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MONETARY SHOCKS AND REAL EXCHANGE RATES IN STICKY PRICE MODELS OF INTERNATIONAL BUSINESS CYCLES

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ABSTRACT

The data show large and persistent deviations of real exchange rates from purchasing power parity. Recent work has shown that to a large extent these movements are driven by deviations from the law of one price for traded goods. In the data, real and nominal exchange rates are about 6 times as volatile as relative price levels and they both are highly persistent, with serial correlations of 0.85 and 0.83, respectively. This paper develops a sticky price model with price discriminating monopolists, which produces deviations from the law of one price for traded goods. Our benchmark model, which has prices set for one quarter at a time and a unit consumption elasticity of money demand, does not come close to reproducing these observations. A model which has producers setting prices for 6 quarters at a time and a consumption elasticity of money demand of 0.27 does much better. In it real and nominal exchange rates are about 3 times as volatile as relative price levels and exchange rates are persistent, with serial correlations of 0.65 and 0.66, respectively.

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There is extensive evidence that there are large and persistent deviations of real exchange rates from purchasing power parity. Mussa (1986) documents that real exchange rates are about as volatile as nominal exchange rates and that both are approximately random walks. This evidence suggests two possibilities: either there are large and persistent changes in the composition of traded and nontraded goods or there are large and persistent deviations from the law of one price in traded goods. Recently there have been a number of studies documenting that even at a very disaggregated level, there are large and persistent deviations from the law of one price in traded goods (see, for example, Engel 1993 and Knetter 1993).

The conventional wisdom is that these observations are the result of monetary shocks, and they can best be understood in a model with sticky prices. The pricing-to-market literature has also argued that deviations from the law of one price arise from price discrimination by monopolists. (See Dornbusch 1987 and Krugman 1987 for the basic theory and Marston 1990, Knetter 1989, and the forthcoming survey by Goldberg and Knetter for empirical work.) The purpose of this paper is to develop a general equilibrium model with sticky prices and price discriminating monopolists. We go on to ask whether a quantitative version of the model can generate large and persistent movements in exchange rates following monetary shocks. We find that even when producers set prices for 6 quarters at a time, the model can go only part way in generating the kind of large and persistent movements in real exchange rates we see in the data.

Our model is a two country variant of the one used by Chari, Kehoe and McGrattan (1996). The standard model in the literature on sticky prices is a static one in which imperfectly competitive firms set nominal prices, and real money balances enter the consumer's utility function. (See, for example, Blanchard and Kiyotaki 1987 and Ball and Romer 1989 and 1990.) Our benchmark model basically takes this setup and turns it into a two country business cycle model by adding time and uncertainty and allowing the monopolists to price discriminate. In our model there is a continuum of monopolistically competitive firms in each country that produces differentiated products using labor and capital. These firms set nominal prices in the local currency of each country before the realization of shocks. Markets are segmented in that only the firm is permitted to sell its goods in each country. This permits firms to charge different prices in the two countries for the same good. Consumers in each country are infinitely lived and have preferences over consumption, leisure, and the real money balances of the local currency. In each country there are stochastic shocks to the money growth rate and technology.

In the benchmark version of our model prices are set for one quarter at a time. We find that exchange rates are neither volatile nor persistent. In the data, nominal and real exchange rates are about 6 times as volatile as relative price levels across countries. (This statistic and the others that follow all refer to Hodrick-Prescott filtered data.) In the benchmark model nominal exchange rates are about twice as volatile as relative price levels, and real exchange rates are only slightly more volatile than relative price levels. In the data, nominal and real exchange rates are highly serially correlated (i.e., the autocorrelations are 0.83 and 0.85, respectively). In the model nominal exchanges are highly persistent (0.84), but real exchange rates are not (0.20). An interesting feature of our benchmark model is that, as in the data, output is more highly correlated across countries than is consumption. Backus, Kehoe and Kydland (1993) show that standard real business cycle models cannot produce this ordering and that the failure to do so is a major anomaly for such models.

To generate volatility and persistence from monetary shocks, we need some mechanism to magnify the effects of monetary shocks on exchange rates. Following a positive monetary shock, interest parity implies a large depreciation in exchange rates if there are large or persistent declines in nominal interest rates. In our benchmark model money growth is positively serially correlated, so that a positive monetary shock raises expected inflation rates and thus nominal interest rates. Thus, in our benchmark economy the effects of monetary shocks on exchange rates are diluted rather than magnified. We make two changes to our benchmark economy intended to deliver a magnification effect. We assume that prices are set for 6 quarters at a time in order to reduce the expected inflation effect. To generate slow movements in prices, we let prices be set in a staggered fashion. In particular, we assume that each quarter, 1/6 of these firms choose new prices, which are then fixed for 6 quarters. We also change our preferences so that they imply a low consumption elasticity of money demand. With these two changes we get some, but not enough, magnification effects. In this version of the model, nominal and real exchange rates are a little less than 4 times as variable as countries' relative price levels (3.25 and 3.49, respectively). They are also somewhat serially correlated (0.66 and 0.65, respectively). We also did experiments in economies in which prices are set for longer periods of time. We found that the results were not substantially different. We conclude that, even with what we consider to be extreme amounts of price stickiness, sticky price models can account for about one-half of the fluctuations in the data.

In terms of the literature, there are a number of papers that investigate the effects of sticky prices in international models. In some of this literature, such as Svensson and van Wijnbergen (1989) and Obstfeld and Rogoff (1995), monopolists do not price discriminate across countries, so there are no deviations from the law of one price. (Although there can be some interesting real exchange rate movements if there are nontraded goods.) More closely related are the works by Betts and Devereux (1996) and Kollman (1996), who consider economies with price discriminating monopolists but without capital. Betts and Devereux show that a low consumption elasticity of money demand is necessary to generate volatility in exchange rates. Kollman considers a price setting framework similar to that in Calvo (1983) in which prices are set for an expected length of 12 quarters at a time and shows that the model generates volatile exchange rates. None of the models in these papers includes capital, and thus they are not set up to address the standard international business cycle facts emphasized by Backus, Kehoe, and Kydland (1994). (See that paper for how abstracting from investment in capital affects the basic comovements of the trade balance, output, and the terms of trade.)

Finally, for some other work on the implications of sticky prices for monetary policy under fixed exchange rates, see Ohanian and Stockman (1993).

1. The World Economy

Consider a two country world economy consisting of a home country and a foreign country. Each country is populated by a large number of identical, infinitely lived consumers. In each period t, the economy experiences one of finitely many events s_t. We denote by $s^t = (s_0, \ldots, s_t)$ the history of events up through and including period t. The probability, as of period zero, of any particular history s^t is $\pi(s^t)$. The initial realization s_0 is given.

In each period t the commodities in this economy are labor, a consumption-capital good, money, a continuum of intermediate goods indexed by $i \in [0, 1]$ produced in the home country and a continuum of intermediate goods indexed $i \in [0, 1]$ produced in the foreign country. In terms of notation, goods produced in the home country are subscripted with an H, while those produced in the foreign country are subscripted with an F. In the home country final goods are produced from intermediate goods at history s^t according to a production function that combines features from the industrial organization literature (see Dixit and Stiglitz 1977) and the trade literature (see Armington 1969):

$$(1) \qquad y(s^t) = \left[\omega_1 \left(\int_0^1 y_H(i, s^t)^\theta di\right)^{\rho/\theta} + \omega_2 \left(\int_0^1 y_F(i, s^t)^\theta di\right)^{\rho/\theta}\right]^{\frac{1}{\rho}}$$

where $y(s^t)$ is the final good and $y_H(i, s^t)$ and $y_F(i, s^t)$ are intermediate goods produced in the home and foreign countries, respectively. This specification of technology will allow our model to be consistent with three features of the data. The parameter θ will determine the markup of price over marginal cost. The parameter ρ, along with θ, will determine the elasticity of substitution between home and foreign goods. Finally the parameters ω_1 and ω_2, together with ρ and θ, will determine the ratio of imports to gross domestic product (GDP).

Final goods producers behave competitively. In the home country in each period t producers choose inputs $y_H(i, s^t)$ for $i \in [0, 1]$ and $y_F(i, s^t)$ for $i \in [0, 1]$ and output $y(s^t)$ to maximize profits given by

$$\text{(2)} \qquad \max \; P(s^{t-1})y(s^t) - \int_0^1 P_H(i, s^{t-1})y_H(i, s^t)\, di - \int_0^1 P_F(i, s^{t-1})y_F(i, s^t)\, di,$$

subject to (1) where $P(s^{t-1})$ is the price of the final good at s^{t-1}, $P_H(i, s^{t-1})$ is the price of the home intermediate good i at s^{t-1}, and $P_F(i, s^{t-1})$ is the price of foreign intermediate good i at s^{t-1}. These prices are in units of the domestic currency. These prices do not depend on s_t, because date t prices in our economy are set before the realization of the date t shocks. Solving the problem in (2) gives the input demand functions

$$\text{(3)} \qquad y_H^d(i, s^t) = \frac{[\omega_1 P(s^{t-1})]^{\frac{1}{1-\rho}}\, P_H(s^{t-1})^{\frac{\rho-\theta}{(1-\rho)(\theta-1)}}}{P_H(i, s^{t-1})^{\frac{1}{1-\theta}}} y(s^t)$$

and

$$\text{(4)} \qquad y_F^d(i, s^t) = \frac{[\omega_2 P(s^{t-1})]^{\frac{1}{1-\rho}}\, P_F(s^{t-1})^{\frac{\rho-\theta}{(1-\rho)(\theta-1)}}}{P_F(i, s^{t-1})^{\frac{1}{1-\theta}}} y(s^t)$$

where $P_H(s^t) = \left(\int_0^1 P_H(i, s^t)^{\frac{\theta}{\theta-1}} di\right)^{\frac{\theta-1}{\theta}}$ and $P_F(s^t) = \left(\int_0^1 P_F(i, s^t)^{\frac{\theta}{\theta-1}} di\right)^{\frac{\theta-1}{\theta}}$. Using the zero profit condition, we have that in a symmetric equilibrium with $P_H(i, s^{t-1}) = P_H(s^{t-1})$ for all i and $P_F(i, s^{t-1}) = P_F(s^{t-1})$ for all i,

$$P(s^{t-1}) = \left(\omega_1^{\frac{1}{1-\rho}} P_H(s^{t-1})^{\frac{\rho}{\rho-1}} + \omega_2^{\frac{1}{1-\rho}} P_F(s^{t-1})^{\frac{\rho}{\rho-1}}\right)^{\frac{\rho-1}{\rho}}.$$

