Vertical International Trade as a Monetary Transmission Mechanism in an Open Economy*

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Abstract

This paper analyzes a two-country general equilibrium model with multiple stages of production and sticky prices. Working through the cross-country input-output relations and endogenous price stickiness, the model is able to generate the observed cross-country correlations in real GDP, consumption, investment, and employment following monetary shocks. In accordance with the data, it predicts a larger output correlation than the consumption correlation. The model also generates persistent fluctuations of real exchange rates. Thus, vertical international trade plays an important role in propagating monetary shocks in an open economy.

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1 Introduction

The rising integration of world markets has brought with it an increasing amount of disintegration of production process in the global economy. Firms in different countries tend to specialize in different stages of production, and, as pointed out by Feenstra (1998), "there is no single measure that captures the full range of these activities, but ... they have all increased since the 1970s." Hummels et al. (1999) document the changed nature of trade in the recent decades, during which countries are increasingly interconnected in a vertical trading chain, with each country specializing in particular stages of a good's production sequence. They find that, as of 1995, such vertical trade represents as much as 30% of world exports.

In this paper, we study the role of a vertically disintegrated international chain of production in transmitting monetary shocks across countries. A thesis of our paper is that the assumption of cross-country input-output relations at different stages of production is crucial for explaining the observed international comovements in aggregate variables such as real GDP, consumption, investment, and employment. We construct a dynamic stochastic general equilibrium monetary model which incorporates a cross-country chain of production. The model embodies a powerful international monetary transmission mechanism by which monetary shocks can cause significant international comovements as well as persistent deviations of real exchange rate from the purchasing power parity (PPP) under a flexible exchange rate regime.

The role of the cross-country chain of production in transmitting monetary shocks has not received as much attention as it deserves. As is shown in this paper, a model with a single production stage in the spirit of Chari, et al. (1998b) is not able to transmit a temporary monetary shock in one country (say, home) into another (say, foreign) to generate international comovements or real exchange rate persistence. With a single production stage, a transitory monetary shock cannot generate persistent real effects (e.g., Chari, et al. (1998a); Huang and Liu (1999)). Following the shock in the home country, there will be a temporary rise in aggregate output and other aggregate variables such as consumption, investment, and employment in the home country, while the foreign country will experience a temporary decline in these aggregates. Since the real exchange rate is related to the cross-country marginal rate of substitution in consumption, its response to the shock is also temporary. To explain the international comovements as well as real exchange rate persistence, we build in our model a chain of production structure in the spirit of Blanchard (1983) and staggered price contracts in the spirit of Taylor (1980).[1] Our model is an open-economy extension of Huang and Liu (1999). Specifically, we assume that production of final consumption goods requires multiple stages of processing, from raw materials to intermediate goods, then to semi-finished goods and finished goods. Intermediate goods production requires both domestically produced raw materials and those imported; semi-finished goods production requires both domestically made intermediate goods and those imported, and so on. The staggering in price setting means that, in each country, at each stage, and in each period, a fraction of firms can set new prices while others cannot; once a price is set, it remains fixed for a certain period of time (e.g., one year). It is this input-output connection across countries at different production stages along with the staggered price setting that drives a significant international comovements and persistence real exchange rate movements following monetary shocks.

In the literature, it has been a challenging task to identify mechanisms that can generate the observed international correlations and persistence in real exchange rate. The standard one-good model encounters enormous difficulties in explaining the cross-country comovements as surveyed by Baxter (1995), because there is a strong tendency for capital to move to its most productive location, leading to a sharp rise in the returns to labor in the country experiencing an investment boom, while the returns to labor are relatively low in the other country. Backus, et al. (1995) study an international real business cycle model and identify the tendency of the model to generate low or even negative cross-country output correlation as one of the key anomalies in such models. Yet, a more robust anomalous result in this class of models, as pointed out by Backus, et al. (1995), is that the model tends to generate a higher consumption correlation than the output correlation, which is at odds with the data. More recently, there emerges a new line of research that emphasizes the importance of multi-sector models in explaining the international comovements. For example, Kouparitsas (1998) constructs a model with a primary goods sector and a manufacturing sector (which uses primary goods as inputs) and studies the transmission of technology shocks between Northern countries and Southern countries. Ambler, et al. (1998) find that adding multiple sectors on top of the baseline economy of Backus, et al. (1992) can help explain the observed international correlations in aggregate investment and employment. These multi-sector models are similar

[1] See Taylor (1999) for a comprehensive survey on the evidence of staggered price contracts.

in spirit to our chain-of-production model with three exceptions. First, the driving forces of aggregate fluctuations in these models are technology shocks, while those in ours are monetary shocks. Second, and more importantly, these models predict that the anomalous order between output correlation and consumption correlation remains robust, while in our model, the order is in accordance with the data. Third, these authors focus on explaining the international correlations in quantity variables, while we study both the quantity comovements and the real exchange rate persistence. The work by Beaudry and Devereux (1995) is also closely related to ours. They find that, when sticky prices are combined with increasing returns to scale in technologies, monetary shocks can be transmitted to generate persistent real exchange rate movements. Our model suggests an alternative monetary transmission mechanism. It reveals that the empirically relevant cross-country connections through trade in goods at different production stages can be a powerful mechanism in generating the observed international comovements and the persistent deviations of real exchange rate from PPP.

The paper is organized as follows. Section 2 presents a two-country general equilibrium business cycle model with a vertical cross-country chain of production. Section 3 describes the calibration strategies. Section 4 reports our main findings. Section 5 concludes the paper. The Appendix describes the computation methods.

2 The Model Economy

In the model economy, there are two large countries, a home country and a foreign country, each populated by a large number of identical, infinitely-lived households. In each period t, the economy experiences a realization of shocks s_t, while the history of events up to date t is denoted by $s^t \equiv (s_0, \cdots, s_t)$ with probability $\pi(s^t)$. The initial realization s_0 is given.

Production of consumption goods in each country requires N stages of processing, from raw materials to intermediate goods, then to more advanced intermediate goods, and so on. At each stage, in each country, there is a continuum of firms producing differentiated goods indexed in the interval $[0, 1]$, with an elasticity of substitution of $\theta > 1$. In each country, production of intermediate goods at a stage $n \in \{2, \ldots, N\}$ requires using all intermediate goods at stage $n-1$, both domestically produced and imported from the other country, while production of goods at the first stage ($n = 1$) requires homogeneous labor services and capital provided by domestic households. The households in both countries have access to a complete-contingent bond market (see Figure 1 for an illustration of this chain-of-production structure).

