Volatile and Persistent Exchange Rates: How Important are Distribution Costs?

Yi Jin*
Department of Economics
The University of Kansas

Zhixiong Zeng†
Department of Economics
The Chinese University of Hong Kong

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Abstract

This paper studies the role played by distribution costs in shaping exchange rate behavior within a flexible price framework. We assume, realistically, that transactions on tradable goods require a component of nontradable distribution services. This naturally drives a wedge between retail prices in different countries, leading to deviations from the Law of One Price. We show that with empirically plausible size of distribution costs the model generates highly volatile nominal and real exchange rates and the comovement between real and nominal exchange rates. It is also shown that distribution costs for imported goods account for the bulk of exchange rate variations. Our model, however, is less successful in replicating the high persistence of exchange rates.

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*Department of Economics, The University of Kansas, Summerfield Hall, Lawrence, KS 66044. Tel: (785) 864-2848, Fax: (785) 864-5270, Email: yjin@ku.edu.

†Department of Economics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong. Phone: (852) 2609-8183, Fax: (852) 2603-5805, Email: zxzeng@cuhk.edu.hk.

1 Introduction

The fact that fluctuations of real exchange rates are highly volatile and persistent has been the central puzzle in international business cycles. It is also well known that nominal and real exchange rates are strongly positively correlated. These characteristics of exchange rate movements have long been a source of difficulty for theoretical modeling. In this paper we attempt to develop a quantitative dynamic general equilibrium model that is capable of replicating these salient features. Our model differs from the literature in that it is a flexible-price framework, where the key element is a distribution cost on traded goods.

Empirical studies have shown that real exchange rate movements largely reflect deviations from the Law of One Price. As Engel (1999) points out, relative prices of nontradable goods appear to account for almost none of the movements of U.S. real exchange rates. Therefore a satisfactory theory of exchange rates will have to allow for cross-country differences in the prices of traded goods. The importance of deviations from the Law of One Price has often been taken as evidence in favor of sticky price models. That is, exchange rate fluctuations are thought to result from the interaction of monetary shocks and sticky prices. A recent quantitative general equilibrium model of this story is developed by Chari, Kehoe, and McGrattan (2002). They show that if risk aversion is high and preferences are separable in leisure, then their model can account for the volatility of real exchange rates. With price-stickiness of at least one year, their model also produces real exchange rates that are quite persistent, but less so than in the data. Their results, however, rely on a process of money growth that is chosen to enable their model to generate observed output movements. As a result, the standard deviation of money growth rate in their simulation is twice as large as that in the data. Therefore, it remains unclear whether a sticky price model can generate the observed exchange rate volatility from a process of money growth that is estimated from the data. Kollmann (2001) studies an open economy model with both staggered prices and staggered wages, where the money supply process is estimated from the G7 data. In his model, although the predicted variability of the nominal and real exchange rate is noticeably higher than in standard Real Business Cycle models with flexible price and wages, they are still not high enough. The standard deviations of exchange rates in his model are only half of the actual values.

In this paper, we offer an alternative explanation for the observed exchange rate behavior in a framework of flexible prices and wages. In particular, we assume, realistically, that transactions on tradable goods require an important component of nontradable distribution services. This naturally drives a wedge between retail prices in different countries and lead to deviations from the Law of One Price. Distribution costs have often been thought of as too small to be an important determinant of the real exchange rate fluctuations. This is partly because the transportation costs associated with international trade are usually estimated to be small. However, distribution is much more than transporting goods across countries. It also includes wholesale and retail services, marketing and advertisement, and local transportation services, etc. The importance of distribution costs is emphasized in a recent paper by Burstein, Neves, and Rebelo (2003), who document that distribution costs are very large for the average consumer goods: they represent more than 40% of the retail prices of these goods in the US and roughly 60% of the retail prices in Argentina. Their study focuses on a widely studied episode, Argentina's 1991 Convertibility Plan, and show that introducing a distribution sector in an otherwise standard model of exchange-rate-based stabilizations dramatically improves its ability to rationalize observed real exchange rate dynamics.