The technology for producing each intermediate good i is a standard constant returns to scale production function

$$y_H(i, s^t) + y_H^*(i, s^t) = F(k(i, s^t), l(i, s^t)),$$

where $k(i, s^t)$ and $l(i, s^t)$ are the inputs of capital and labor, respectively, and $y_H(i, s^t)$ and $y_H^*(i, s^t)$ are the amounts of this intermediate good used in home and foreign production of the final good, respectively. Intermediate goods producers behave as imperfect competitors. They set prices for one period in local currency units and do so before the realization of event s_t. In particular, at time t an intermediate goods producer of good i in the home country chooses a price $P_H(i, s^{t-1})$ in units of the home currency for goods sold in the home country and a price $P_H^*(i, s^{t-1})$ in units of the foreign currency for goods sold in the foreign country to maximize

$$\max \sum Q(s^t|s^{t-1})\{\left[P_H(i, s^{t-1}) - P(s^{t-1})v(s^t)\right] y_H^d(i, s^t) \\ + \left[e(s^t)P_H^*(i, s^{t-1}) - P(s^{t-1})v(s^t)\right] y_H^{*d}(i, s^t)\} \tag{5}$$

where $Q(s^t|s^{t-1})$ is the price of one unit of local currency at s^t in units of local currency at state s^{t-1}, $e(s^t)$ is the exchange rate. The term $v(s^t)$ is the unit cost of production given by

$$v(s^t) = \min_{k,l} \; r(s^t)k + w(s^t)l, \tag{6}$$

subject to

$$F(k, l) \geq 1,$$

where $r(s^t)$ is the rental rate on capital and $w(s^t)$ is the real wage rate. The solution to the problem stated in (5) is

$$P_H(i, s^{t-1}) = \frac{P(s^{t-1}) \sum Q\left(s^t|s^{t-1}\right) y\left(s^t\right) v(s^t)}{\theta \sum Q\left(s^t\right) |s^{t-1}) y\left(s^t\right)}$$

and

$$P_H^*(i, s^{t-1}) = \frac{P(s^{t-1}) \sum Q(s^t|s^{t-1}) y^*\left(s^t\right) v(s^t)}{\theta \sum Q\left(s^t|s^{t-1}\right) y^*\left(s^t\right) e(s^t)}.$$

Consumer preferences in the home country are given by

$$\sum_{t=0}^{\infty} \sum_{s^t} \beta^t \pi(s^t)\, U\left(c(s^t), l(s^t), M(s^t)/P(s^{t-1})\right), \tag{7}$$

where $c(s^t)$, $l(s^t)$, and $M(s^t)$ are consumption, labor, and nominal money balances, respectively. There are complete markets in this economy. We represent the asset structure by having complete contingent one-period nominal bonds denominated in the home currency. We let $B_H(s^{t+1})$ denote the home consumer's holdings of this bond, which pays one unit of the home currency if state s^{t+1} occurs and 0 otherwise, and we let $Q(s^{t+1}|s^t)$ denote the price of one unit of such a bond at date t and state s^t in units of the domestic currency. For notational simplicity we assume that claims to the capital stock in each country are held by the residents of that country and cannot be traded.

In each period $t = 0, 1, \ldots$, consumers choose their time t allocations after the realization of the event s_t. The problem of consumers is to choose rules for consumption $c(s^t)$, labor $l(s^t)$, investment $x(s^t)$, nominal money balances $M(s^t)$, and one-period nominal bonds $B_H(s^{t+1})$ to maximize (7) subject to the sequence of budget constraints

$$\begin{aligned}
&P(s^{t-1})(c(s^t) + x(s^t)) + M(s^t) + \sum_{s^{t+1}} Q(s^{t+1}|s^t)B_H(s^{t+1}) \\
&\quad \leq P(s^{t-1})\left[r(s^t)k(s^{t-1}) + w(s^t)l(s^t)\right] + M(s^{t-1}) + B_H(s^t) + \Pi(s^t) + T(s^t),
\end{aligned}$$

the borrowing constraint

$$B_H(s^{t+1}) \geq -P(s^{t-1})\bar{b}_H,$$

and the law of accumulation for capital

$$k(s^t) = (1-\delta)k(s^{t-1}) + x(s^t) - \phi(\frac{x(s^t)}{k(s^{t-1})})k(s^{t-1}).$$

Here $\Pi(s^t)$ is the profits of the home country intermediate goods producers, $T(s^t)$ is transfers of home currency, and the positive constant $\bar{b}_H$ constrains the amount of real borrowing of the consumer. The function ϕ represents costs of adjusting the capital stock. The initial conditions $M(s^{-1})$, $k(s^{-1})$, and $B_H(s^0)$ are given. The first order conditions for the consumer can be written as

$$\begin{aligned}
&-\frac{U_l(s^t)}{U_c(s^t)} = w(s^t), \\
&\frac{U_m(s^t)}{P(s^{t-1})} - \frac{U_c(s^t)}{P(s^{t-1})} + \beta \sum_{s_{t+1}} \pi(s^{t+1}|s^t)\frac{U_c(s^{t+1})}{P(s^t)} = 0, \\
&Q(s^t|s^{t-1}) = \beta\pi(s^t|s^{t-1})\frac{U_c(s^t)}{U_c(s^{t-1})}\frac{P(s^{t-2})}{P(s^{t-1})},
\end{aligned}$$

and

$$\frac{U_c(s^t)}{\beta\phi'(\frac{x(s^t)}{k(s^{t-1})})} = \sum \pi(s^{t+1}|s^t)U_c(s^{t+1})\left\{r(s^{t+1}) + \left[1-\delta + \phi(\frac{x(s^{t+1})}{k(s^t)}) + \phi'(\frac{x(s^{t+1})}{k(s^t)})\frac{x(s^{t+1})}{k(s^t)}\right] / \phi'(\frac{x(s^t)}{k(s^{t-1})})\right\}.$$

Here $U_c(s^t)$, $U_l(s^t)$, and $U_m(s^t)$ denote the derivatives of the utility function with respect to its arguments, and $\pi(s^{t+1}|s^t) = \pi(s^{t+1})/\pi(s^t)$ is the conditional probability of s^{t+1} given s^t.

The problems of the final goods producers, the intermediate goods producers, and the consumers in the foreign country are analogous to these problems. Allocations and prices in the foreign country are denoted with an asterisk.

The money supply processes in the home and foreign countries are given by

(8) $M(s^t) = \mu(s^t)M(s^{t-1})$

and

(9) $M^*(s^t) = \mu^*(s^t)M^*(s^{t-1})$,

where $\mu(s^t)$ and $\mu^*(s^t)$ are stochastic processes and $M(s^{-1})$ and $M^*(s^{-1})$ are given. New money balances of the home currency are distributed to consumers in the home country in a lump-sum fashion by having transfers satisfy

(10) $T(s^t) = M(s^t) - M(s^{t-1})$.

Likewise the transfers of foreign currency to foreign consumers satisfy

(11) $T^*(s^t) = M^*(s^t) - M^*(s^{t-1})$.

In terms of market clearing conditions, consider first the factor markets. Notice that the capital stock chosen by consumers in period $t-1$ for rental in period t is $k(s^{t-1})$, while the labor supply in period t is $l(s^t)$. In turn, each intermediate goods producer i chooses his factor demands after the realization of uncertainty s_t in period t, so the demands for capital and labor are $k(i, s^t)$ and $l(i, s^t)$, respectively. Factor market clearing thus requires that

$$(12) \quad k(s^{t-1}) = \int k(i, s^t)\, di,$$
$$(13) \quad l(s^t) = \int l(i, s^t)\, di.$$

The market clearing condition for the contingent bonds is

$$(14) \quad B_H(s^t) + B_H^*(s^t) = 0,$$

where $B_H^*(s^t)$ denotes the foreign consumer's holdings of the home country bonds.

An *equilibrium* for this economy is a collection of allocations for home consumers $c(s^t)$, $l(s^t)$, $x(s^t), k(s^t)$, $M(s^t)$, $B_H(s^{t+1})$, allocations for foreign consumers $c^*(s^t)$, $l^*(s^t)$, $x^*(s^t)$, $k^*(s^t)$, $M^*(s^t)$, $B_H^*(s^{t+1})$, allocations and prices for home intermediate goods producers $y_H(i, s^t)$, $y_H^*(i, s^t)$ and $P_H(i, s^{t-1})$, $P_H^*(i, s^{t-1})$ for $i \in [0, 1]$, allocations and prices for foreign intermediate good producers $y_F(i, s^t)$, $y_F^*(i, s^t)$ and $P_F(i, s^{t-1})$, $P_F^*(i, s^{t-1})$ for $i \in [0, 1]$, and allocations for home and foreign final goods producers $y(s^t), y^*(s^t)$, final goods prices $P(s^{t-1})$, $P^*(s^{t-1})$, real wages $w(s^t)$, $w^*(s^t)$, rental rates $r(s^t), r^*(s^t)$, and bond prices $Q(s^{t+1}|s^t)$ that satisfies the following conditions: (i) taking as given the prices, consumer allocations solve the consumers' problem; (ii) taking as given all prices but his own, prices of each intermediate goods producer solve (5); (iii) taking as given the prices, the final goods producers' allocations solve the final goods producers' problem; (iv) the market clearing conditions (12)–(14) hold; and (v) the money supply processes and transfers satisfy (8)–(11).