The utility function of the representative household in the home country is given by

$$\sum_{t=0}^{\infty}\sum_{s^t}\beta^t\pi(s^t)\left[\ln(\hat{C}(s^t))+\eta\ln(1-L(s^t))\right],$$

where $\beta\in(0,1)$ is a subjective discount factor, $\hat{C}(s^t)=\left[bC(s^t)^{\nu}+(1-b)(M(s^t)/\bar{P}(s^t))^{\nu}\right]^{1/\nu}$ is a CES composite of consumption and real money balances, $L(s^t)$ denotes labor hours, and $\bar{P}(s^t)$ is the price level. The budget constraint of the household is given by

$$\begin{aligned}(1)\qquad & \bar{P}(s^t)[C(s^t)+K(s^t)-(1-\delta)K(s^{t-1})]+\sum_{s^{t+1}}D(s^{t+1}|s^t)B(s^{t+1})+M(s^t)\\ \leq\ & W(s^t)L(s^t)+R^k(s^t)K(s^{t-1})+\Pi(s^t)+B(s^t)+M(s^{t-1})+T(s^t),\end{aligned}$$

where $K(s^t)$ denotes the capital stock, $0<\delta<1$ is the depreciation rate, $B(s^{t+1})$ is a one-period nominal bond that costs $D(s^{t+1}|s^t)$ dollars at s^t and pays off one dollar in the next period contingent upon the realization of s^{t+1}, $W(s^t)$ and $R^k(s^t)$ are the nominal wage and nominal rental rate, $\Pi(s^t)$ is the household's claim to all firms' profits, and $T(s^t)$ is a nominal lump-sum transfer from the government.

The consumption/investment good is a composite of all goods produced at the final stage in both the home country and the foreign country. Let $Y(s^t)$ denote this composite, that is,

$$(2)\qquad Y(s^t)=\left[\omega_1\left(\int_0^1 Y_{NH}(i,s^t)^{\frac{\theta-1}{\theta}}di\right)^{\frac{\rho\theta}{\theta-1}}+\omega_2\left(\int_0^1 Y_{NF}(i,s^t)^{\frac{\theta-1}{\theta}}di\right)^{\frac{\rho\theta}{\theta-1}}\right]^{\frac{1}{\rho}},$$

where $Y_{NH}(i,s^t)$ and $Y_{NF}(i,s^t)$ are type i goods produced at the final stage in the home country and in the foreign country, respectively, and $\rho>0$ determines the elasticity of substitution between domestically produced goods and imported goods. We thus have

$$(3)\qquad C(s^t)+K(s^t)-(1-\delta)K(s^{t-1})=Y(s^t).$$

The household maximizes its utility subject to (1)-(3) and a borrowing constraint $B(s^t)\geq-\bar{B}$ for some large positive number $\bar{B}$, for each s^t and each $t\geq0$, with initial conditions $K(s^{-1})$, $M(s^{-1})$, and $B(s^0)$ given. The implied demand functions for a type i good produced at stage N in the home country and in the foreign country are respectively given by

$$(4)\qquad Y_{NH}^d(i,s^t)=[\omega_1\bar{P}(s^t)]^{\frac{1}{1-\rho}}\bar{P}_H(s^t)^{\theta-\frac{1}{1-\rho}}P_{NH}(i,s^t)^{-\theta}Y(s^t),$$

and

$$Y_{NF}^{d}(i,s^t) = [\omega_2 \bar{P}(s^t)]^{\frac{1}{1-\rho}} \bar{P}_F(s^t)^{\theta - \frac{1}{1-\rho}} P_{NF}(i,s^t)^{-\theta} Y(s^t), \tag{5}$$

where $\bar{P}_j(s^t) = \left(\int_0^1 P_{Nj}(i,s^t)^{1-\theta} di\right)^{\frac{1}{1-\theta}}$ for $j = H, F$, and the price level is given by

$$\bar{P}(s^t) = \left(\omega_1^{\frac{1}{1-\rho}} \bar{P}_H(s^t)^{\frac{\rho}{\rho-1}} + \omega_2^{\frac{1}{1-\rho}} \bar{P}_F(s^t)^{\frac{\rho}{\rho-1}}\right)^{\frac{\rho-1}{\rho}}. \tag{6}$$

Production technology for type i good at stage $n \in \{2, \ldots, N\}$ is given by

$$\begin{aligned} &Y_{nH}(i,s^t) + Y_{nH}^{*}(i,s^t) = \\ &\left[\omega_1 \left(\int_0^1 Y_{n-1,H}(i,j,s^t)^{\frac{\theta-1}{\theta}} dj\right)^{\frac{\rho\theta}{\theta-1}} + \omega_2 \left(\int_0^1 Y_{n-1,F}(i,j,s^t)^{\frac{\theta-1}{\theta}} dj\right)^{\frac{\rho\theta}{\theta-1}}\right]^{\frac{1}{\rho}}, \end{aligned} \tag{7}$$

where $Y_{n-1,H}(i,j,s^t)$ is the home country's output of good j produced at stage $n-1$ and used by i as input, and $Y_{n-1,F}(i,j,s^t)$ is the counterpart in the foreign country. In (7), $Y_{nH}(i,s^t)$ and $Y_{nH}^{*}(i,s^t)$ are type i goods produced at stage n to be used at stage $n+1$ in the home country and in the foreign country, respectively. The production technology for type i goods at the first stage ($n = 1$) is a standard Cobb-Douglas function given by $Y_{1H}(i,s^t) + Y_{1H}^{*}(i,s^t) = K(i,s^t)^{\alpha} L(i,s^t)^{1-\alpha}$, where $K(i,s^t)$ and $L(i,s^t)$ are the capital and labor used in producing i, $Y_{1H}(i,s^t)$ and $Y_{1H}^{*}(i,s^t)$ are the output of good i at the first stage to be used by firms at stage 2 in the home country and in the foreign country, respectively.

Firms are monopolistic competitors in output markets and price-takers in input markets. They take goods demand functions as given and set prices in a staggered fashion. In particular, in each period t, a fraction $1/J$ of firms at each stage can set new prices upon the realization of s^t. Once a price is set, it remains fixed for J periods. We sort the indices of firms at each stage so that those indexed by $i \in [0, 1/J]$ set prices in periods $t, t+J, t+2J, \cdots$; those indexed by $i \in (1/J, 2/J]$ set prices in periods $t+1, t+J+1, t+2J+1, \cdots$; and so on.

Upon the realization of s^t, a home firm $i \in [0,1]$ at a stage $n \in \{1, \ldots, N\}$ that can set new prices chooses a price $P_{nH}(i,s^t)$ in units of the home currency for goods sold in the home country and a price $P_{nH}^{*}(i,s^t)$ in units of foreign currency for goods sold in the foreign country to maximize

$$\sum_{\tau=t}^{t+J-1} \sum_{s^\tau} D(s^\tau | s^t) \{[P_{nH}(i,s^t) - V_n(i,s^\tau)] Y_{nH}^{d}(i,s^\tau) + [e(s^\tau) P_{nH}^{*}(i,s^t) - V_n(i,s^\tau)] Y_{nH}^{d*}(i,s^\tau)\},$$

taking its unit cost function $V_n(i, s^\tau)$ and output demand schedule $Y^d_{nH}(i, s^\tau)$ as given, where $e(s^t)$ is the nominal exchange rate. The unit cost function $V_n(i, s^t)$ is derived by minimizing production cost subject to the production technologies. In particular, for $n = 1$, we have