Unlike Burstein *et al.,* who focus on the behavior of real exchange rates during a particular episode of exchange-rate-based stabilizations, in this paper we concentrate on the business cycle properties of exchange rates. We show that the performance of the model along this dimension are greatly improved with the presence of distribution costs. Due to the presence of such costs, nominal exchange rate movements are not translated into exactly offsetting movements in the cross-country price ratio, leading to fluctuations in the real exchange rate. These costs also magnify the responses of the real exchange rate to fluctuations in nontradable goods prices, as transactions on tradable goods require the usage of nontradable distribution services. We also find that when distribution costs are reasonably large, the export-import quantity ratio becomes the dominant source of fluctuations in both nominal and real exchange rates.

The volatilities and persistence of exchange rates generated by our model are remarkable. Our results are also consistent with the observed positive correlations between nominal and real exchange rates. We also find that distribution costs associated with imported goods, rather than those associated with domestically produced goods, are the dominant factor in accounting for the high volatilities of exchange rates. In addition, the model does not give rise to severe "consumption-real exchange rate anomaly": the high correlation between real exchange rates and relative consumption across countries does not result from our simulation.[1]

Within our flexible-price framework, we model the real effects of money shocks using the liquidity effect models of Lucas (1990), Fuerst (1992), and Christiano and Eichenbaum (1995). Related to our paper, Ho (1993) conducts a theoretical study of two-country economies based on the liquidity effect hypothesis. In another paper based on the similar hypothesis, Schlagenhauf and Wrase (1995) carry out a quantitative investigation of an open economy. Their model does not generate the observed volatility and persistence of real exchange rates. In our model, it turns out that the high volatility and persistence of exchange rates cannot be reproduced without the aid of distribution costs.

The rest of the paper is organized as follows. Section 2 presents stylized facts of exchange rate movements. The structure of the model is laid out in Section 3, followed by the numerical results described in Section 4. The last section offers concluding remarks.

2 Stylized Facts

In this section we review some of the salient features of exchange rate fluctuations, as a basis of comparison with theoretical economies. These properties refer to moments of Hodrick-Prescott filtered (logged) variables. Detailed information on the data sets and

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[1] This anomaly is referred to by Chari, Kehoe, and McGrattan (2002). The main discrepancy between their model and the data is that their model generates a high correlation between real exchange rates and the ratio of consumption across countries, while the data show no clear pattern between these variables.

how we construct each country's tradable and nontradable goods price index is provided in the Data Appendix.

Table 1 reports properties of exchange rates and consumer price indices (CPI) relative to the United States for 14 industrialized countries. The first three columns display, for each country, the standard deviations of nominal and real exchange rates, as well as the price ratio, which is computed by dividing one country's CPI by the US CPI. Compared to the relative price level, both nominal and real exchange rates are highly volatile, with a standard deviation of 8.52% and 8.15%, respectively. Among the 14 countries, Norway is the only one that has a standard deviation below 7%. But both its nominal and real exchange rates are still about 3.5 times more volatile than its price ratio. It is also clear that both nominal and real exchange rates for all the countries are highly persistent, with an average auto-correlation of 0.84 and 0.83, respectively. Furthermore, nominal and real exchange rates are strongly correlated with each other: the correlation is as high as 0.98. These results are consistent with existing evidence in the literature. Next, we discuss evidence on what accounts for the high volatility of real exchange rates by decomposing the real exchange rate variance into a tradable goods component and a nontradable goods component.