In what follows we will focus on the symmetric equilibrium in which all the intermediate goods producers in the same country make identical decisions. Thus, for the home country $P_H(i, s^{t-1}) = P_H(s^{t-1})$, $P_H^*(i, s^{t-1}) = P_H^*(s^{t-1})$, $y_H(i, s^t) = y_H(s^t)$, and $y_H^*(i, s^t) = y_H(s^t)$ for all $i \in [0, 1]$ and likewise for the foreign country. We are interested in a stationary equilibrium and thus restrict the stochastic processes for the growth rates of the money supplies to be

Markovian. To make the economy stationary, all nominal variables are deflated by the level of the relevant money supply. A stationary equilibrium for this economy consists of stationary decision rules and pricing rules which are functions of the state of the economy. The state of the economy at the time monopolists make their pricing decisions (that is, before the event s_t is realized) must record the capital stocks in the two countries together with the shocks from period $t-1$. The shocks from period $t-1$ are needed because they help forecast the shocks in period t. Thus the aggregate state for the monopolists is

$$X_{mt} = \left[k(s^{t-1}), k^*(s^{t-1}), \mu(s^{t-1}), \mu^*(s^{t-1})\right].$$

The state of the economy at the time the rest of the decisions are made (that is, after the event s_t is realized) also includes the current shocks. The aggregate state for the consumers is

$$X_t = \left[X_{mt}, \mu(s^t), \mu^*(s^t)\right].$$

We compute the equilibrium using standard methods to obtain linear decision rules. We checked the accuracy of the linear decision rules against nonlinear decision rules obtained by the finite element method. (See McGrattan 1996.)

2. Some Intuition

In this section we gain some intuition for the workings of our model by considering a version that allows us to get analytical results. Consider a deterministic version of our model without capital (i.e., $\alpha = 1$). We set the growth rate of money to zero, and we use a utility function of the form

$$U\left(c, l, M/P\right) = \log c + \gamma \log(1-l) + \phi \log M/P.$$

Starting from a steady state with zero debt, we suppose that a one-time unanticipated shock occurs in period 1, after monopolists have set prices. We show that under our assumptions a one-time monetary shock of 1% in the home country leads to the following outcomes. In period 1 home consumption of both home and foreign goods rises by 1%, foreign consumption is unaffected, home and foreign employment rise to meet world demand, the real and nominal exchange rates depreciate by 1%, and net exports are unaffected. In the following period, the economy returns to a new steady state with the same real allocations. The domestic price level rises by 1% and the nominal exchange rate stays at its depreciated level, while the real exchange rate returns to its old steady state level. In order for these outcomes to constitute an equilibrium, debt at the end of period 1 should be zero or, equivalently, net exports in period 1 must be zero. Net exports are given by

$$NX_t = e_t P^*_{Ht} c^*_{Ht} - P_{Ft} c_{Ft}.$$

We will show that on impact, e_1 goes up by 1%, c_{F1} goes up by 1% and c^*_{H1} is unaffected. Since net exports are zero in the original steady state and prices are set before the shock, net exports in period 1 are thus also zero. To show that e_1 and c_{F1} go up by 1% and c^*_{H1} is unaffected, we begin by considering the money demand equation and the bond price equation in the home country. With our utility function these can be written as

$$(15) \quad \frac{M_t}{P_t} = \frac{\phi c_t}{1 - Q_t}$$

and

$$(16) \quad Q_t = \beta \frac{P_t c_t}{P_{t+1} c_{t+1}}.$$

Substituting for c_t from (15) into (16) and using $M_{t+1} = M_t$ for $t \geq 1$, we obtain

$$Q_t = \frac{\beta(1 - Q_t)}{(1 - Q_{t+1})}.$$

This difference equation has a unique steady state β, which is unstable. Since $Q_0 = \beta$, it follows that

$$Q_1 = Q_2 = Q_0 = \beta.$$

When we use a similar argument, it follows that

$$Q_1^* = Q_2^* = Q_0^* = \beta.$$

Next, in a deterministic model, interest rate parity holds from period 1 onward:

$$(17) \quad Q_t = \frac{Q_t^* e_t}{e_{t+1}}.$$

Since $Q_1 = Q_1^*$, it follows that $e_1 = e_2$, and thus the exchange rate depreciates by 1% on impact. Since in period 1 prices have already been set, it follows from (15) that c_1 rises by 1% and by a similar argument that c_1^* is unchanged. Since the relative price of home to foreign goods has not changed in the impact period, it follows from (4) that c_{F1} rises by 1% and c_{H1}^* is unchanged. Notice, of course, that since the local currency prices of the goods are all set before the shock, the depreciation of the exchange rate implies a 1% deviation from the law of one price for both home goods and foreign goods in the impact period, in that $e_1 P_{H1}^*/P_{H1}$ and $e_1 P_{F1}^*/P_{F1}$ both rise by 1%.

Since it is not possible to obtain analytical results for versions of our model with capital and more general utility functions we turn now to a calibrated model.

3. Calibration

We consider a utility function of the form

$$U(c, l, \frac{M}{P}) = \left[(ac^v + (1-a)(M/P)^v)^{\frac{\gamma}{v}} (1-l)^{1-\gamma}\right]^{1-\sigma} / (1-\sigma)$$

and a production function of the form

$$f(k, l) = Ak^{\alpha} l^{1-\alpha}.$$

The stochastic process for the growth rate of the money stock for the home country is given by

$$(18) \quad \log \mu_t = \rho_\mu \log \mu_{t-1} + (1 - \rho_\mu) \log \overline{\mu} + \epsilon_{\mu t},$$

where ϵ_μ is a normally distributed mean zero shock with a standard deviation σ_μ. The stochastic process for money in the foreign country is the same. We assume that the two processes for money are independent.

The parameter values on an annualized basis that we use are reported in Table 1. Consider first the preference parameters. The discount factor β, the share parameter γ, the curvature parameter σ and the capital share parameter α are all standard from the business cycle literature (see, for example, Chari, Christiano, and Kehoe 1994). To obtain a and v we drew on the money demand literature. Our model can be used to price a variety of assets, including a nominal bond which costs one dollar at s^t and pays $R(s^t)$ dollars in all states s^{t+1}. The first order condition for this asset can be written as

$$U_m(s^t) = U_c(s^t)\left(\frac{R(s^t)-1}{R(s^t)}\right).$$

When we use our specification of utility, the first order condition can be rewritten as

$$(19)\quad \log\frac{M(s^t)}{P(s^{t-1})} = -\frac{1}{1-v}\log\frac{a}{1-a} + \log c(s^t) - \frac{1}{1-v}\log\left(\frac{R(s^t)-1}{R(s^t)}\right).$$

We use Mankiw and Summers' (1986) money demand regressions to obtain v. We set $-1/(1-v)$ equal to their estimate of the interest elasticity of money demand (-0.054) and obtain $v=-17.52$. To obtain a we set $M(s^t)/(P(s^{t-1})c(s^t))$ equal to the average ratio of M1 to quarterly nominal consumption expenditures in the postwar period (1.2), and we set $R(s^t)$ equal to the average quarterly yield on three month Treasury bills in the postwar period (i.e., $R(s^t) = 1.0495^{\frac{1}{4}}$). Substituting these values into (19) yields $a = 0.73$.

Consider next the technology parameters. We calibrate θ as follows. In a symmetric steady state, $P_H = P_F = P$ and the markup of price to marginal cost is

$$\frac{P_H}{Pw} = \frac{1}{\theta}.$$

Following the procedure described by Chari, Kehoe, and McGrattan (1996), we obtain $\theta = 0.9$ (i.e., a markup of about 11%). In our model the elasticity of substitution between home goods and foreign goods is $1/(1-\rho)$. Following the work of Backus, Kehoe and Kydland (1992), we use an elasticity of 1.5. To set ω_1 and ω_2, note that in a symmetric steady state,

$$\frac{y_H}{y_F} = \left[\frac{\omega_1}{\omega_2}\right]^{\frac{1}{1-\rho}}.$$

In U.S. data, imports are roughly 15% of GDP. This implies that $y_H/y_F = .85/.15$. Together with our normalization, this gives the values of ω_1 and ω_2. We consider an adjustment function of the form

$$\phi(\frac{x}{k}) = \frac{b}{2}(\frac{x}{k} - \delta)^2.$$

Notice that with this specification at the steady state, both the costs of adjustment and the marginal costs of adjustment are 0. We set $b = 2$.

Finally, the parameters governing the stochastic process for money growth were obtained from running a regression of the form (18) on quarterly data on M1 from 1973 through 1995 obtained from Citibase. We obtained $\overline{\mu} = (1.068)^{1/4}$, $\rho_\mu = 0.57$ and $\sigma_\mu = 0.0092$.

4. Findings for the Benchmark Model

It turns out that the impulse responses from our calibrated model are similar to those described in Section 2. The calibrated model differs from the example of Section 2 in two ways. In the calibrated model money growth is persistent and the utility function is nonseparable between consumption and real balances. We consider a shock to money growth that in one year leads to a 1% rise in the level of the money supply relative to trend. Figures 1–5 show that on impact home consumption rises by almost 3% and GDP rises by about 4%, home and foreign employment rise to meet world demand, foreign consumption is essentially constant, real and nominal exchange rates depreciate by about 1%, home nominal interest rates rise and home real interest rates fall, and foreign interest rates are essentially constant. These figures also show that in the next period consumption, employment, and GDP at home and abroad all essentially return to their old steady state levels. The nominal exchange rate keeps depreciating, and the real exchange rate essentially returns to its steady state level in the period after the impact.

Here home nominal interest rates rise on impact because with serially correlated money growth, the expected inflation rate rises. Since foreign interest rates are unchanged, this rise in home interest rates induces undershooting of the nominal exchange rate, relative to its new steady state value.

In addition to the impulse responses following money shocks, we are also interested in standard business cycle statistics for this economy. To make our numbers comparable to those in the literature, we add technology shocks of the form considered in Backus, Kehoe, and Kydland (1992). The domestic production function now includes a domestic technology shock z_t and is written as

$$z_t f(k_t, l_t).$$

The foreign production function includes a foreign technology shock z_t^*. These technology shocks are assumed to follow a vector stochastic process of the form

$$(z_{t+1}, z_{t+1}^*)' = A(z_t, z_t^*)' + (\varepsilon_{zt}, \varepsilon_{zt}^*)'$$

where the innovations satisfy $corr(\varepsilon_z \varepsilon_z^*) = 0.258$ and $var\varepsilon_z = var\varepsilon_z^* = 0.0085^2$. We report the values of A in Table 1. The timing in the model is as follows. First the technology shocks are realized, then the monopolists set prices, then the money shocks are realized and consumers and final goods producers make their decisions. We adopt this timing rather than an alternative in which monopolists set prices before the realization of the current technology shocks because under the alternative timing, positive technology shocks lead to reductions in employment.