$$V_1(i, s^t) = \min_{K,L} R^k(s^t)K + W(s^t)L,$$

subject to $K^\alpha L^{1-\alpha} \geq 1$; and for $n \in \{2, \ldots, N\}$,

$$V_n(i, s^t) = \min_{Y_{n-1,H}(i,j), Y_{n-1,F}(i,j)} \int_0^1 P_{n-1,H}(j, s^t) Y_{n-1,H}(i,j) dj + \int_0^1 P_{n-1,F}(j, s^t) Y_{n-1,F}(i,j) dj,$$

subject to $[\omega_1 \left(\int_0^1 Y_{n-1,H}(i,j)^{\frac{\theta-1}{\theta}} dj\right)^{\frac{\rho\theta}{\theta-1}} + \omega_2 \left(\int_0^1 Y_{n-1,F}(i,j)^{\frac{\theta-1}{\theta}} dj\right)^{\frac{\rho\theta}{\theta-1}}]^{1/\rho} \geq 1$. The resulting demand functions for type i goods are

$$Y^d_{nH}(i, s^t) = [\omega_1 \bar{P}_n(s^t)]^{\frac{1}{1-\rho}} \bar{P}_{nH}(s^t)^{\theta - \frac{1}{1-\rho}} P_{nH}(i, s^t)^{-\theta} Y_{n+1}(s^t), \tag{8}$$

and

$$Y^d_{nF}(i, s^t) = [\omega_2 \bar{P}_n(s^t)]^{\frac{1}{1-\rho}} \bar{P}_{nF}(s^t)^{\theta - \frac{1}{1-\rho}} P_{nF}(i, s^t)^{-\theta} Y_{n+1}(s^t), \tag{9}$$

where $Y_{n+1}(s^t) \equiv \int_0^1 [Y_{n+1,H}(j, s^t) + Y^*_{n+1,H}(j, s^t)] dj$, $\bar{P}_{nk}(s^t) = \left(\int_0^1 P_{nk}(i, s^t)^{1-\theta} di\right)^{\frac{1}{1-\theta}}$ for $k = H, F$, and

$$\bar{P}_n(s^t) = \left(\omega_1^{\frac{1}{1-\rho}} \bar{P}_{nH}(s^t)^{\frac{\rho}{\rho-1}} + \omega_2^{\frac{1}{1-\rho}} \bar{P}_{nF}(s^t)^{\frac{\rho}{\rho-1}}\right)^{\frac{\rho-1}{\rho}} \tag{10}$$

is the price index of goods produced at stage n. The unit production cost function of firm i derived from the cost-minimization problem is given by

$$V_n(s^\tau) \equiv V_n(i, s^\tau) = \bar{P}_{n-1}(s^\tau), \quad V_1(s^\tau) = \tilde{\alpha} R^k(s^\tau)^\alpha W(s^\tau)^{1-\alpha} \tag{11}$$

where $n \in \{2, \ldots, N\}$, and $\tilde{\alpha} = \alpha^{-\alpha}(1-\alpha)^{\alpha-1}$. Given constant returns to scale, it is also the marginal cost function. Note that V_n is firm-independent. Firm i's profit maximization problem yields the optimal price setting rules

$$P_{nH}(i, s^t) = \frac{\theta}{\theta-1} \frac{\sum_{\tau=t}^{t+J-1} \sum_{s^\tau} D(s^\tau|s^t) V_n(s^\tau) Y^d_{nH}(i, s^\tau)}{\sum_{\tau=t}^{t+J-1} \sum_{s^\tau} D(s^\tau|s^t) Y^d_{nH}(i, s^\tau)}, \tag{12}$$

and

$$P^*_{nH}(i, s^t) = \frac{\theta}{\theta-1} \frac{\sum_{\tau=t}^{t+J-1} \sum_{s^\tau} D(s^\tau|s^t) V_n(s^\tau) Y^{d*}_{nH}(i, s^\tau)}{\sum_{\tau=t}^{t+J-1} \sum_{s^\tau} D(s^\tau|s^t) e(s^\tau) Y^{d*}_{nH}(i, s^\tau)}, \tag{13}$$

where $n \in \{1, \ldots, N\}$. To understand the pricing rules, notice that the firm sets its price equal to a constant markup over a weighted average of its marginal costs in the subsequent J

periods, with the weights given by (normalized) discounted total demand for its output in the corresponding periods.

The problems of the representative household and of the intermediate goods producers at each stage in the foreign country are analogous to the above problems. To help further exposition, we write out the budget constraint facing the foreign household:

$$
\begin{aligned}
(14) \qquad & \bar{P}^*(s^t)[C^*(s^t) + K^*(s^t) - (1-\delta)K^*(s^{t-1})] + \frac{1}{e(s^t)} \sum_{s^{t+1}} D(s^{t+1}|s^t) B^*(s^{t+1}) + M^*(s^t) \\
\leq \; & W^*(s^t)L^*(s^t) + R^{k*}(s^t)K^*(s^{t-1}) + \Pi^*(s^t) + \frac{B^*(s^t)}{e(s^t)} + M^*(s^{t-1}) + T^*(s^t),
\end{aligned}
$$

where the variables with stars are the foreign counterpart of the home country's corresponding variables.

The money supply process in the two countries are given by $M(s^t) = \mu(s^t)M(s^{t-1})$ and $M^*(s^t) = \mu^*(s^t)M^*(s^{t-1})$. The money growth rate $\mu(s^t)$ in the home country follows a stationary stochastic process given by

$$
(15) \qquad \ln \mu(s^t) = \rho_\mu \ln \mu(s^{t-1}) + \varepsilon_t,
$$

where $0 < \rho_\mu < 1$ and ε_t is an i.i.d., normally distributed stochastic process with zero mean and variance σ_μ^2. The process of $\mu^*(s^t)$ is the same. Newly created money is injected into the economy via a lump-sum transfer in each country, that is, $T(s^t) = M(s^t) - M(s^{t-1})$ and $T^*(s^t) = M^*(s^t) - M^*(s^{t-1})$.

Finally, the market clearing conditions for labor and capital in the home country are given by $\int_0^1 L^d(i,s^t)di = L(s^t)$ and $\int_0^1 K^d(i,s^t)di = K(s^{t-1})$, and those in the foreign country are analogous. The bond market clearing condition is $B(s^t) + B^*(s^t) = 0$. Note that, while firms at the first stage choose capital and labor after the realization of s^t, the household chooses capital stock before the realization of s^t.

An equilibrium for this economy is a collection of allocations $\{C(s^t),\, I(s^t),\, L(s^t),\, K(s^t),\, M(s^t),\, B(s^{t+1})\}$ for the household in the home country; allocations $\{C^*(s^t),\, I^*(s^t),\, L^*(s^t),\, K^*(s^t),\, M^*(s^t),\, B^*(s^{t+1})\}$ for the household in the foreign country; allocations $\{Y_{nH}(i,s^t),\, Y^*_{nH}(i,s^t)\}$ and prices $\{P_{nH}(i,s^t), P^*_{nH}(i,s^t)\}$ for home intermediate goods producers, where $i \in [0,1]$ and $n \in \{1,\ldots,N\}$; allocations $\{Y_{nF}(i,s^t), Y^*_{nF}(i,s^t)\}$ and prices $\{P_{nF}(i,s^t), P^*_{nF}(i,s^t)\}$ for foreign intermediate goods producers, where $i \in [0,1]$ and $n \in \{1,\ldots,N\}$; price indices $\{\bar{P}_n(s^t), \bar{P}^*_n(s^t)\}$ for $n \in \{1,\ldots,N\}$; wages $\{W(s^t), W^*(s^t)\}$; rental rates $\{R^k(s^t), R^{k*}(s^t)\}$; and bond prices $D(s^{t+1}|s^t)$ that satisfy the following four conditions: (i) households' allocations solve the their utility maximization problems, taking prices as given; (ii) the prices of each intermediate goods producer solve its profit-maximization problem; (iii) markets for labor, capital, money, and bond all clear; (iv) the money policy rules are as specified.

