] | [3,41] | [7,42] | [4,33] | [7,36] | [9,54] | [4,35] | [8,38] |
| VAR #7 | 10 | 1 | 2 | 14 | 5 | 4 | 24 | 5 | 6 |
| | [5,37] | [2,24] | [2,25] | [9,40] | [4,38] | [5,27] | [9,52] | [4,39] | [6,29] |
| | Neutral Technology (NT) Shocks | | | | | | | | |
| VAR #2 | 16 | 29 | 18 | 16 | 29 | 21 | 16 | 29 | 21 |
| | [2,21] | [5,38] | [3,26] | [2,24] | [5,40] | [4,27] | [2,25] | [6,41] | [4,28] |
| VAR #5 | 16 | 36 | 19 | 14 | 46 | 23 | 13 | 47 | 23 |
| | [2,24] | [3,39] | [2,21] | [2,23] | [4,47] | [4,24] | [2,24] | [5,48] | [4,23] |
| VAR #6 | 11 | 26 | 15 | 10 | 36 | 23 | 7 | 37 | 22 |
| | [2,23] | [3,30] | [2,21] | [2,28] | [4,37] | [5,25] | [2,27] | [6,39] | [5,25] |
| VAR #7 | 7 | 28 | 13 | 9 | 28 | 16 | 10 | 29 | 16 |
| | [2,23] | [5,37] | [3,23] | [2,20] | [5,41] | [3,26] | [2,23] | [6,41] | [4,26] |

Variance decomposition for bilateral real exchange rates of Canada (Cd), Japan (Jp) and United Kingdom (UK)

Numbers in square brackets represent a 68% probability interval based on 500 Monte Carlo replications

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# 7 Appendix

## 7.1 Data Description

The data were acquired through several sources.

- **Exchange rates**

Exchange rates come from Global Insight. End-of-the period (month or quarter) observations are constructed using daily spot bid London close quotes. If the end-of-the-period day coincides with a holiday or a weekend, the quote from the immediately preceding business day is used as the observation. The trade-weighted exchange rate corresponds to the index constructed by the Board of Governors using major currencies (TWEXMMTH).

- **Interest rates**

The domestic interest rates correspond to the effective fed funds rate from the St. Louis Fed's database. The 3-month Treasury bill comes from the St. Louis Fed's database. For the foreign countries, the short-term interest rates are 3-month treasury bill rates from Global Insight. The foreign interest rate in Section 4.4 is a weighted average of several interest rates, where the countries and weights correspond to those used in the index TWEXMMTH.

- **VAR with uncertainty shocks**

The data for the volatility indicator, industrial production, and consumer price index are taken from Bloom's (2008) database available at http://www.stanford.edu/~nbloom/index_files/Page315.htm. For the VAR in Section 4.4 the domestic stock market volatility is taken from Bloom (2008). The foreign measure corresponds to actual monthly return volatilities computed as the monthly standard deviation of the daily TSX Composite Index. The data are taken from the Haver database and start in 1984. For the UK and Japan, daily observations are only available starting in the late 1990s.

- **VAR with technology shocks**

The price of investment series was kindly provided by Ricardo DiCecio from the St. Louis Fed. Labor productivity in the US is constructed as the ratio of output to hours worked, which is the definition pursued in Fisher (2006). Inflation in US is constructed using the consumer price index. The CPI, output, and hours worked come from Global Insight. Finally, foreign labor productivity corresponds to labor productivity of the total economy available from the OECD economic indicators database.

### 7.2 Newspaper Quotes

"The violent currency swings show little sign of disappearing as uncertainty over the economic outlook remains. The dollar fell 13% against the euro in little more than two weeks in early December." (Swimming with the Currency, WSJ January 6, 2009)

"The euro reversed its losses from the last two days against the dollar Thursday as investors took profits and on indications that healthier euro zone nations might support those under greater economic stress." (Sentiment Towards Euro Improves, WSJ, February 19, 2009)

"The financial market turmoil that began in August has put serious pressure on the US dollar: by end-November the dollar had fallen by some 6% since August against a trade-weighted currency basket tracked by the US Federal Reserve." (Prospects for the dollar next year, The Economist, December 19, 2007).

"The dollar is likely to decline by at least another 15-20 per cent on average. Growth differentials have now moved against the US, which may experience the slowest expansion of any G7 country in 2007 ... The sharp pick-up in US productivity growth that underpinned the strong dollar for a decade has been fading." (Europe must look east to deal with the strong euro, Financial Times, October 12, 2007).