In Table 2 we report on the Hodrick-Prescott filtered statistics for the data and the benchmark economy. In the appendix we describe how the statistics for the data are computed. In simulating our economy we need to take a stand on the magnitude of the monetary and real shocks. In terms of the real shocks, we have direct measurement of the technology parameter, and we simply use the estimated standard deviation. In terms of the monetary shocks, what matters in our model is the part of monetary fluctuations which is unanticipated by private agents. Since it is difficult to separate out the unanticipated part from the anticipated part in the data, we use the following procedure. We choose the standard deviation of the monetary shocks so that, together with the technology shocks set as above, the standard deviation of output in our benchmark economy is roughly that in the data. This led to a standard deviation of the innovations to money growth of 0.35%, which is 38% of that in the data.

We focus on the properties of the nominal and real exchange rates. In the data nominal and real exchange rates are more than 6 times as variable as relative price levels, while in the model nominal exchange rates are about twice as variable as the relative price levels and real exchange rates are only slightly more variable than the relative price levels. In the data nominal and real exchange rates are highly serially correlated (0.83 and 0.85, respectively). In the model nominal exchange rates are highly serially correlated (0.82), but real exchange rates are not (0.20). Finally, in the data nominal and real exchange rates are highly correlated (0.99), while in the model they are not (0.27).

In terms of the real allocations, in the data output is more correlated across countries (cross correlation of 0.70) than is consumption (cross correlation of 0.46). The model produces the same ordering of cross correlations (0.41 for output and 0.30 for consumption). Backus, Kehoe, and Kydland (1993) argue that this ordering of cross correlations is a major anomaly for standard real business cycle models. In both the data and the model, the trade balance is countercyclical (the correlation between the ratio of net exports to output and output is -0.28 in the data and -0.44 in the model).

In Table 2 we also report on the business cycle statistics in a version of our model with only money shocks. The table shows that the properties of exchange rates are similar to those in the model with both money and technology shocks.

It is clear that this model does not generate the kind of variability, persistence and comovements of exchange rates that we see in the data.

5. Staggered Price Setting

In our intuitive example, nominal exchange rates move as much as the money supply. In our calibrated economy, the nominal exchange rates move less than the money supply in the impact period. In the data, nominal exchange rates move much more than do money supplies. Thus, if money shocks are to account for most of the movements in exchange rates, the effects of money shocks on exchange rates must be magnified. (In Dornbusch's 1976 terminology, exchange rates must overshoot.)

To understand how our model needs to be changed to generate a magnification effect, we iterate on (17) to obtain

$$e_1 = \left[\frac{Q_1 Q_2 \cdots Q_{t-1}}{Q_1^* Q_2^* \cdots Q_{t-1}^*}\right] e_t.$$

In standard models money is neutral in the long run, so that in the long run the exchange rate moves as much as the money supply. In response to domestic monetary shocks, foreign interest rates typically do not change very much. The only way to obtain a magnification effect is for money shocks to lead to large or persistent decreases in nominal interest rates (increases in bond prices). In the data, exchange rate movements are also persistent, so that if exchange rates are going to be driven mostly by money shocks, we need money shocks to lead to persistent decreases in nominal interest rates. That is, we need persistent liquidity effects. In our intuitive example, interest rates do not move at all, so there is no magnification. In our calibrated economy interest rates actually rise, because the expected inflation rate rises, so that the magnification effect goes the wrong way.

In order to generate persistent liquidity effects, clearly the expected inflation effect must be small. One way to get this is to consider economies in which, in equilibrium, prices move slowly in response to monetary shocks. The obvious way is to have prices set for many periods at a time. With simultaneous price setting the price level moves infrequently but by large amounts. This is contrary to the data. One way to have slow movement of the price level is to have prices set for many periods at a time, but in a staggered fashion. (See Taylor (1980), Blanchard (1983), and Chari, Kehoe and McGrattan (1996) for models with staggered price setting.)

Consider a version of our model with staggered price setting. In this version the intermediate goods producers set prices for N periods and do so in a staggered fashion. In particular, in each period t fraction $1/N$ of the home country producers choose a home currency price $P_H(i, s^{t-1})$ for the home market and a foreign currency price $P_H^*(i, s^{t-1})$ for the foreign market before the realization of the event s_t. These prices are set for N periods, so for this group of intermediate goods producers,

$$P_H(i, s^{t+\tau-1}) = P_H(i, s^{t-1}) \text{ and } P_H^*(i, s^{t+\tau-1}) = P_H^*(i, s^{t-1})$$

for $\tau = 0, \ldots, N-1$. The intermediate goods producers are indexed so that producers indexed $i \in [0, 1/N]$ set new prices in 0, N, $2N$, etc., while producers indexed $i \in [1/N, 2/N]$ set new prices in 1, $N+1$, $2N+1$, etc., for the N cohorts of intermediate goods producers. At time t each producer in a cohort chooses prices $P_H(i, s^{t-1})$ and $P_H^*(i, s^{t-1})$ to maximize discounted profits from periods t to $t + N - 1$. That is, each solves

$$(20) \qquad \max_{\substack{P_H(i,s^{t-1}) \\ P_H^*(i,s^{t-1})}} \sum_{\tau=t}^{t+N-1} \sum_{s^\tau} Q(s^\tau | s^{t-1}) \{ \left[P_H(i, s^{t-1}) - P(s^{\tau-1}) v(s^\tau) \right] y_H(i, s^\tau) + \left[e(s^\tau) P_H^*(i, s^{t-1}) - P(s^{\tau-1}) v(s^\tau) \right] y_H^*(i, s^\tau) \}$$

where $Q(s^\tau | s^{t-1})$ is the price of one unit of home currency in s^τ in units of the home currency at s^{t-1}, $y_H(i, s^t)$ and $y_H^*(i, s^t)$ are given in (3) and (4) and $v(s^t)$ is the unit cost of production given in (6). In what follows we focus on the symmetric equilibrium in which all the intermediate goods producers of the same cohort make identical decisions. Thus $P_H(i, s^{t-1}) =$

$P_H(j, s^{t-1})$, $P_H^*(i, s^{t-1}) = P_H^*(j, s^{t-1})$, $y_H(i, s^t) = y_H(j, s^t)$, and $y_H^*(i, s^t) = y_H^*(j, s^t)$ for all $i, j \in [0, 1/N]$, and so on, for the N cohorts.

We consider an economy with $N = 6$, so that prices are set for 6 quarters at a time. In unreported experiments we find that staggered price setting alone does not induce persistent liquidity effects. The failure of magnification arises because a money injection drives real interest rates up and therefore nominal interest rates up. After the shock the growth rate of consumption, employment and real balances are all negative. The consumption effect tends to reduce real interest rates, while the employment and real balance effects tend to raise real interest rates. It turns out that the employment and real balance effects dominate, so that real interest rates rise.

These experiments led us to consider a parameterization of our model intended to produce a liquidity effect. Consider a standard money demand function of the form

$$\log \frac{M(s^t)}{P(s^{t-1})} = \alpha_0 + \alpha_1 \log c(s^t) - \alpha_2 \log \left(\frac{R(s^t) - 1}{R(s^t)} \right).$$

In the models considered thus far, we chose parameters to match standard money demand regressions which yield $\alpha_1 = 1$ and $\alpha_2 = -0.054$. There is some uncertainty about these parameter estimates. For example, Lieberman (1980) reports a much lower value of the consumption elasticity, namely, $\alpha_1 = 0.27$. This lower consumption elasticity can generate a liquidity effect. Intuitively, for given sized increases in real money balances and consumption, interest rates rise less the smaller is α_1 and may even fall.

We considered a version of our staggered price setting model with a low consumption elasticity ($\alpha_1 = 0.27$). Specifically, we considered a utility function of the form

$$U(c, l, \frac{M}{P}) = \left[(ac^{v_1} + (1-a)(M/P)^{v_2})^{\frac{\gamma}{v_1}} (1-l)^{1-\gamma} \right]^{1-\sigma} / (1-\sigma).$$

This utility function gives rise to a money demand function of the form

$$\log \frac{M(s^t)}{P(s^{t-1})} = \alpha_0 + \frac{1 - v_1}{1 - v_2} \log c(s^t) - \frac{1}{1 - v_2} \log \left(\frac{R(s^t) - 1}{R(s^t)} \right).$$

To get the low consumption elasticity of 0.27, we set v_2 as before and set $v_1 = -4$. It turns out that with these parameters and the standard deviations of the shocks as in the benchmark, output is extremely volatile, with a standard deviation of 13%. The enormous movement in output in response to monetary shocks occurs because altering the consumption elasticity in the money demand equation substantially increases the labor supply elasticity. An attractive way to decrease volatility is to increase the adjustment costs, since there is a lot of uncertainty on the size about the adjustment costs. We choose a much higher adjustment cost parameter, $b = 10$. In Figures 6-10 we report the impulse responses. The size of the money shock is set so that the money supply rises by 1% above trend in the impact period. The impulse responses show that consumption and GDP rise a little over 4% and employment by about 8% in the impact period. Foreign consumption, GDP, and employment also rise. The exchange rate depreciates on impact, then appreciates. Nominal and real interest rates fall and then return to their steady state values. The low consumption elasticity induces a decline in interest rates and thus yields a magnification effect on exchange rates. As apparent by comparing Figures 3 and 4, the magnification effect is modest.

In Table 2 we report on business cycle statistics for this model, labelled *6 quarter stickiness*. We set the standard deviation of the money shock as in the benchmark model. Focusing on exchange rates, we see that nominal and real exchange rates are less than four times as variable as relative price levels (3.25 and 3.49, respectively). The exchange rates are both somewhat serially correlated (0.66 and 0.65, respectively) and highly cross-correlated (0.87). GDP is somewhat more volatile in this model (2.20) than in the benchmark model or the data.