Given the Markov money supply process (15), a stationary equilibrium in this economy consists of stationary decision rules which are functions of the state of the economy. In period t, in each country and at each production stage, there are $J-1$ prevailing prices that were set in period $t-J+1$ through period $t-1$ due to staggered price contracts. Thus, the state of the economy in period t must record the prices set in the previous $J-1$ periods in addition to the beginning-of-period capital stocks and the exogenous money growth rates. To induce stationarity, we divide all prices by the appropriate money stocks. Thus, the state at s^t is given by

$$\left[K(s^{t-1}), K^*(s^{t-1}), \mu(s^t), \mu^*(s^t), \frac{P(s^{t-J+1})}{M(s^t)}, \dots, \frac{P(s^{t-1})}{M(s^t)}, \frac{P^*(s^{t-J+1})}{M^*(s^t)}, \dots, \frac{P^*(s^{t-1})}{M^*(s^t)}\right],$$

where $P(s^t) \equiv \{P_{nH}(s^t), P_{nF}(s^t)\}_{n\in\{1,2,3,4\}}$ and $P^*(s^t) \equiv \{P^*_{nH}(s^t), P^*_{nF}(s^t)\}_{n\in\{1,2,3,4\}}$. The stationary equilibrium decision rules are computed using standard log-linearization methods.

3 The Calibration

The parameters to be calibrated include the subjective discount factor β, the preference parameters b, ν and η, the capital income share α, the capital depreciation rate δ, the goods demand elasticity parameter θ, parameters in the aggregation technology ρ, ω_1, and ω_2, and the monetary policy parameters ρ_μ and σ_μ. The calibrated values are summarized in Table I.

In our baseline model, we set $J = 4$ so that a period in the model corresponds to a quarter. Following the standard business cycle literature, we choose $\beta = 0.96^{1/4}$. To assign values for b and ν, we use the money demand equation (derived from the first order conditions of the household's problem):

$$\ln\left(\frac{M(s^t)}{\bar{P}(s^t)}\right) = -\frac{1}{1-\nu}\ln\left(\frac{b}{1-b}\right) + \ln(C(s^t)) - \frac{1}{1-\nu}\log\left(\frac{R(s^t)-1}{R(s^t)}\right),$$

where $R(s^t) = \left(\sum_{s^{t+1}} D(s^{t+1}|s^t)\right)^{-1}$ is the gross nominal interest rate. The regression of this equation as performed in Chari, et al. (1998b) implies that $\nu = -1.56$ and $b = 0.98$ for quarterly U.S. data with a sample range from quarter one in 1960 to quarter four in 1995. The parameter η is selected to match an average share of time allocated to market activity of 1/3, as in most business cycle studies.

We next choose $\alpha = 1/3$ and $\delta = 1 - 0.92^{1/4}$ so that the baseline model predicts an annualized capital-output ratio of 2.6 and an investment-output ratio of 0.21. We set $\theta = 10$, corresponding to a steady state markup of 11%. As shown in Chari, et al. (1998a), this value of θ is consistent with a price-cost margin of 0.25 as found by Domowitz, et al. (1986). We choose $\rho = 1/3$ so that the elasticity of substitution between domestically produced goods and imported goods is 1.5, which is the value used in Backus, et al. (1994). To assign values for ω_1 and ω_2, we first choose a normalization $\omega_1^{\frac{1}{1-\rho}} + \omega_2^{\frac{1}{1-\rho}} = 1$ so that when $\bar{P}_{nH} = \bar{P}_{nF}$, we have $\bar{P}_n = \bar{P}_{nH}$. We then use the steady state relation that $Y_H/Y_F = [\omega_1/\omega_2]^{\frac{1}{1-\rho}}$. The imported goods share in U.S. GDP is about 15%, implying that $Y_H/Y_F = 0.85/0.15$. These two conditions give us values for ω_1 and ω_2.

Finally, the serial correlation parameter ρ_μ for money growth is set to 0.57 and the standard deviation of ε_t to $\sigma_\mu = 0.0092$, based on quarterly U.S. data on M1 from 1959:3 through 1995:2 obtained from Citibase (see also Chari, et al. (1998b)). We assume that the monetary shocks are independent across countries.

4 Main Findings

In Table II, we report the cross-country correlation statistics computed from the data and from two different models: our baseline model with four production stages (i.e., $N = 4$) and its counterpart with a single production stage.[2]

The table shows that there are significant cross-country aggregate comovements in the data: real GDP, consumption, investment, and employment are all significantly and positively correlated across countries. Yet, in a single-stage model, the correlation statistics are too low (or

[2] We choose $N = 4$ as our benchmark for the following reasons. In computing the producer price indices (PPI) based on stages of production, the Bureau of Labor Statistics classifies all industries into three production stages: raw materials, intermediate goods, and finished goods. The service industry is not included. Thus, in a closed economy, there are at least four production stages. In an open economy, as noted by Feenstra (1998), it is likely to have more stages involved. Thus $N = 4$ is a lower bound of the number of stages. As we will show, having more stages will only strengthen the cross-country correlations and magnify the real exchange rate persistence.

even negative), a key anomaly in a standard international business cycle model (e.g., Backus, et al. (1995) and Baxter (1995)). In contrast, the baseline model with a chain of production produces statistics that are much closer to the data: the correlations are all significantly positive, and more importantly, the output correlation is larger than the consumption correlation, in accordance with the data.

To gain intuition, we compute the equilibrium impulse responses to a temporary monetary shock in the home country. In particular, we choose the magnitude of ε_0 in (15) so that the home country's money stock rises by 1% one year after the shock occurs (that is, at the end of the initial price contract period) while we set $\varepsilon_t^* = 0$ for all t. In the Appendix, we describe the computation methods in more details. The results are presented in Figures II through V.

Figure II displays the impulse responses of aggregate variables in the baseline economy. In response to the shock, aggregate variables including real GDP, consumption, investment, and employment rise in both countries. There are two driving forces for this result. One works through the intersectoral and international input-output relations, the other through (endogenous) price stickiness embodied in the chain, and the two interact with each other.