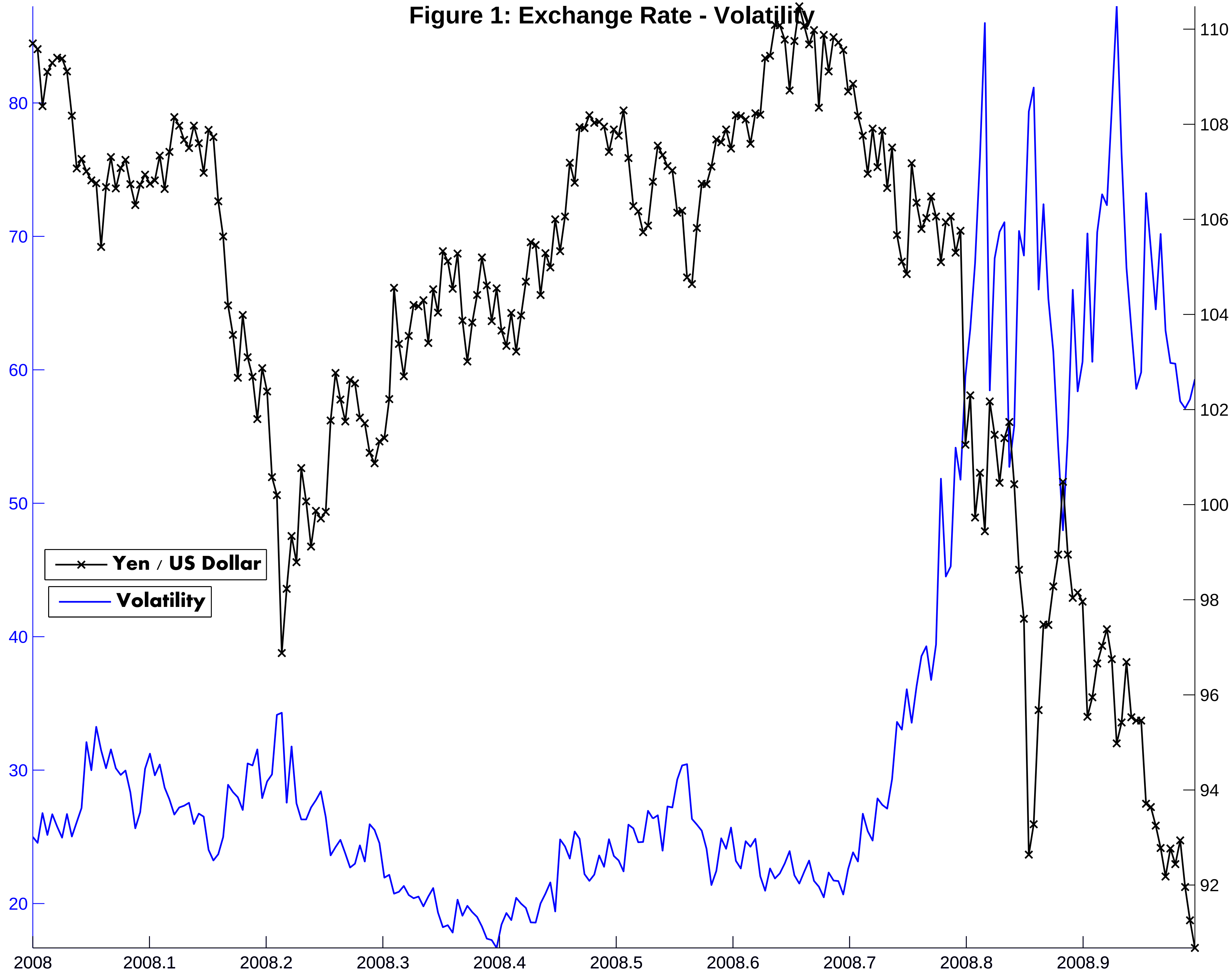
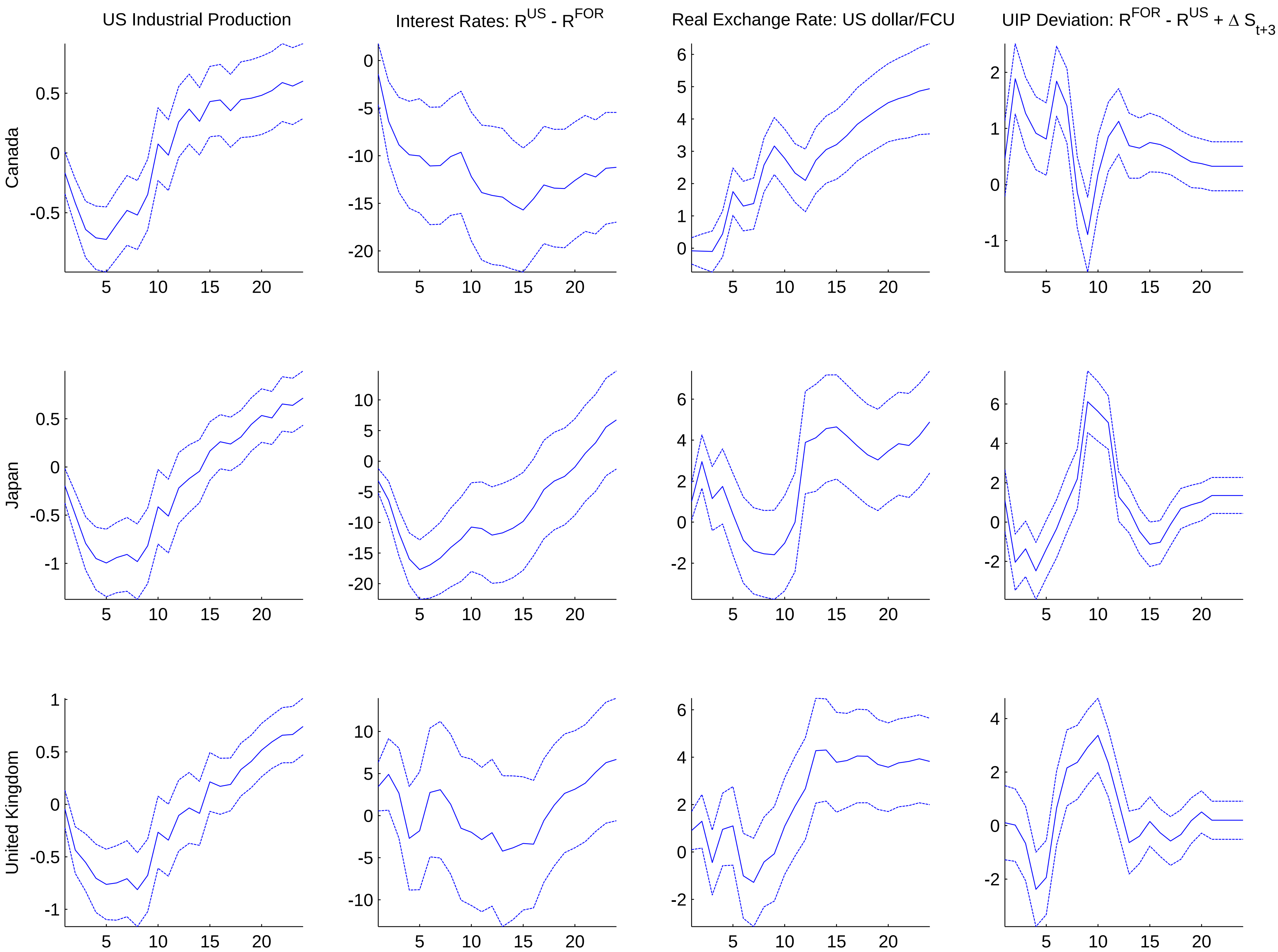
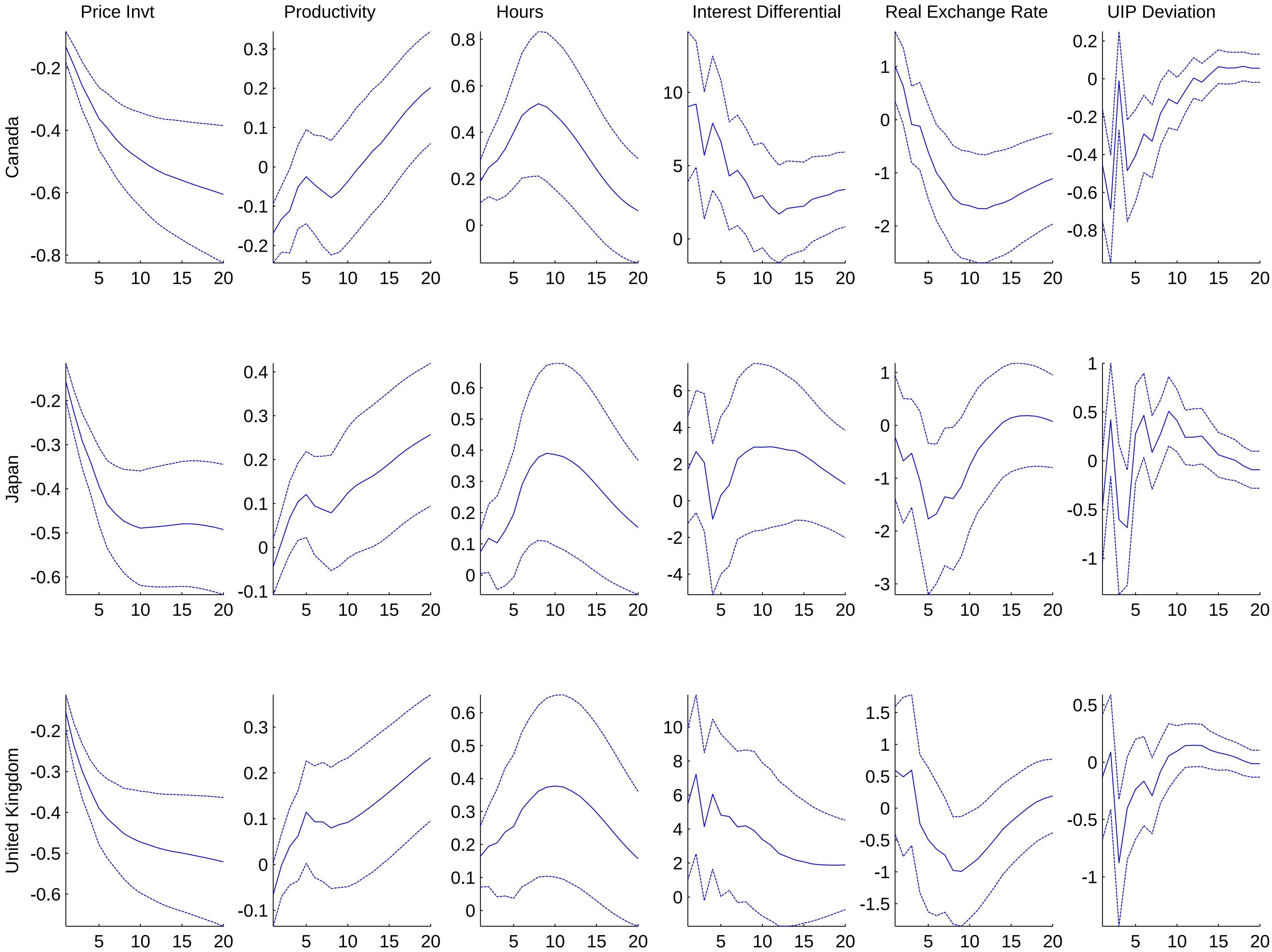