In terms of the real allocations, the model again produces the same ordering of cross correlations for output and consumption as in the data (0.70 and 0.46 in the data and 0.74 and 0.23 in the model). The trade balance in this version of the model is again countercyclical as in the data (the correlation between the ratio of net exports to output and output is -0.28

in the data and -0.31 in the model).

In terms of the business cycle statistics, this model is better than the benchmark model. However, it still goes only part way toward generating the kind of volatility and persistence of exchange rates we see in the data. We also experimented with a model with 12 price-setting cohorts, each of whom sets prices for 12 quarters. This model did not produce substantially greater volatility or persistence in exchange rates, but it did substantially raise the volatility of output.

In some unreported work, we experimented with versions of our models without capital (i.e., $\alpha = 1$). These versions gave results for exchange rates that are broadly similar to those in the models with capital. However, these models counterfactually imply that the trade balance is highly procyclical. The comovements of the trade balance and output are central to any model of international business cycles. As such models without capital are, at best, pedagogical tools.

6. Conclusion

The central puzzle in international fluctuations is the evidence of large and persistent deviations of exchange rates from purchasing power parity. In this paper we have investigated whether such deviations can arise from monetary shocks in sticky price models. We have found that we need low consumption elasticities of money demand and extreme price stickiness in order to generate volatility and persistence in real and nominal exchange rates. Even with such features, exchange rates are only a little over one-half as volatile as in the data.

The analysis in this paper suggests that future research should concentrate on generating persistent liquidity effects. It is not clear that sticky prices will play a central role in generating these liquidity effects.

Appendix

In this appendix we report business cycle statistics for the data and our model. We focus on the nominal exchange rate, the ratio of price levels, and the real exchange rate.

The indices upon which our statistics are based are constructed as follows. We obtained exchange rate data measured as dollars per unit of foreign currency for each of seven European countries: Austria, Finland, France, Germany, Italy, Switzerland, and the United Kingdom. (These countries are the same as those studied in Backus, Kehoe, and Kydland 1992.) Our constructed index e_t between these European countries and the United States is given by

$$e_t = \frac{\sum_{i=1}^{7} \omega_{it} \hat{e}_{it} / \hat{e}_{i0}}{\sum_{i=1}^{7} \omega_{it}}$$

where ω_{it} is the dollar value of exports plus imports between country i and the United States in period t, $\hat{e}_{it}$ is the exchange rate for country i in period t, and $\hat{e}_{i0}$ is the exchange rate for country i in the first quarter of 1973. We constructed a price index for the European countries in an analogous fashion. The real exchange rate index is defined to be

$$q_t = \frac{e_t P_t^*}{P_t}$$

where P_t is the price index in the United States with the first quarter of 1973 normalized to be 1. All of our data are obtained from DRI's International Monetary Fund database. Details are available upon request.

Our business cycle statistics for both the model and the data are based on logged, HP-filtered values of the relevant indices. The model is described in the paper. We assume that the money supply processes for both the domestic and the foreign countries follow the same stochastic process and are mutually independent.

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Table 1. Parameter Values

Benchmark parameters	
Preferences	$\beta = 0.99$, $a = 0.73$, $\nu = -17.52$, $\gamma = 0.25$, $\sigma = 5$
Final goods technology	$\rho = 1/3$, $\omega_1/\omega_2 = 3.18$
Intermediate goods technology	$\alpha = 1/3$, $\delta = 0.026$, $\theta = 0.9$, $b = 2$
Money growth process	$\bar{\mu} = 1.015$, $\rho_\mu = 0.57$, $\sigma_\mu = 0.0035$
Technology shock process	$A = \begin{pmatrix} 0.906 & 0.088 \\ 0.088 & 0.906 \end{pmatrix}$, $\text{corr}(\varepsilon_z, \varepsilon_z^*)$=0.258, $\text{var}(\varepsilon_z) = \text{var}(\varepsilon_z^*) = 0.00852^2$
6 Quarter Stickiness	
same as benchmark except	$\nu_1 = -4$, $\nu_2 = -17.52$, $b = 10$

Table 2. Business Cycle Statistics †

Statistics	Data	Benchmark Economy: Both Shocks	Benchmark Economy: Money Only	6 Qtr. Stickiness: Both Shocks	6 Qtr. Stickiness: Money Only
Standard deviations (%):					
Real GDP	1.79	1.77 (.14)	1.51 (.11)	2.20 (.25)	2.10 (.24)
Price ratio	1.30	0.58 (.07)	0.45 (.04)	0.61 (.08)	0.59 (.08)
Real exchange rate	7.93	0.72 (.11)	0.58 (.05)	2.13 (.29)	2.07 (.27)
Nominal exchange rate	8.45	1.26 (.22)	1.23 (.21)	1.98 (.27)	1.93 (.26)
Autocorrelations:					
Real GDP	0.88	0.13 (.12)	-0.10 (.10)	0.61 (.07)	0.58 (.07)
Price ratio	0.87	0.49 (.10)	0.40 (.10)	0.71 (.04)	0.70 (.04)
Real exchange rate	0.85	0.20 (.19)	-0.04 (.11)	0.65 (.06)	0.65 (.07)
Nominal exchange rate	0.83	0.82 (.06)	0.84 (.04)	0.66 (.07)	0.66 (.07)
Cross correlations:					
Foreign and domestic consumption	0.46	0.30 (.11)	0.16 (.10)	0.26 (.16)	0.23 (.16)
Foreign and domestic GDP	0.70	0.41 (.10)	0.53 (.08)	0.72 (.08)	0.74 (.07)
Real and nominal exchange rate	0.99	0.27 (.12)	0.24 (.03)	0.87 (.04)	0.87 (.04)
Net exports/output and output	-0.28	-0.44 (.08)	-0.47 (.08)	-0.27 (.14)	-0.31 (.14)

† Statistics are based on Hodrick-Prescott (1980) filtered data. Entries are averages over 100 simulations of 91 quarters each; numbers in parentheses are standard deviations.