Through the input-output relations, the chain of production generates an equilibrium "snake effect," as we have shown in a closed economy model (see Huang and Liu (1999)). The snake effect implies that prices adjust less rapidly and by a smaller amount at later production stages than at earlier stages, as firms' marginal costs diminish from less processed stages to more advanced stages along the chain. The snake effect thus leads to price level inertia and aggregate output persistence. In the open economy here, the same intuition applies. Following the shock, real GDP in the home country rises because staggered price contracts prevent price level from fully rising. With the higher real income, the household raises its demand for goods produced at the final stage in both countries. To meet this higher demand, firms that cannot adjust prices have to raise their demand for intermediate goods, both domestically produced and imported. The intermediate goods producers that cannot adjust prices then have to raise their demand for raw materials produced in both countries. Finally, the raw material producers who cannot adjust prices have to increase their demand for labor and capital, pushing up real wages and thus households' real income in both countries. Additionally, the household in the foreign country receives higher wage income from its raw material producing sector because, in that sector, firms who cannot adjust prices have to employ more workers in order to meet the higher demand from intermediate goods producers in both countries. With this higher income, the foreign household demands more goods produced at the final stage in both countries, which in turn raises the demand for intermediate goods in both countries, and so on. This reinforces the initial effect of the home country's higher demand for the foreign's products at each stage, leading to a tendency of aggregate comovements across countries.

To induce *actual* aggregate comovements, however, sluggish price adjustments are essential. Since the money supply in the foreign country is unchanged, a quick rise in price level will lower the real money balances held by the foreign households and hence dampen their aggregate demand. The snake effect embodied in the chain helps resolve this problem for it leads to sluggish price adjustments in both countries. In the home country, since prices do not fully rise following the shock, the nominal exchange rate depreciation translates into real depreciation at each production stage. At more advanced processing stages, however, the magnitude of real depreciation is larger since price adjustments are smaller. The real depreciation of home currency lowers the effective prices of those goods exported to the foreign country (in foreign currency units). Meanwhile, in the foreign country, the snake effect dampens the adjustments in prices of its domestically produced goods. Thus, the more production stages, the more likely to have a lower overall price level (which is an average of imported goods prices and domestically produced goods prices). In our baseline model with four stages, the foreign's real money balances indeed rise, so does the aggregate demand. Comparing Figures II and III confirms this intuition. Figure III displays the impulse responses of the same set of variables when there is a single production stage (for a similar model, see Chari, et al. (1998b)). Although employment in both countries rises in response to the home monetary shock, the income effect generated from the rising demand for exported goods is dominated by the quick rise in the price level, leading to a fall in the foreign's aggregate consumption and virtually unchanged investment and output. Thus, the chain of production helps explain the observed international comovements.

Figure II also helps understand the relative order of output correlation and consumption correlation. In accordance with the data, our baseline model predicts that consumption correlation is lower than output correlation (and both are significantly positive). This is so because consumption and real money balances are non-separable in the utility function, and the cross-country correlation between real balances is relatively low. In response to the home monetary shock, real balances in the home country rises since nominal money balance rises and price level does not fully adjust. The real balances in the foreign country rise less quickly since its nominal money stock is unchanged; although we know that, in our baseline economy, the foreign's real balances do rise because of the price level inertia in both countries and the real depreciation in home's currency. Thus the consumption comovement across countries is less pronounced than the output comovement (see the top two panels in Figure II).

Finally, Figures IV and V display the impulse responses of real and nominal exchange rates. Figure IV shows that the chain of production helps generate persistent movements in the real exchange rate. In the baseline economy, the response of real exchange rate at the end of the initial price contract duration is about 26% of its initial response, whereas it returns to the steady state much faster in the single-stage economy. Since the real exchange rate is determined by the cross-country marginal rates of substitution in consumption, and the chain of production generates consumption persistence, the chain also generates real exchange rate persistence. Figure V shows that the baseline model generates nominal exchange rate "overshooting" (as emphasized by Dornbusch (1976)): the initial response of the nominal exchange rate is larger than its long-run value. This is because of the persistent decrease in the nominal interest rate following the shock (i.e., there is a liquidity effect). Lower future nominal interest rates magnify the depreciation of home's currency.

5 Conclusions

A long-standing puzzle in the literature of international business cycles is the inability of a standard business cycle model, based on either real or monetary shocks, in generating the observed cross-country comovements among aggregate economic variables such as real GDP, consumption, investment, and employment. A related challenge is to identify mechanisms that can propagate monetary shocks to generate persistent real exchange rate movements. In this paper, we have analyzed a chain of production mechanism that helps resolve both puzzles. We have shown that, with the cross-country input-output relations, along with endogenous price stickiness, the model is able to generate strong international comovements and substantial persistence in real exchange rate fluctuations.

Our purpose in this paper has been to analyze the role of the cross-country input-output relations in transmitting monetary shocks. We focus on an environment with monetary shocks alone and thus do not attempt to match our model's predictions with the unconditional correlations in the data. However, to assess the quantitative importance of monetary shocks in such an environment, we can calibrate the model using international input-output data. In particular, we need to calibrate the import share at each production stage, the share of labor and capital at each stage, and the total number of stages. This task should be feasible given the renewed interest in studying the empirical importance of international trade at different stages of processing (see, for example, Feenstra (1998) and Hummels, et al. (1998)). We leave this task for future research.

Appendix

In this appendix, we describe the model's equilibrium conditions and computation methods.

The equilibrium conditions derived from firms' problems are described in Section 2. We thus only need to write out the households' first order conditions. The first order conditions for the home country's representative household are given by

$$-\frac{U_l(s^t)}{U_c(s^t)} = \frac{W(s^t)}{\bar{P}(s^t)}, \tag{16}$$

$$\frac{U_m(s^t)}{U_c(s^t)} = 1 - \beta \sum_{s^{t+1}} \pi(s^{t+1}|s^t) \frac{U_c(s^{t+1})\bar{P}(s^t)}{U_c(s^t)\bar{P}(s^{t+1})}, \tag{17}$$

$$D(s^\tau|s^t) = \beta^{\tau-t}\pi(s^\tau|s^t)\frac{U_c(s^\tau)\bar{P}(s^t)}{U_c(s^t)\bar{P}(s^\tau)}, \;\; \tau \geq t, \tag{18}$$

$$U_c(s^t) = \beta \sum_{s^{t+1}} \pi(s^{t+1}|s^t) U_c(s^{t+1}) \left[\frac{R^k(s^{t+1})}{\bar{P}(s^{t+1})} + 1 - \delta \right],$$

where $U_c(s^t)$, $U_l(s^t)$, and $U_m(s^t)$ denote the marginal utility of consumption, leisure, and real money balances, respectively, and $\pi(s^\tau|s^t) = \pi(s^\tau)/\pi(s^t)$ is the conditional probability of s^τ given s^t. Equations (16)-(19) are standard first order conditions with respect to the household's choice of labor, money, bond, and capital, respectively. The foreign household's first order conditions are analogous. Allocations and prices in the foreign country are denoted with star superscripts.

With appropriate substitutions, the equilibrium conditions can be reduced to $4N+4$ equations, including two capital Euler equations, two money demand equations, and $4N$ price decision equations. The decision variables are aggregate consumption for both countries, aggregate capital stocks for both countries, and $4N$ current prices. The four prices at stage n are P_{nH}, P^*_{nH}, P^*_{nF}, and P_{nF}. We focus on a symmetric equilibrium in which firms in the same country and in the same cohort at each stage make identical decisions so that the price decisions of a firm depends only on the stage at which it produces, the time at which it can set a new price, and the country in which it resides.