Figure 1: Exchange Rate - Volatility
Yen / US Dollar
Volatility
80
70
60
50
40
30
20
110
108
106
104
102
100
98
96
94
92
2008
2008.1
2008.2
2008.3
2008.4
2008.5
2008.6
2008.7
2008.8
2008.9

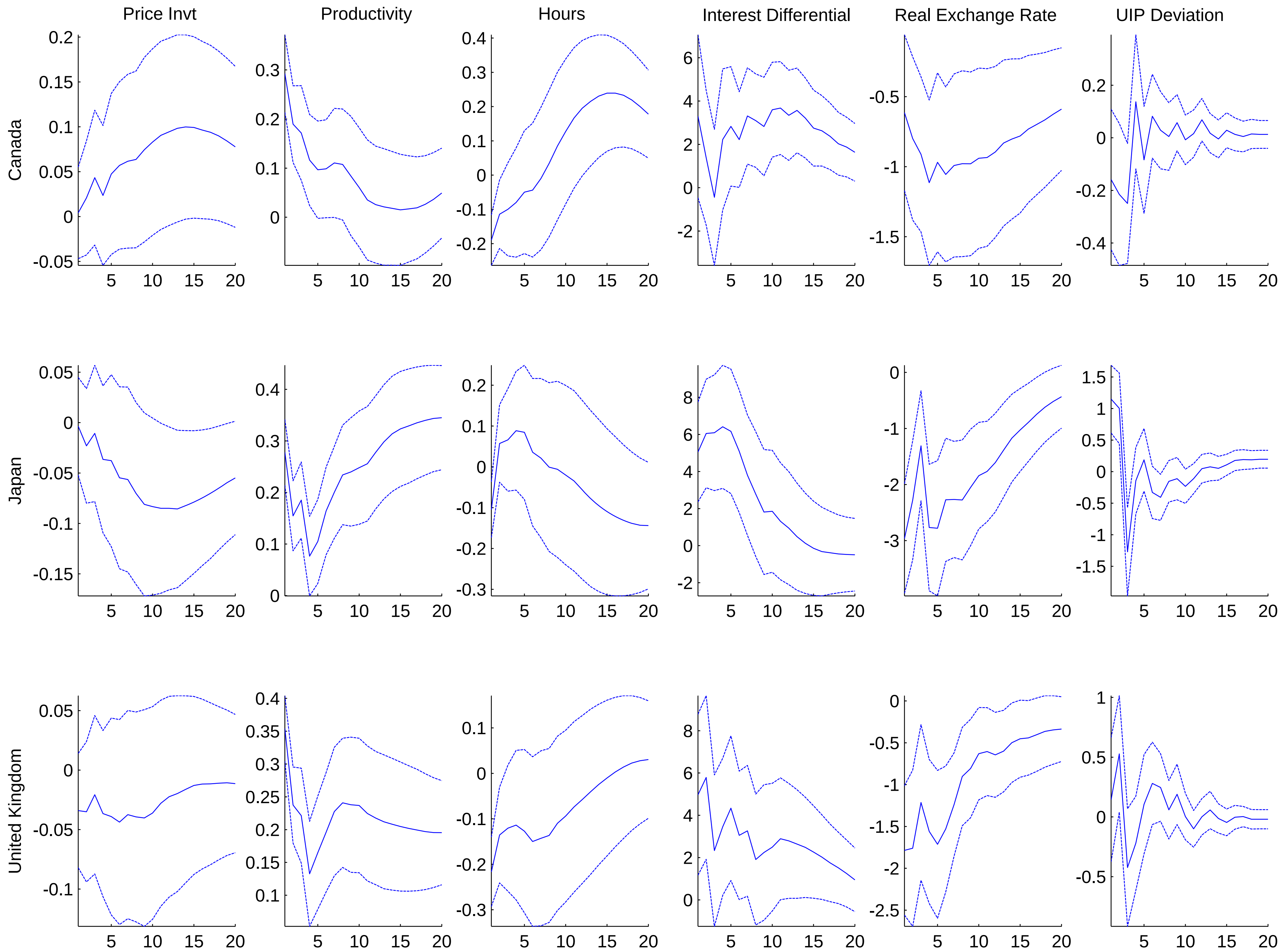
# Figure 2: Volatility Shock



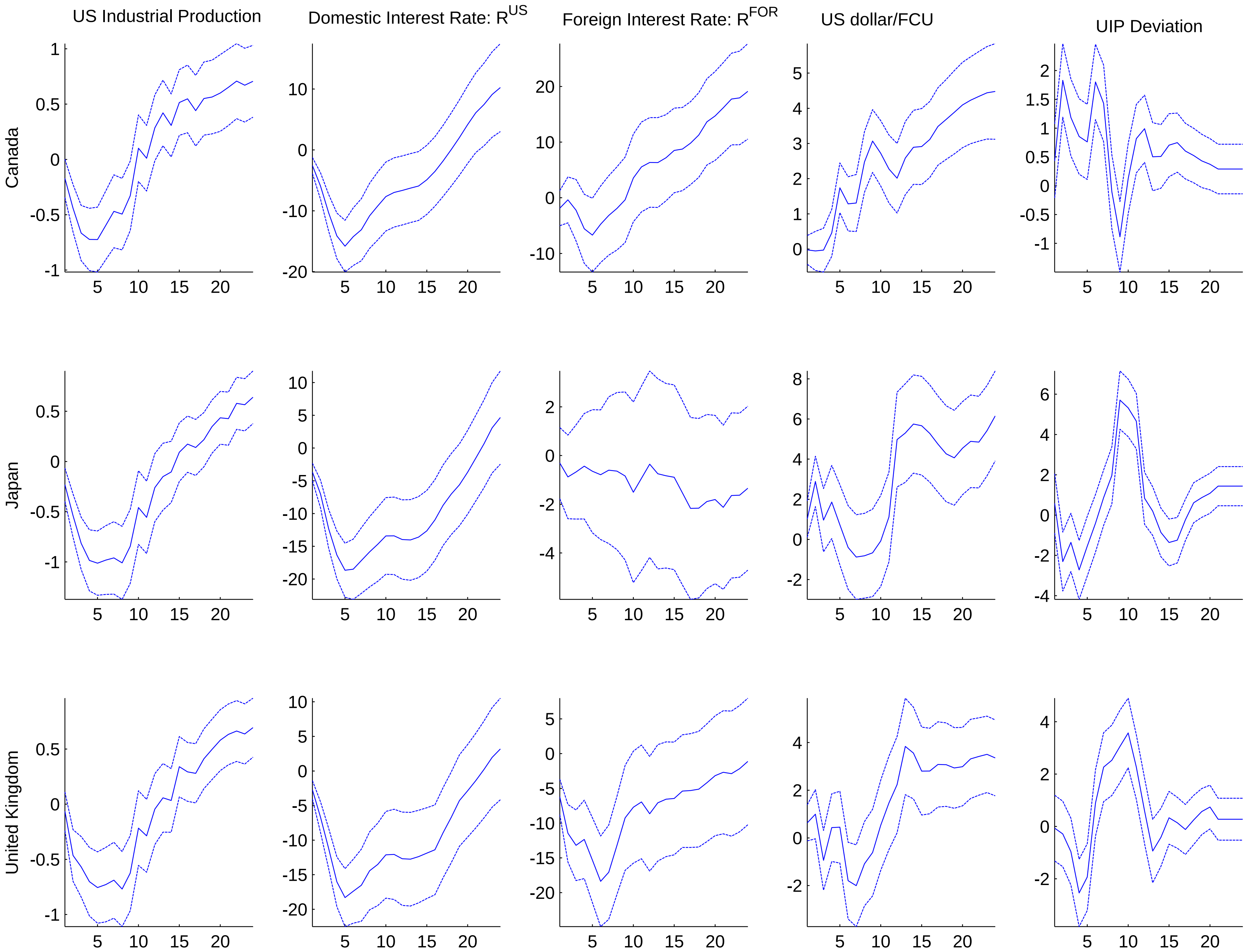
# Figure 3: Investment-Specific Shock



## Figure 4: Neutral Technology Shock



# Figure 5: Volatility Shock



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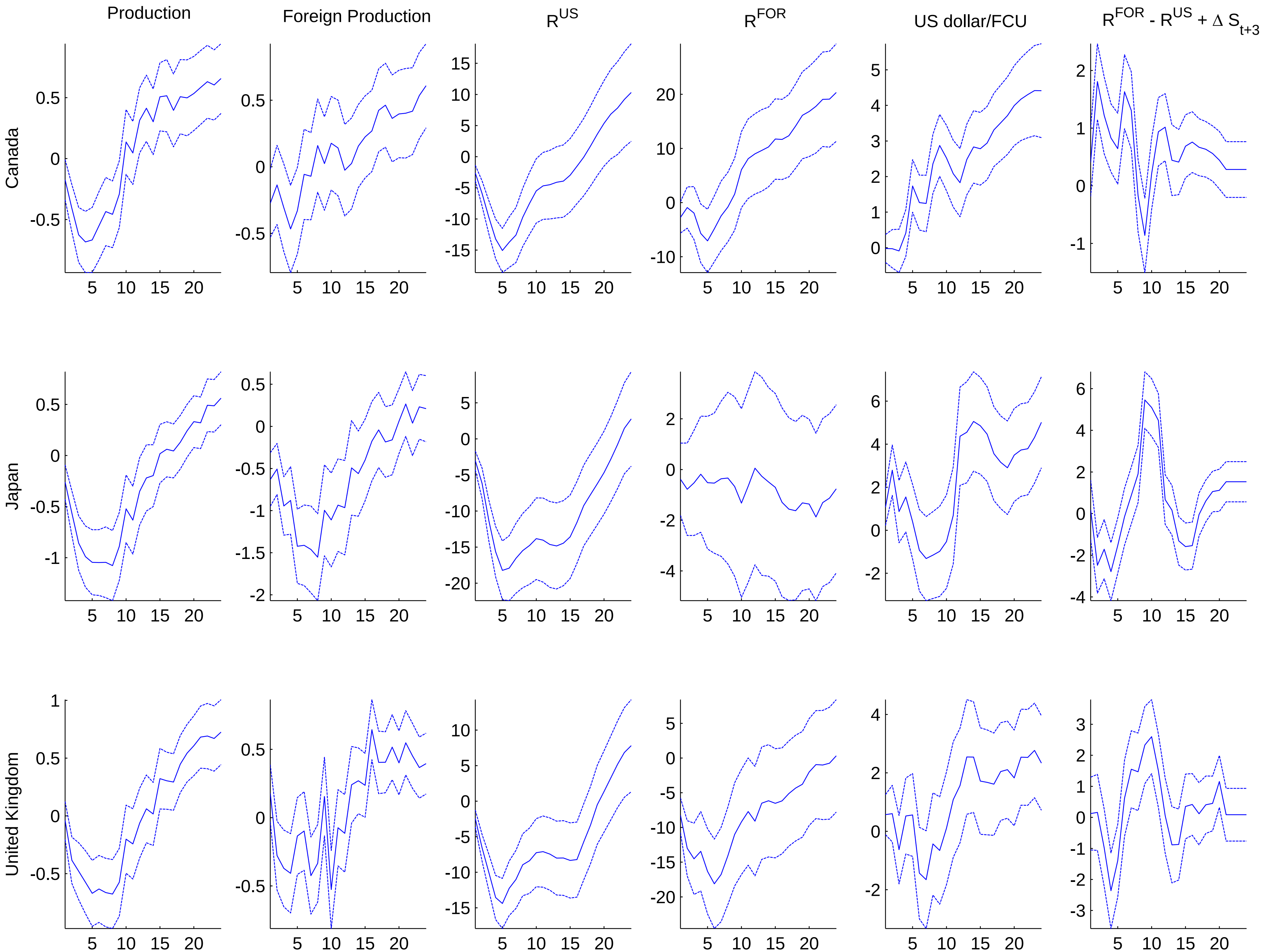
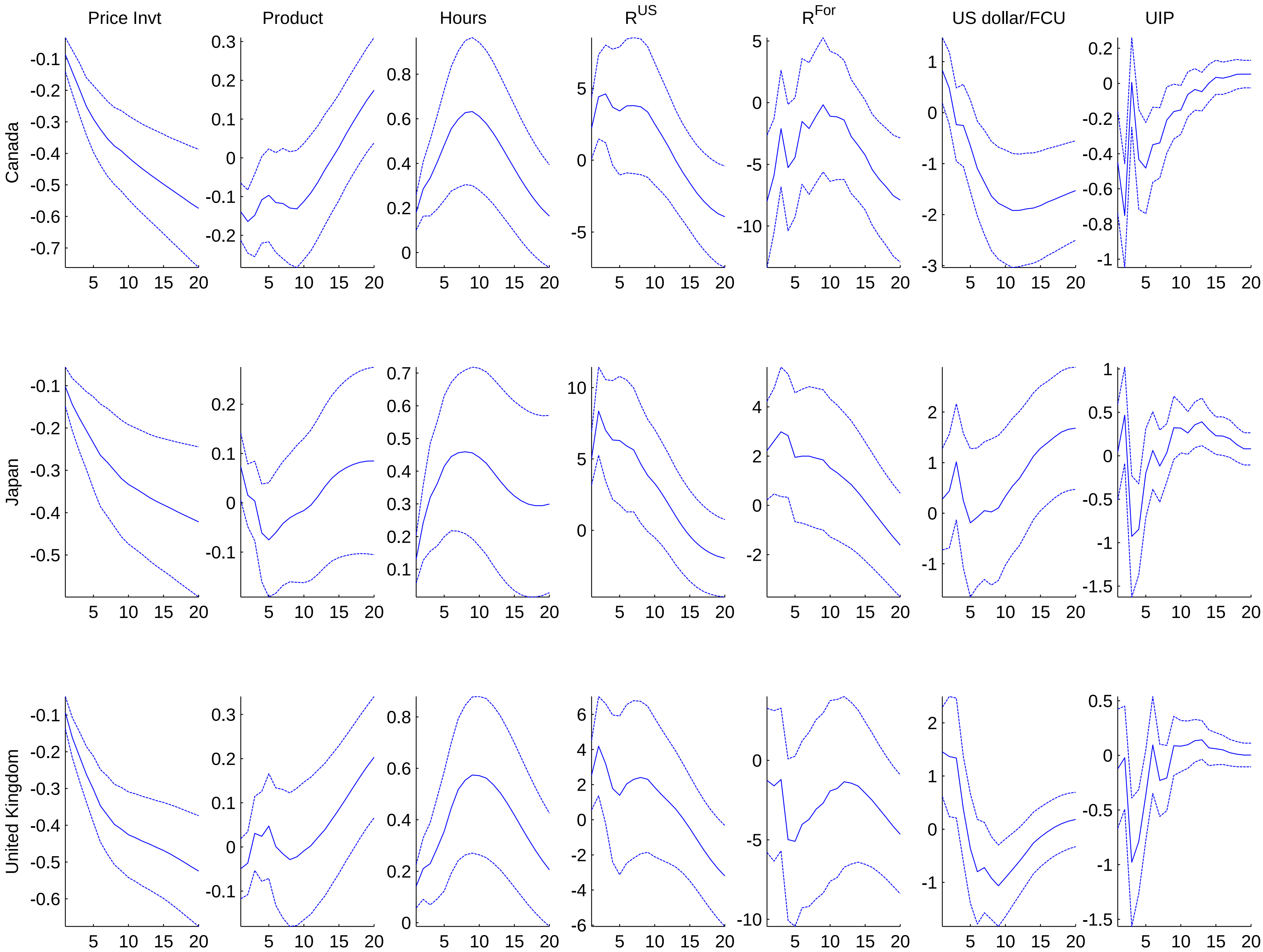
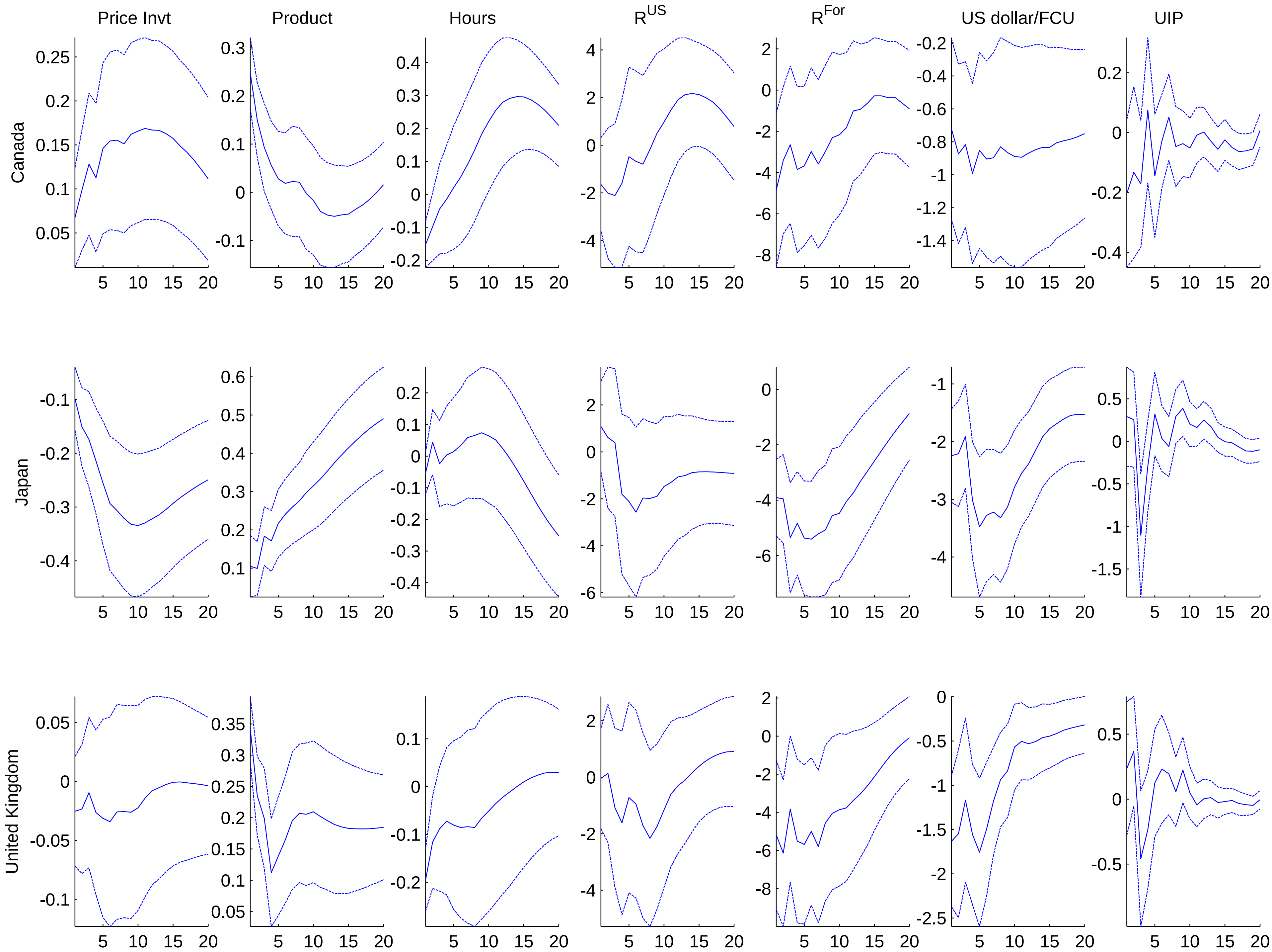