Figure 1. Impulse responses in home country

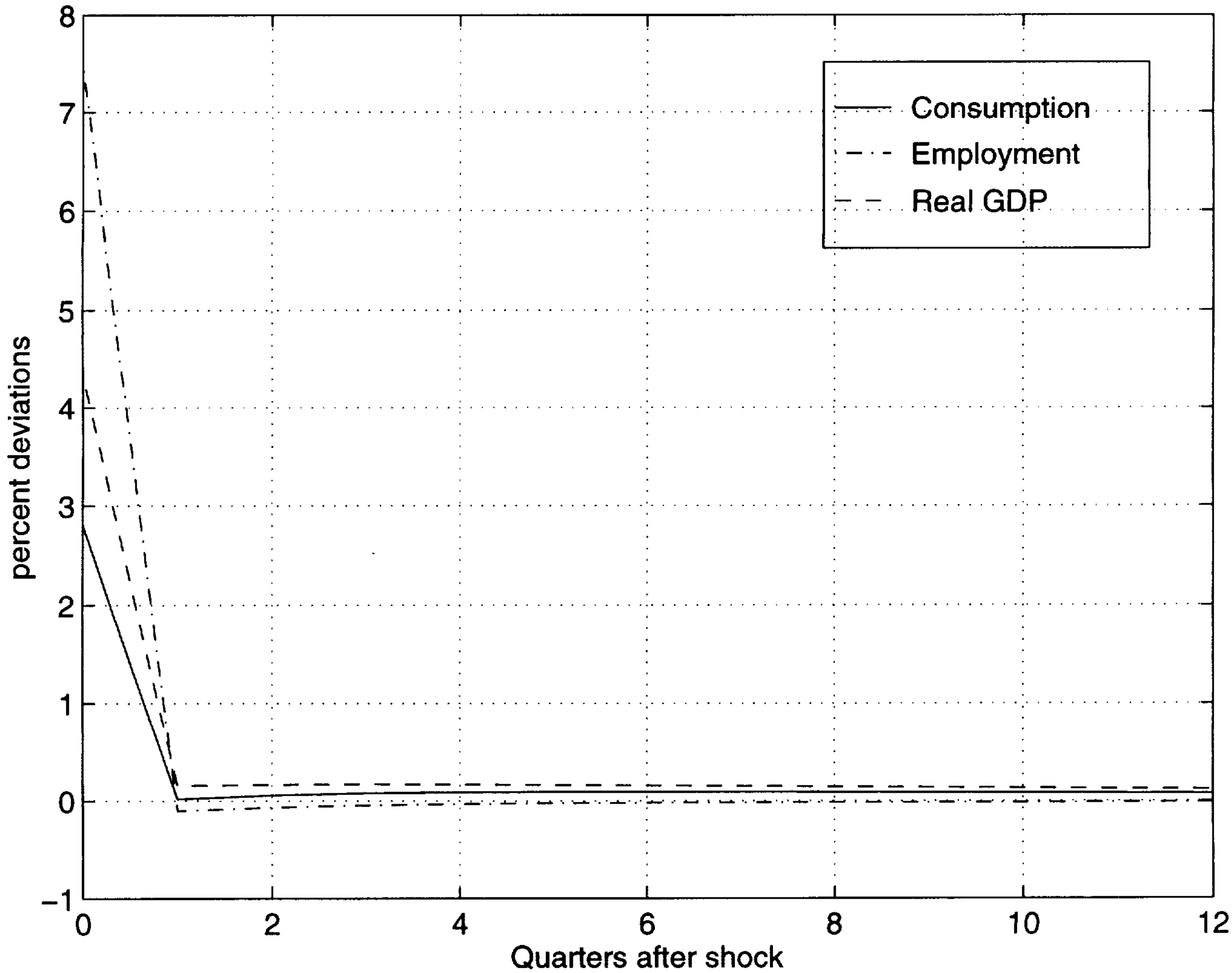

Figure 2. Impulse responses in foreign country

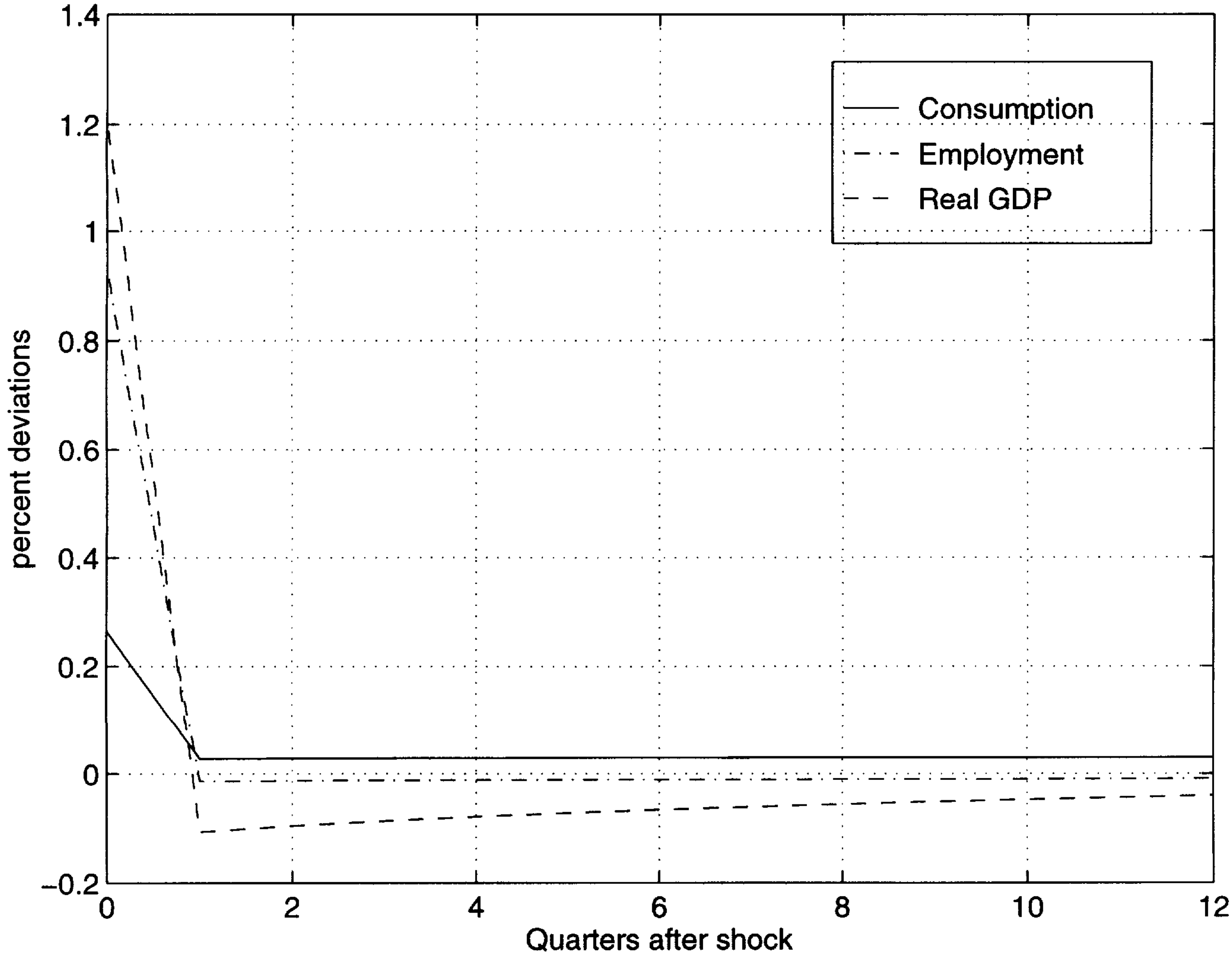

Figure 3. Impulse responses in home country

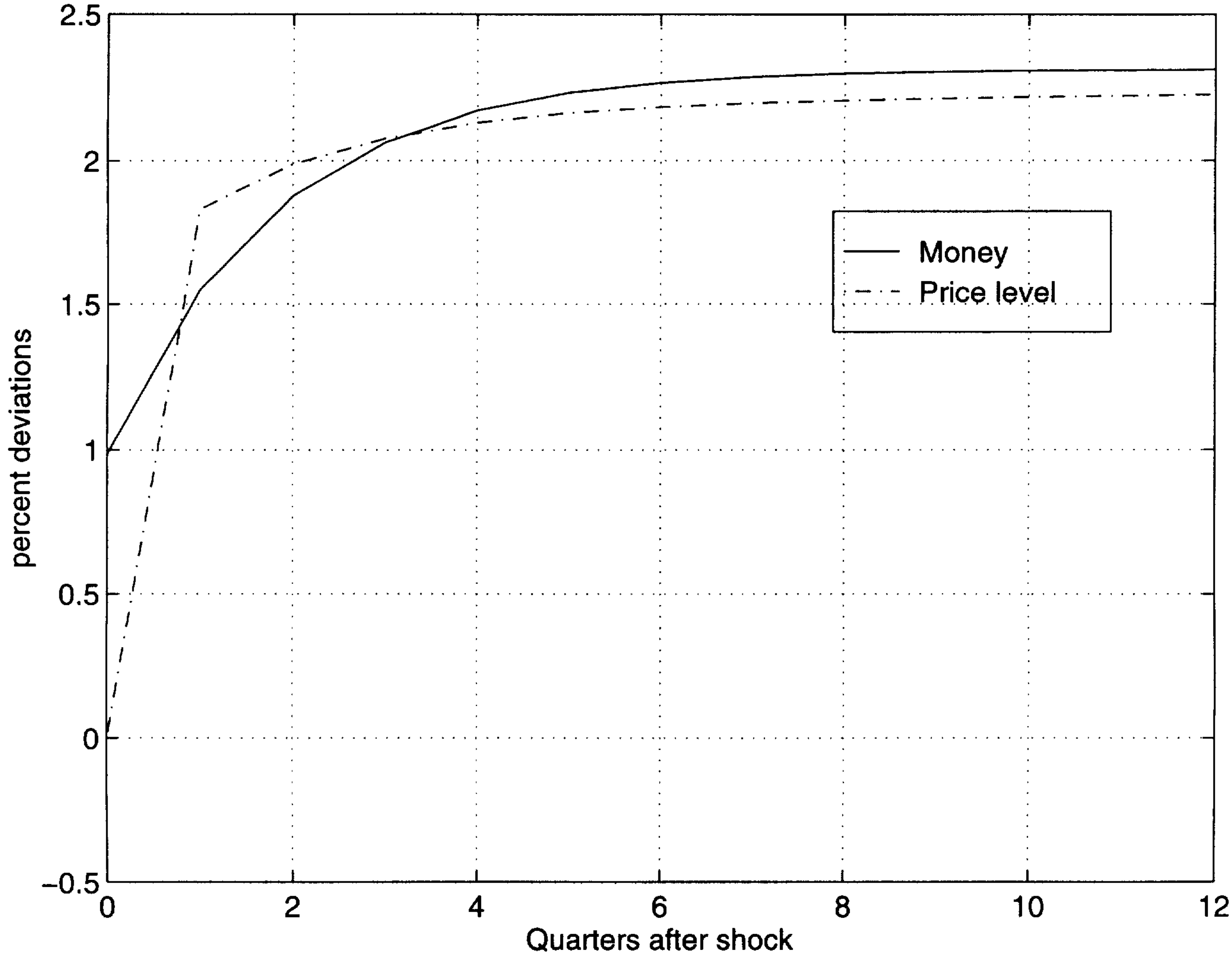