We begin with linking capital and labor inputs to the final aggregate goods. This is accomplished by integrating the goods demand functions (4)-(5), (8)-(9), and the analogous demand functions derived from foreign firms' optimization problems. This results in the following recursive relations:

$$
\begin{aligned}
Y_n(s^t) &= G_{nH}(s^t)Y_{n+1}(s^t) + G^*_{nH}(s^t)Y^*_{n+1}(s^t), \\
Y^*_n(s^t) &= G^*_{nF}(s^t)Y^*_{n+1}(s^t) + G_{nF}(s^t)Y_{n+1}(s^t),
\end{aligned} \tag{19}
$$

where the G terms are given by

$$
\begin{aligned}
G_{nH} &= [\omega_1 \bar{P}_n]^{\frac{1}{1-\rho}} \bar{P}_{nH}^{\theta-\frac{1}{1-\rho}} \int_0^1 P_{nH}(i)^{-\theta} di, \\
G^*_{nH} &= [\omega_2 \bar{P}^*_n]^{\frac{1}{1-\rho}} \bar{P}_{nH}^{*\,\theta-\frac{1}{1-\rho}} \int_0^1 P^*_{nH}(i)^{-\theta} di, \\
G^*_{nF} &= [\omega_1 \bar{P}^*_n]^{\frac{1}{1-\rho}} \bar{P}_{nF}^{*\,\theta-\frac{1}{1-\rho}} \int_0^1 P^*_{nF}(i)^{-\theta} di, \\
G_{nF} &= [\omega_2 \bar{P}_n]^{\frac{1}{1-\rho}} \bar{P}_{nF}^{\theta-\frac{1}{1-\rho}} \int_0^1 P_{nF}(i)^{-\theta} di.
\end{aligned}
$$

The implied relation between capital and labor inputs and aggregate final output is then given by

$$
\begin{aligned}
K(s^{t-1})^{\alpha} L(s^t)^{1-\alpha} &= H_1(s^t)Y(s^t) + H^*_1(s^t)Y^*(s^t), \\
K^*(s^{t-1})^{\alpha} L^*(s^t)^{1-\alpha} &= F^*_1(s^t)Y^*(s^t) + F_1(s^t)Y(s^t),
\end{aligned} \tag{20}
$$

where the terms H_1, H^*_1, F^*_1, and F_1 are functions of the G terms above. In these equations, we have used the factor market clearing conditions. We then use (3) and (20) to express $Y(s^t)$ and $Y^*(s^t)$ in terms of the decision variables.

Next, we express all variables in the $4N$ price decision equations in terms of the aggregate decision variables. This involves, in each country, the N unit cost functions and price indices, in addition to the stage-specific demand functions. Using (11), (16), the factor demand functions derived from firms' cost-minimization problems at the first stage, and the factor market clearing conditions, we obtain

$$V_1(s^t) = \frac{1}{1-\alpha}\left(\frac{L(s^t)}{K(s^{t-1})}\right)^{\alpha}\left(\frac{-U_l(s^t)}{U_c(s^t)}\right)\bar{P}(s^t),$$

and a similar equation for the foreign country. The unit cost function at a stage $n \geq 2$ is simply given by the price index at the previous stage, as shown in (11). In a symmetric equilibrium, firms in the same cohort at each stage make identical price decisions, and thus, at a stage $n \in \{1, \ldots, N\}$, the price indices for the intermediate goods are given by

$$\begin{aligned}
\bar{P}_{nH}(s^t) &= \left[\frac{1}{J}P_{nH}(s^{t-J+1})^{1-\theta} + \frac{1}{J}P_{nH}(s^{t-J+2})^{1-\theta} + \cdots + \frac{1}{J}P_{nH}(s^t)^{1-\theta}\right]^{\frac{1}{1-\theta}},\\
\bar{P}_{nF}(s^t) &= \left[\frac{1}{J}P_{nF}(s^{t-J+1})^{1-\theta} + \frac{1}{J}P_{nF}(s^{t-J+2})^{1-\theta} + \cdots + \frac{1}{J}P_{nF}(s^t)^{1-\theta}\right]^{\frac{1}{1-\theta}},\\
\bar{P}^*_{nF}(s^t) &= \left[\frac{1}{J}P^*_{nF}(s^{t-J+1})^{1-\theta} + \frac{1}{J}P^*_{nF}(s^{t-J+2})^{1-\theta} + \cdots + \frac{1}{J}P^*_{nF}(s^t)^{1-\theta}\right]^{\frac{1}{1-\theta}},\\
\bar{P}^*_{nH}(s^t) &= \left[\frac{1}{J}P^*_{nH}(s^{t-J+1})^{1-\theta} + \frac{1}{J}P^*_{nH}(s^{t-J+2})^{1-\theta} + \cdots + \frac{1}{J}P^*_{nH}(s^t)^{1-\theta}\right]^{\frac{1}{1-\theta}},
\end{aligned}$$

and the price indices for the composite goods are given by

$$\bar{P}_n(s^t) = \left[\omega_1^{\frac{1}{1-\rho}}\bar{P}_{nH}(s^{t-1})^{\frac{\rho}{\rho-1}} + \omega_2^{\frac{1}{1-\rho}}\bar{P}_{nF}(s^{t-1})^{\frac{\rho}{\rho-1}}\right]^{\frac{\rho-1}{\rho}}, \tag{21}$$

$$\bar{P}^*_n(s^t) = \left[\omega_1^{\frac{1}{1-\rho}}\bar{P}^*_{nF}(s^{t-1})^{\frac{\rho}{\rho-1}} + \omega_2^{\frac{1}{1-\rho}}\bar{P}^*_{nH}(s^{t-1})^{\frac{\rho}{\rho-1}}\right]^{\frac{\rho-1}{\rho}}. \tag{22}$$

In addition, the G terms in (19) are given by

$$\begin{aligned}
G_{nH}(s^t) &= [\omega_1\bar{P}_n(s^t)]^{\frac{1}{1-\rho}}\bar{P}_{nH}(s^t)^{\theta-\frac{1}{1-\rho}}[\frac{1}{J}P_{nH}(s^{t-J+1})^{-\theta} + \cdots + \frac{1}{J}P_{nH}(s^t)^{-\theta}],\\
G^*_{nH}(s^t) &= [\omega_2\bar{P}^*_n(s^t)]^{\frac{1}{1-\rho}}\bar{P}_{nH}(s^t)^{*\,\theta-\frac{1}{1-\rho}}[\frac{1}{J}P^*_{nH}(s^{t-J+1})^{-\theta} + \cdots + \frac{1}{J}P^*_{nH}(s^t)^{-\theta}],\\
G^*_{nF}(s^t) &= [\omega_1\bar{P}^*_n(s^t)]^{\frac{1}{1-\rho}}\bar{P}^*_{nF}(s^t)^{\theta-\frac{1}{1-\rho}}[\frac{1}{J}P*_{nF}(s^{t-J+1})^{-\theta} + \cdots + \frac{1}{J}P^*_{nF}(s^t)^{-\theta}],\\
G_{nF}(s^t) &= [\omega_2\bar{P}_n(s^t)]^{\frac{1}{1-\rho}}\bar{P}_{nF}(s^t)^{\theta-\frac{1}{1-\rho}}[\frac{1}{J}P_{nF}(s^{t-J+1})^{-\theta} + \cdots + \frac{1}{J}P_{nF}(s^t)^{-\theta}].
\end{aligned}$$

Finally, we substitute for $R^k(s^t)$ in the capital Euler equation using the equilibrium condition $R^k(s^t)/\bar{P}(s^t) = [\alpha/(1-\alpha)](L(s^t)/K(s^{t-1})(-U_l(s^t)/U_c(s^t))$ derived from firms cost-minimization problem, and substitute for $\bar{P}(s^t)$ in the money demand equation using (21).