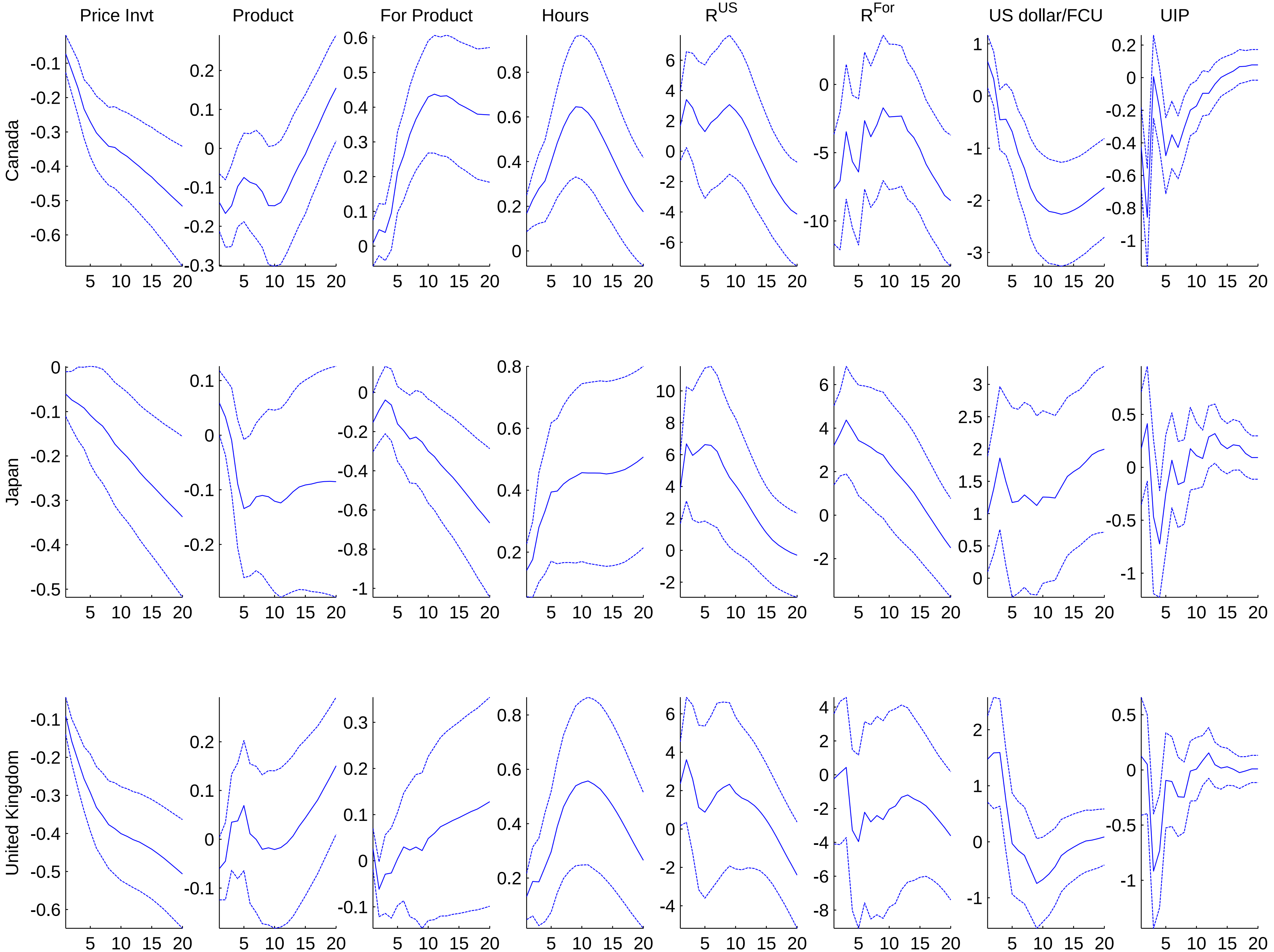
Figure 7: Investment-Specific Shock



# Figure 8: Neutral Technology Shock



# Figure 9: Investment-Specific Shock