Figure 4. Impulse responses of exchange rates

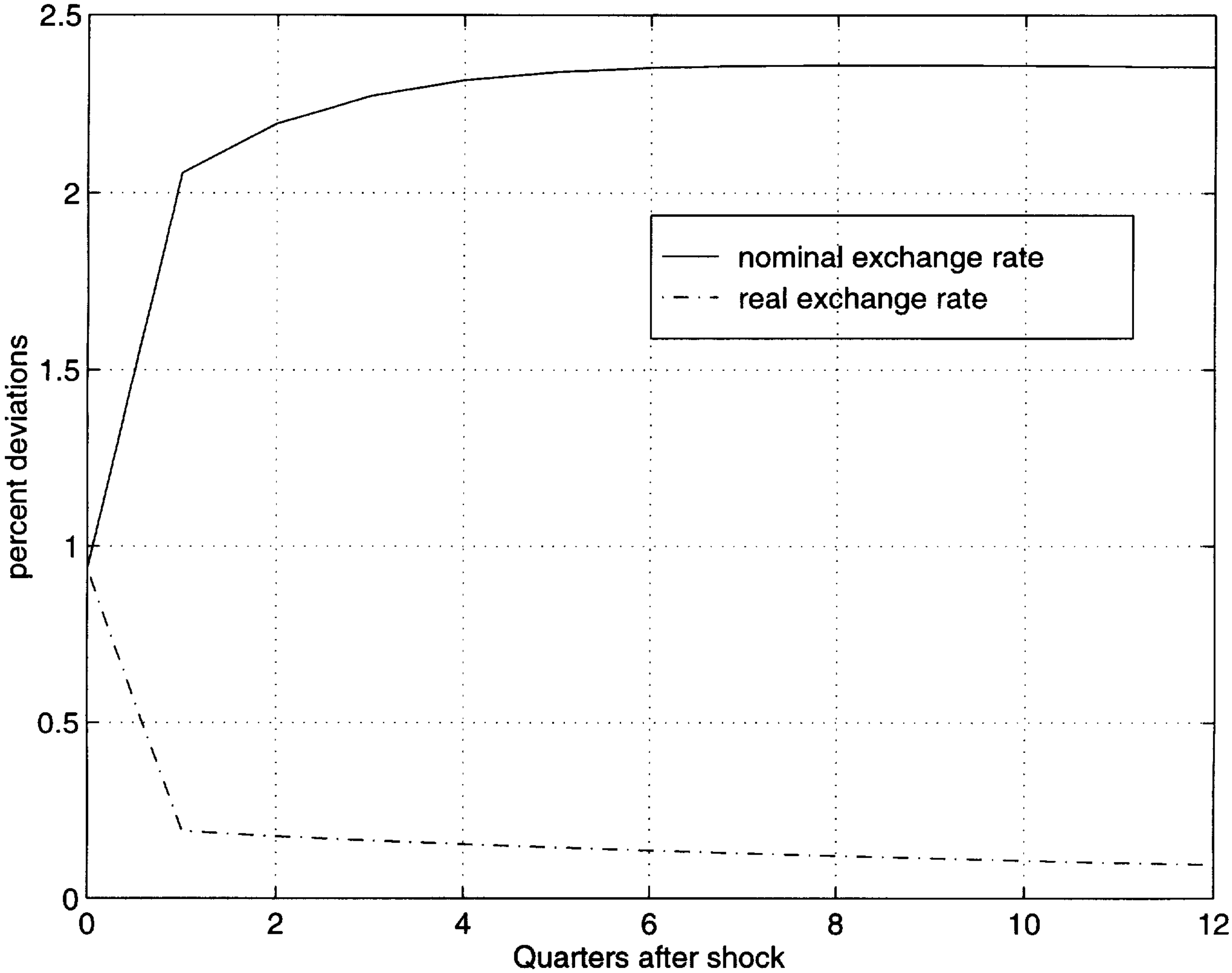

Figure 5. Impulse responses of interest rates

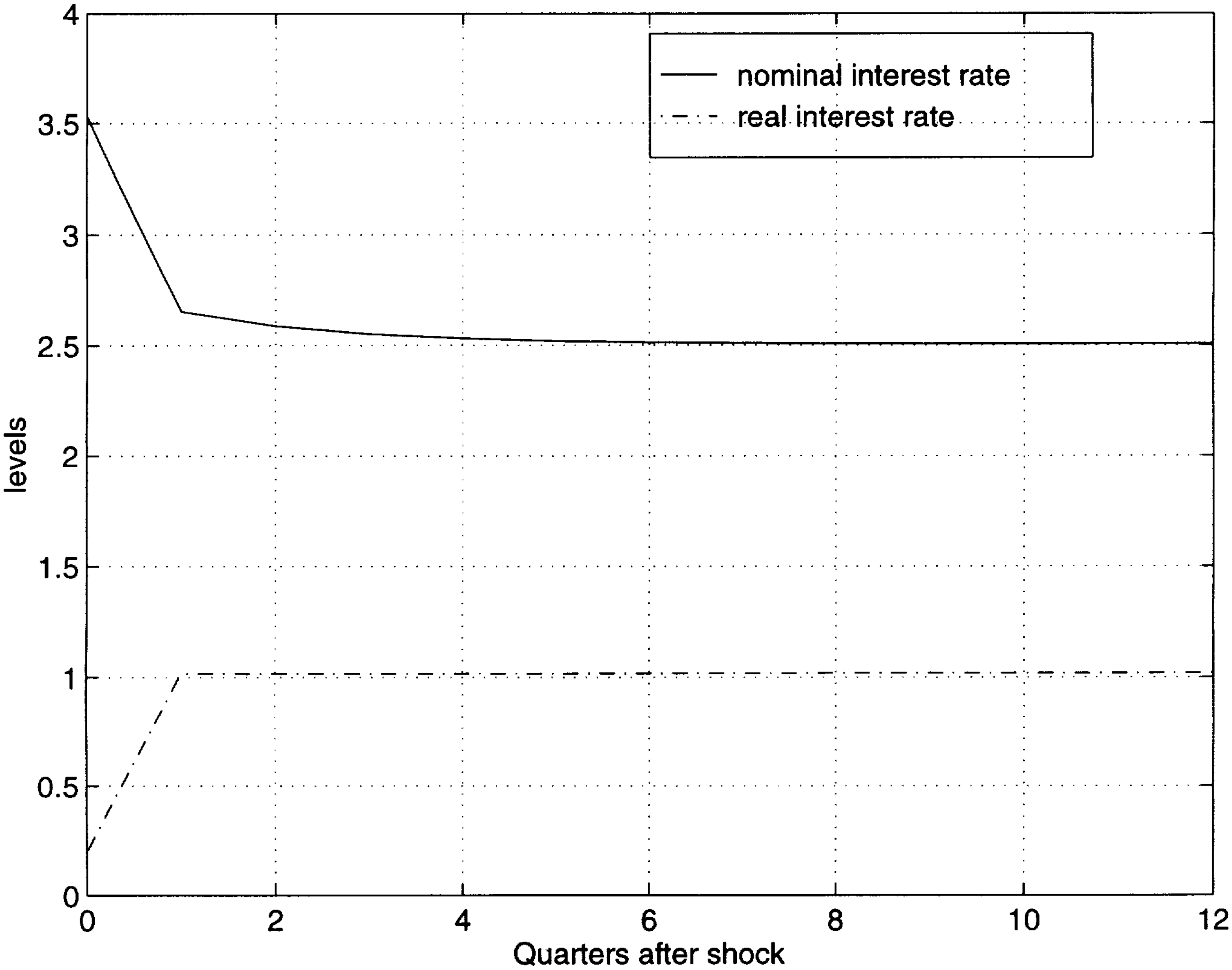

Figure 6. Impulse responses in home country

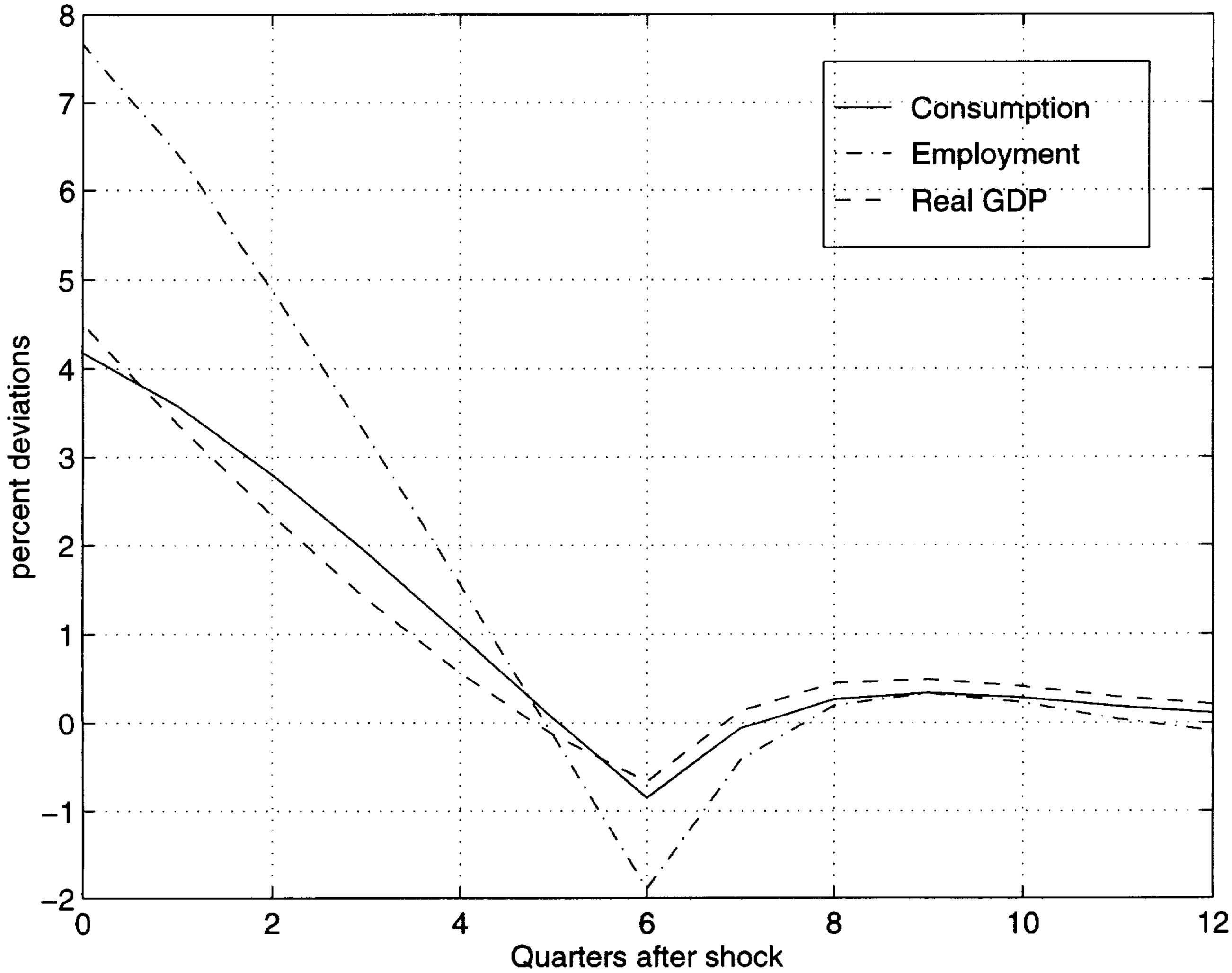

Figure 7. Impulse responses in foreign country