Given these $4N + 4$ equilibrium conditions, we proceed to compute the decision rules for the $4N + 4$ decision variables. This is accomplished by log-linearizing these equations around a deterministic steady state. Upon obtaining the linear decision rules, we use standard computation methods to generate the impulse response functions and obtain cross-country correlation statistics.

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TABLE I

Calibrated parameters

Preferences:	$\beta = 0.96^{1/4}$, $b = 0.98$, $\nu = -1.56$, $\eta = 1.1$
Intermediate goods technologies:	$\alpha = 1/3$, $\theta = 10$
Aggregation technology:	$\rho = 1/3$, $[\omega_1/\omega_2]^{\frac{1}{1-\rho}} = 0.85/0.15$
Capital depreciation rate:	$\delta = 1 - 0.92^{1/4}$,
Money growth process:	$\rho_\mu = 0.57$, $\sigma_\mu = 0.0092$

TABLE II

Cross-country correlations

Statistics	Data	Single-stage model	Baseline model
Foreign and domestic GDP	0.52	-0.10	0.17
Foreign and domestic consumption	0.27	-0.09	0.14
Foreign and domestic investment	0.22	0.01	0.28
Foreign and domestic employment	0.51	0.27	0.67

Note: The statistics are based on logged and Hodrick-Prescott filtered data, taken from Chari, et al. (1998). The model's statistics are averages over 300 simulations of 90 periods each (the first 20 observations in each simulated series are discarded to avoid dependence on initial conditions).