# Figure 10: Neutral Technology Shock

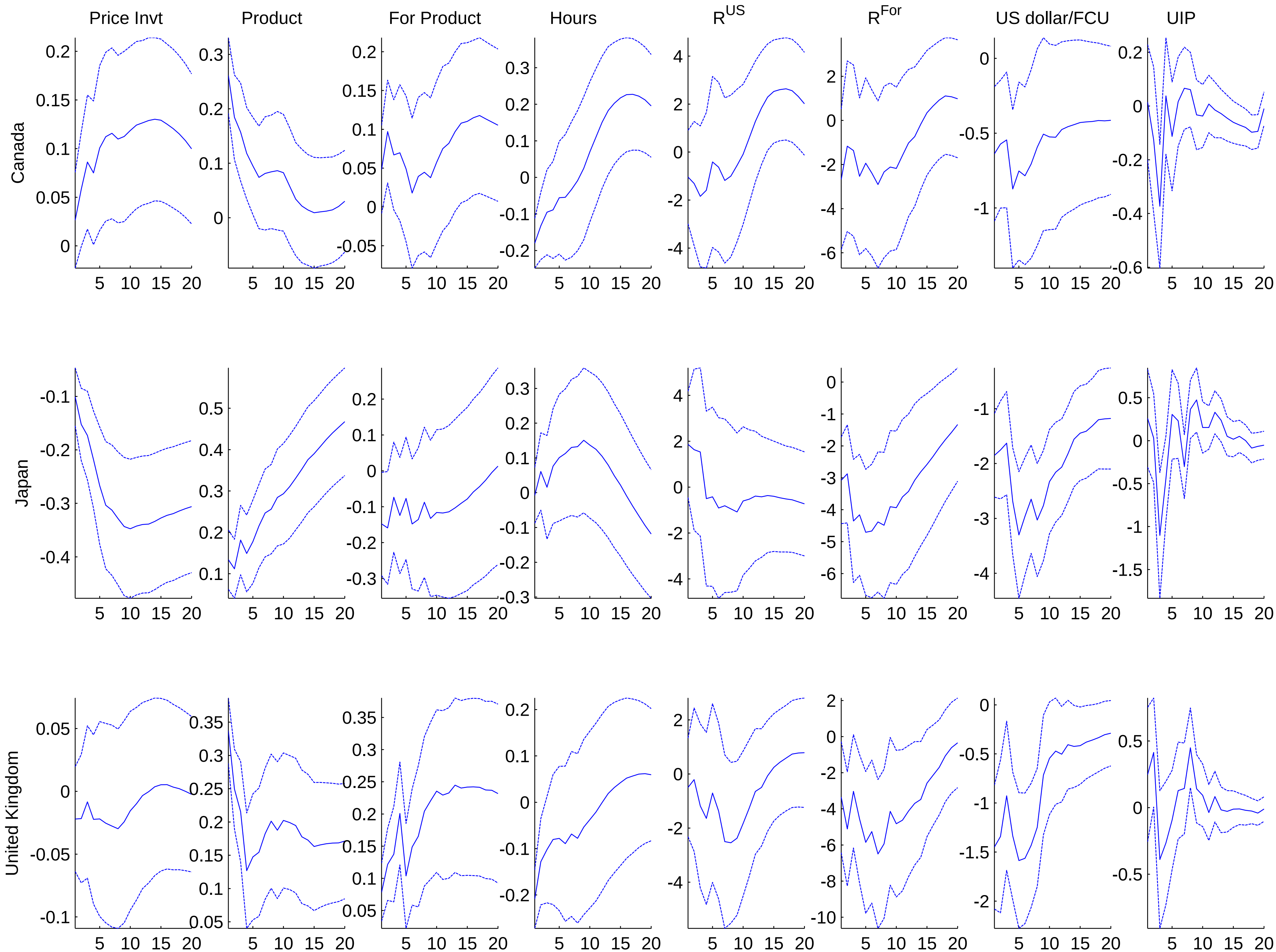
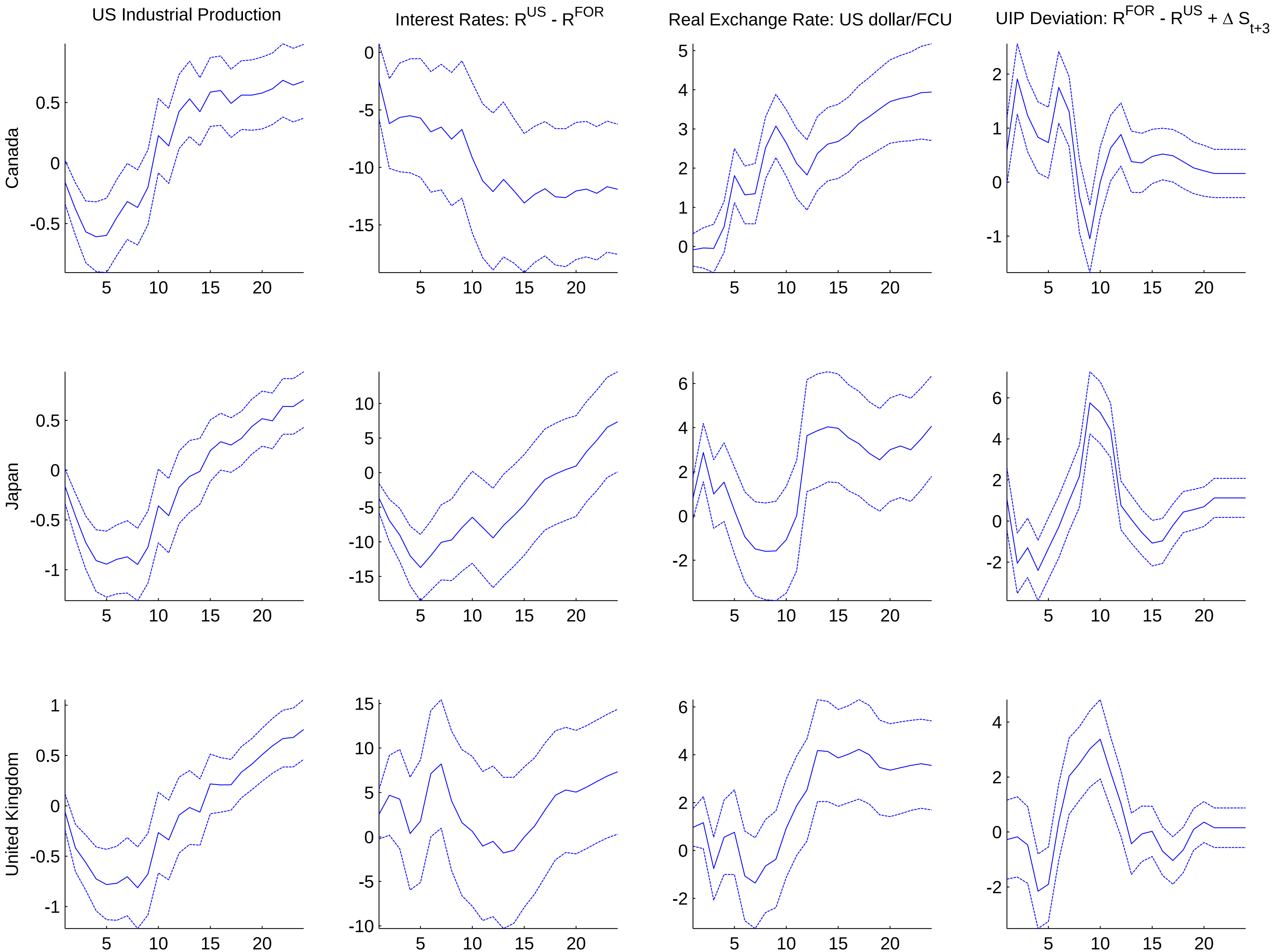
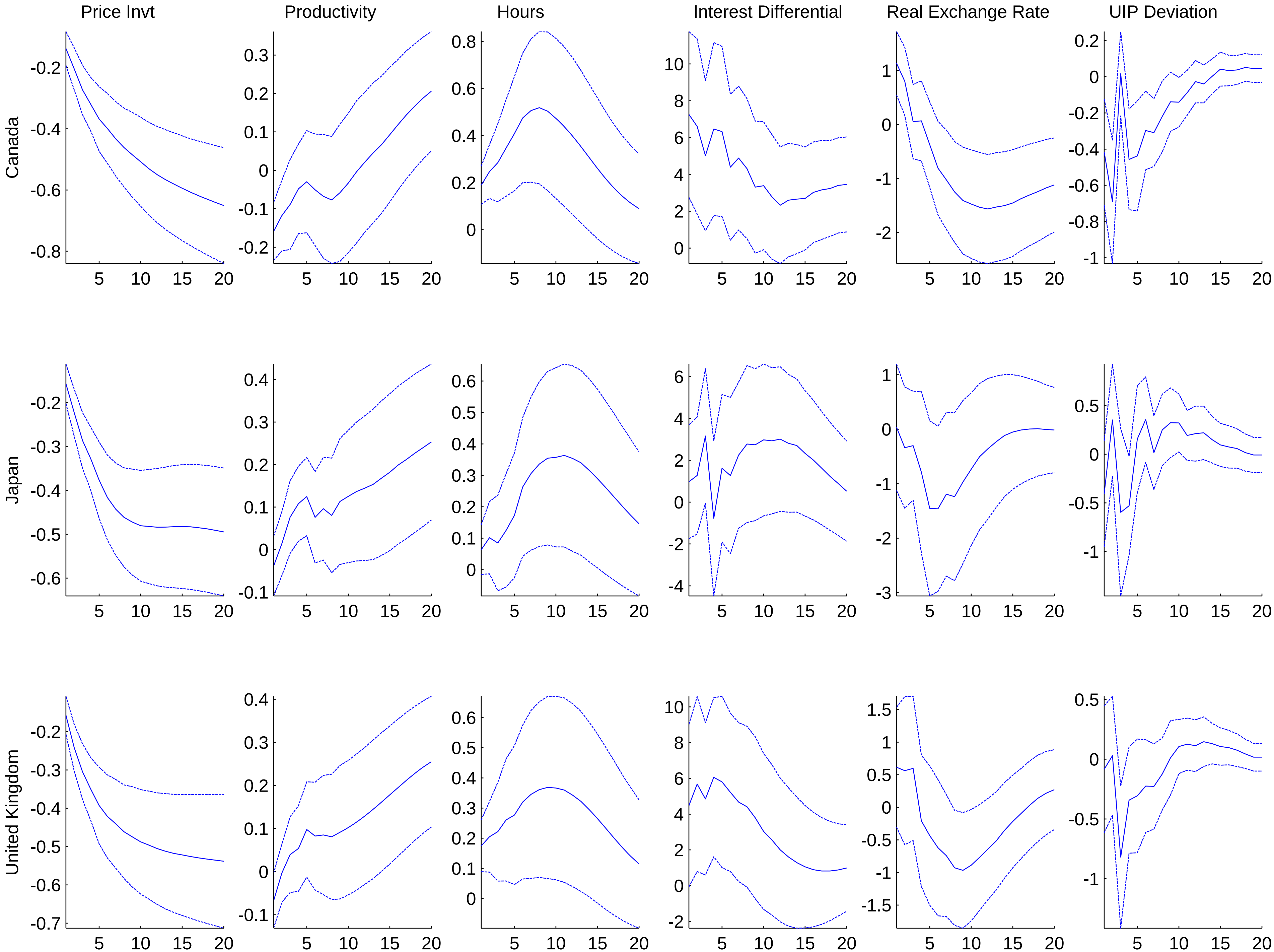