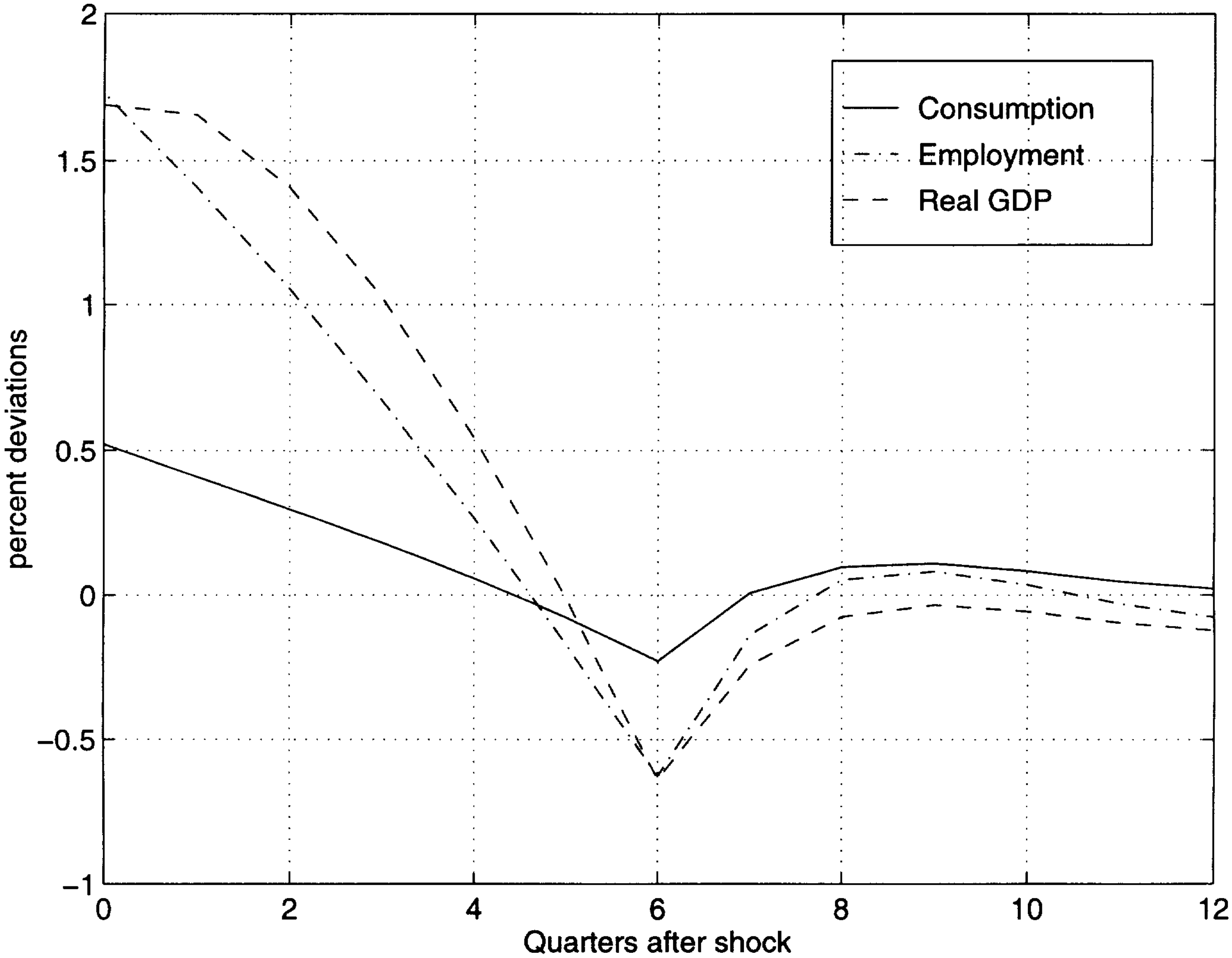

Figure 8. Impulse responses in home country

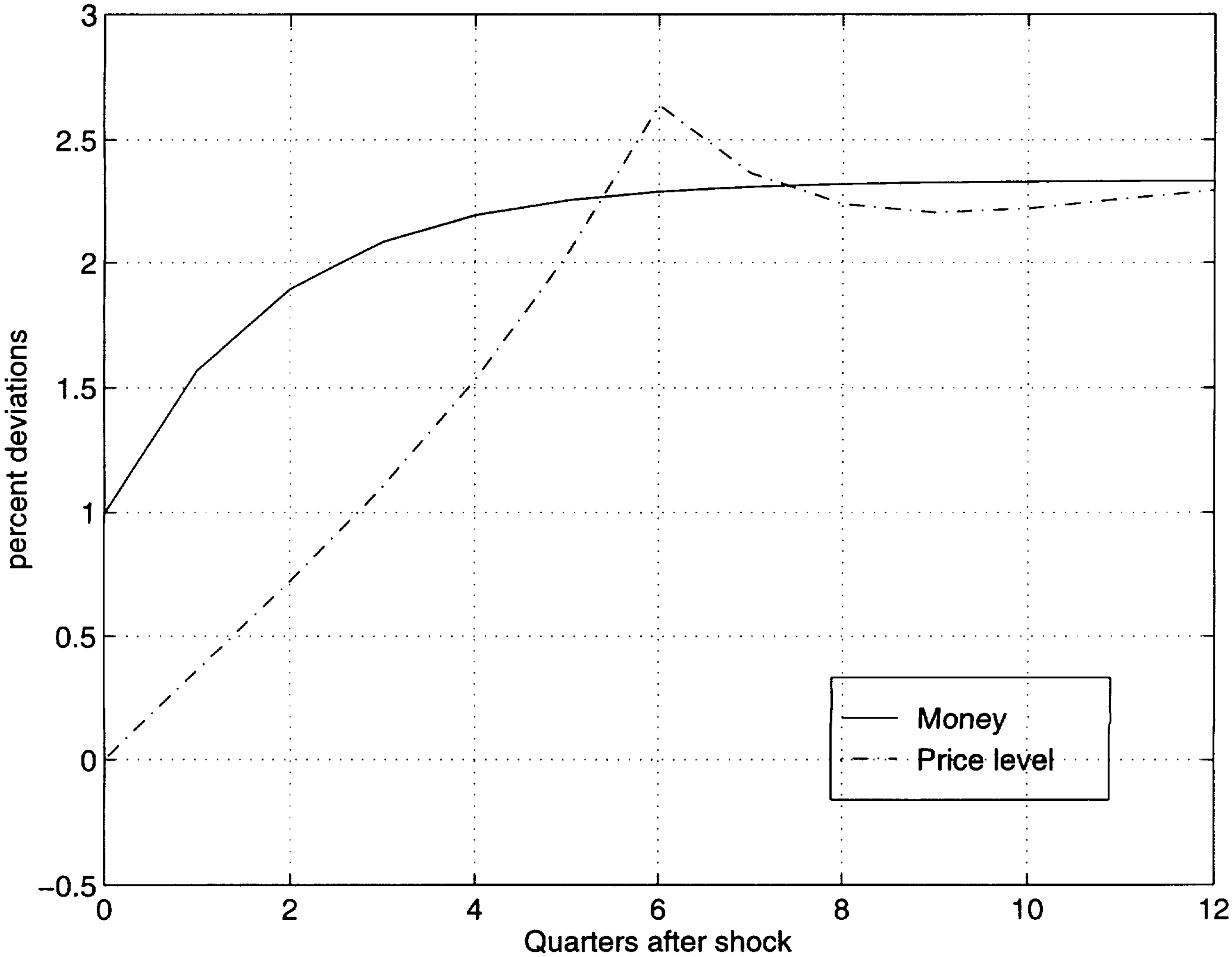

Figure 9. Impulse responses of exchange rates

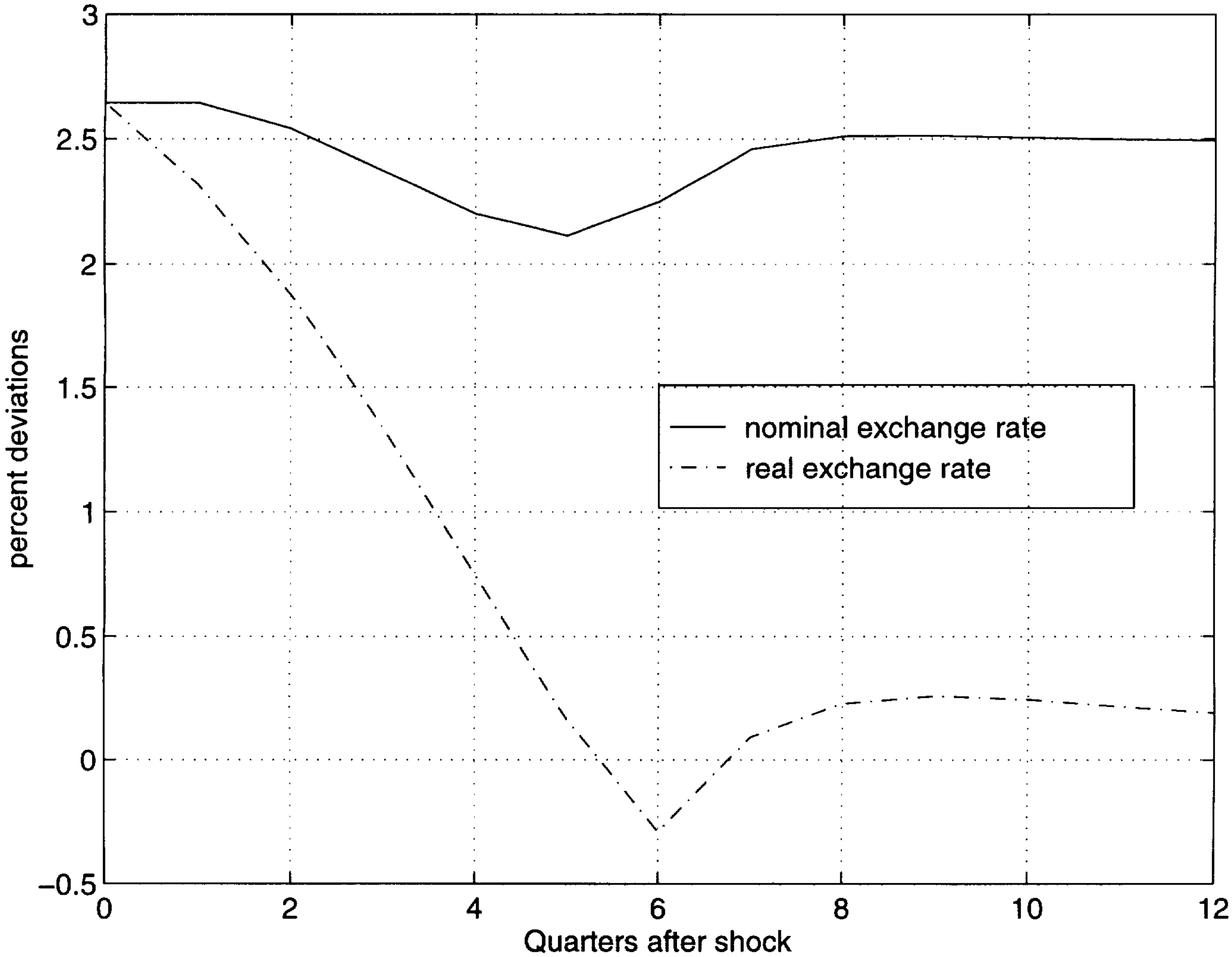

Figure 10. Impulse responses of interest rates