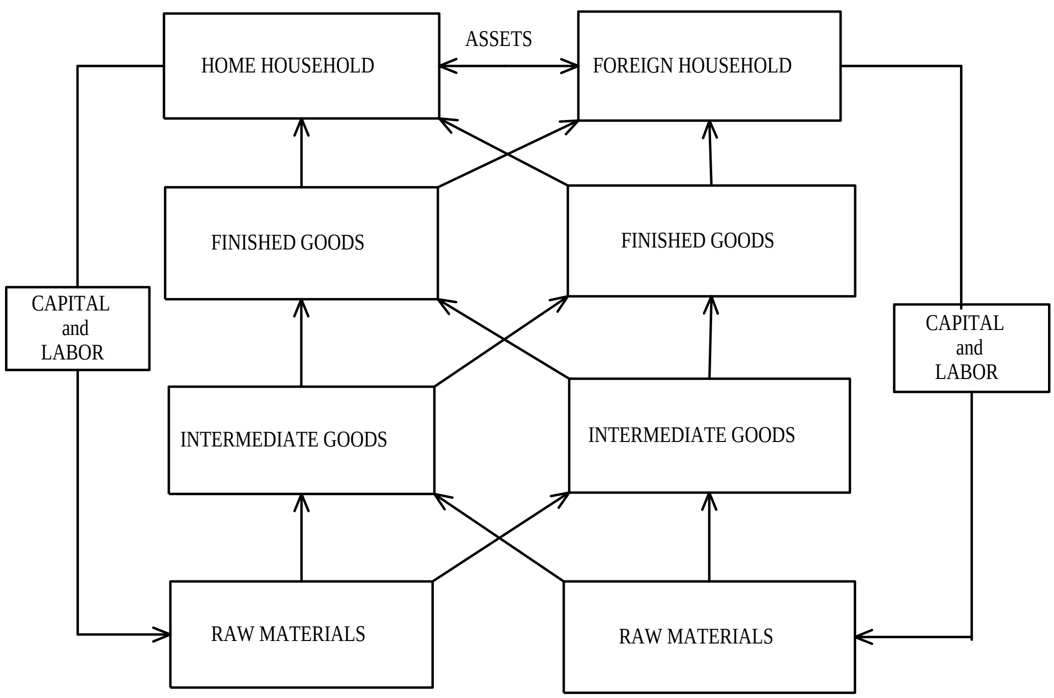

Figure I.—Chain structure of the economy

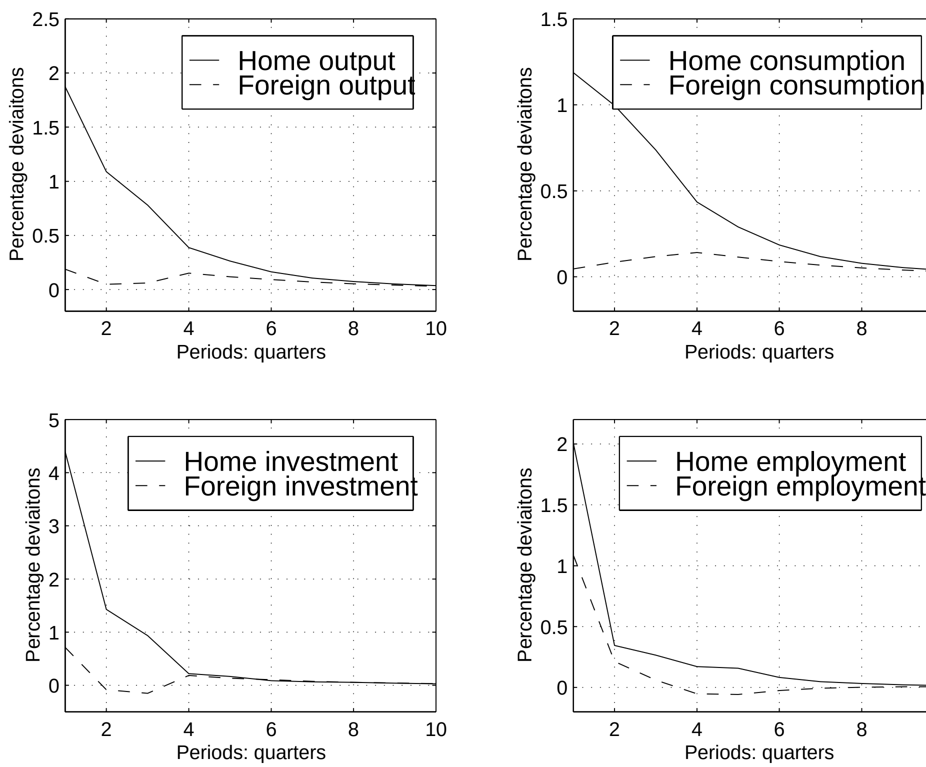

Figure II.—International comovements: the baseline economy

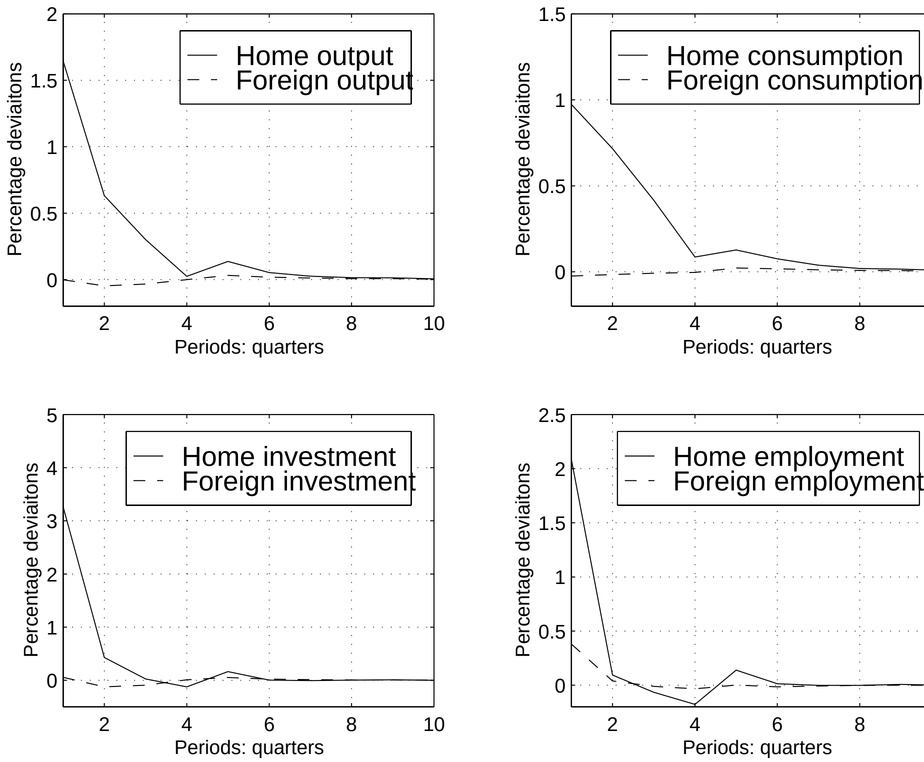

Figure III.—International comovements: the single-stage economy

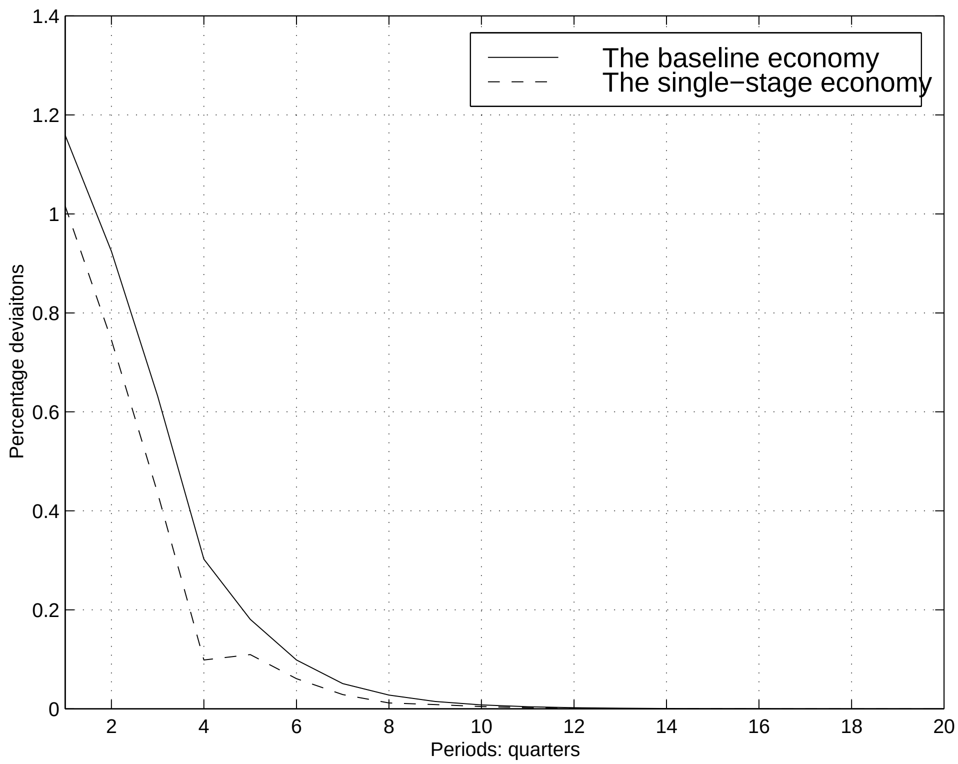

Figure IV.—Response of real exchange rates

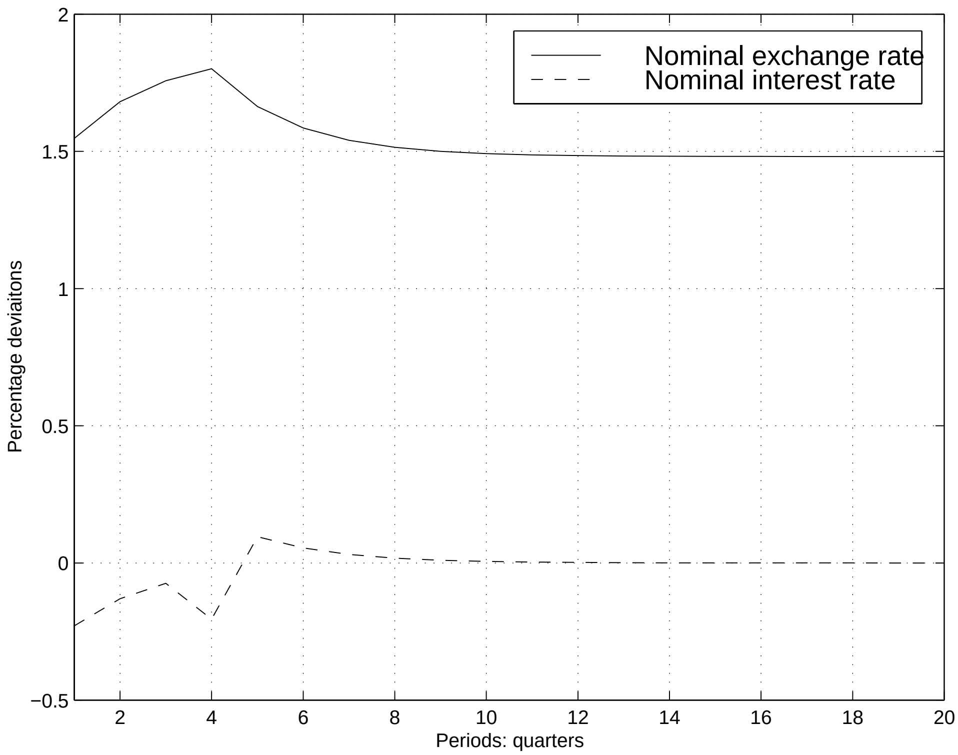

Figure V.—Nominal exchange rate and nominal interest rate:
the baseline economy