Figure 11: Volatility Shock



# Figure 12: Investment-Specific Shock



# Figure 13: Neutral Technology Shock

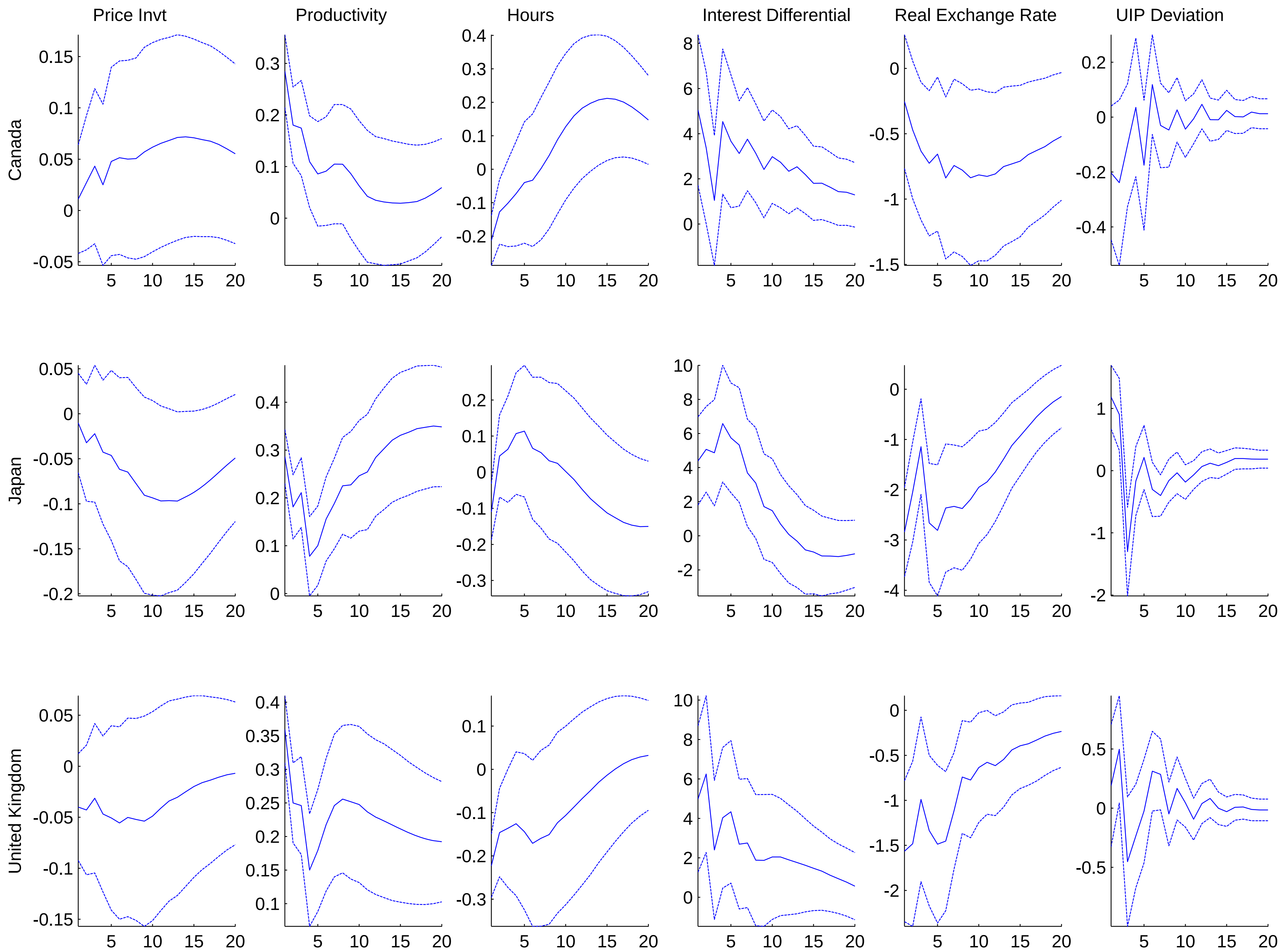
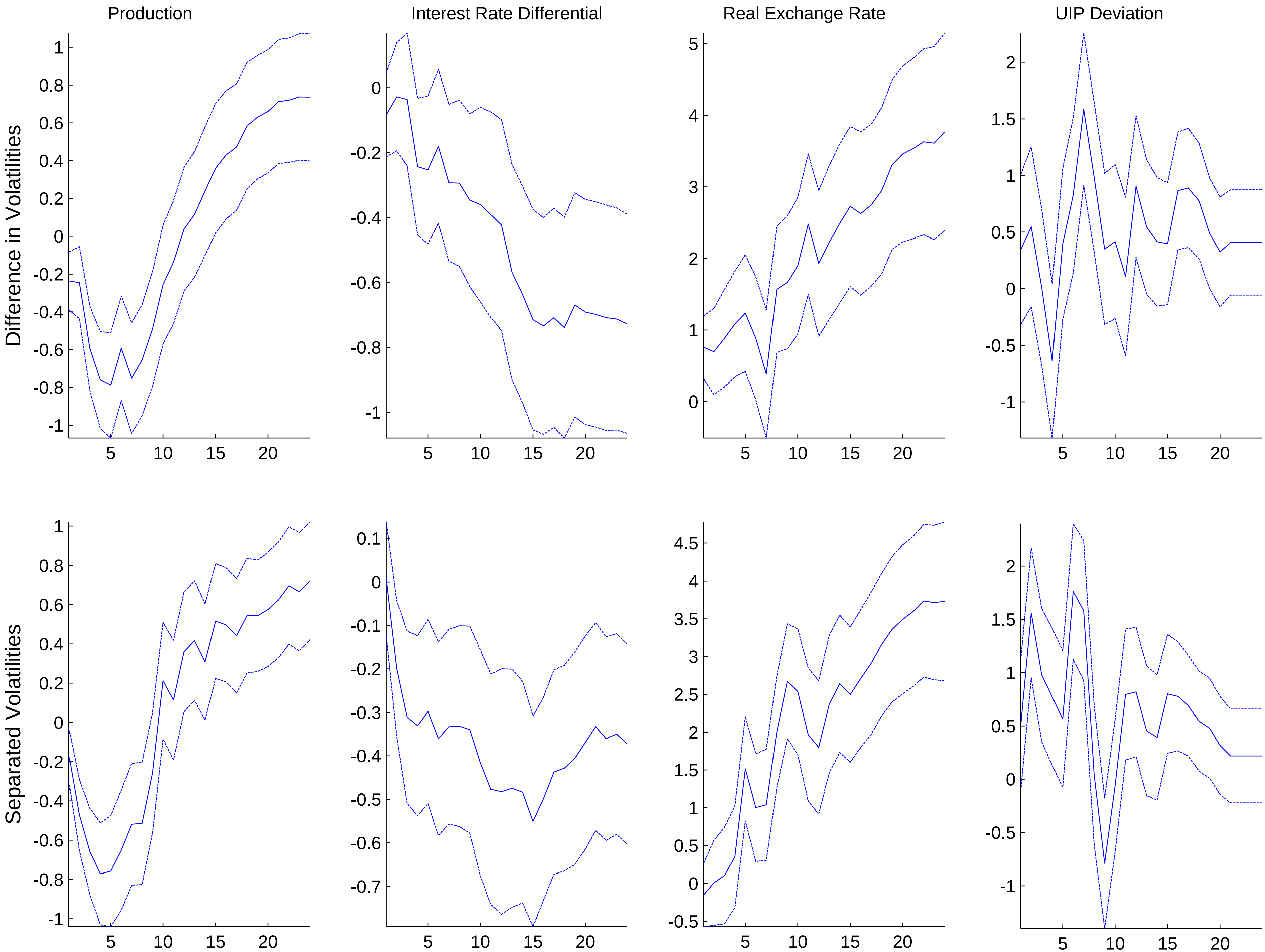


Figure 14: Volatility Shock with Canadian Stock Market Volatility



# Figure 15: Trade Weighted Exchange Rate Impulse Response