Suppose that the price indices in home and foreign countries are given by[2]

$$\begin{aligned} P &= \left(P^{T}\right)^{\gamma}\left(P^{NT}\right)^{1-\gamma} \\ P^{*} &= \left(P^{T*}\right)^{\gamma^{*}}\left(P^{NT*}\right)^{1-\gamma^{*}} \end{aligned}$$

where P^{T} and P^{T*} are tradable goods price indices and P^{NT} and P^{NT*} are nontradable goods price indices. Variables associated with foreign countries are indicated with an asterisk. γ and γ^{*} are the consumption shares of traded goods. The CPI-based real exchange rate (RER) is defined as

$$RER = e\frac{P^{*}}{P} = e\frac{\left(P^{T*}\right)^{\gamma^{*}}\left(P^{NT*}\right)^{1-\gamma^{*}}}{\left(P^{T}\right)^{\gamma}\left(P^{NT}\right)^{1-\gamma}},$$

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[2] A Cobb-Douglas utility function over tradable goods consumption and non-tradable goods consumption delivers this aggregate price level.

where e is the nominal exchange rate. Rewrite this expression as

$$RER = \left(e\frac{P^{T*}}{P^T}\right)\frac{\left(\frac{P^{NT*}}{P^{T*}}\right)^{1-\gamma^*}}{\left(\frac{P^{NT}}{P^T}\right)^{1-\gamma}}.$$

The first term, $\left(e\frac{P^{T*}}{P^T}\right)$, can be regarded as the tradable goods real exchange rate, which we denote by RER^T. The second term is the nontradable goods component, which is actually a *relative* relative price: it is the relative price of nontradables to tradables in one country relative to that relative price in other countries.

If we define q and q^* as the relative price of nontradables to tradables in the two countries, then we have

$$\log(RER) = \log\left(RER^T\right) + \log(Q),$$

where $Q = \frac{(q^*)^{1-\gamma^*}}{(q)^{1-\gamma}}$. We shall succinctly refer to Q as the "nontradable goods relative price". Thus movements in real exchange rates can arise from two sources: deviation from the law of one price for traded goods across countries and movements in the relative prices of nontraded to traded goods across countries. The variance of the real exchange rate can be decomposed as

$$\begin{aligned} var\left[\log(RER)\right] &= var\left[\log\left(RER^T\right)\right] + var(\log Q) \\ &\quad +2cov\left[\log\left(RER^T\right), \log Q\right]. \end{aligned}$$

Table 2 provides the variance decomposition for 6 countries: Belgium, France, Germany, Italy, Japan, and Norway. It is obvious that $var(\log Q)$ is very small compared to $var\left[\log(RER)\right]$. The variance of nontradable goods relative prices has little contribution to the high volatility of real exchange rates. Movements in tradable goods prices account for most of the fluctuations of all-goods real exchange rate. This result is consistent with empirical evidence obtained by Engel (1999) and others.[3]

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[3] For example, Engel (1999) studies the variance decomposition using five different measures of nontraded-goods price and real exchange rates at all possible horizons (from one month to 30 years). He found that relative prices of nontraded goods appear to account for almost none of the movement of U.S. real exchange rates. Chari, Kehoe, and McGrattan also show that the maximum portion of the variance of the real exchange rate attributable to variability in the nontraded goods relative price is only about 2%.

3 The Model

There are two countries in the hypothetical world — the home country and the foreign country. Broadly speaking, each country has three types of agents: households, firms and financial intermediaries. Households own the firms and financial intermediaries in their own country. Firms are allocated to four sectors: tradable goods producing sector, nontradable goods producing sector, distribution service sector, and final goods producing sector. The structures of these two national economies are symmetric, so that it suffices to describe agents and their activities in the home country. We indicate variables associated with the foreign country with an asterisk. In this section we present the optimization problems for households, firms, and financial intermediaries. Competitive equilibrium of the model economy is then defined.

3.1 Households

We consider a representative household, who ranks alternative stream of consumption and leisure according to the following criterion function

$$E_0 \sum_{t=0}^{\infty} \beta^t U\left[g\left(C_t^T, C_t^{NT}\right), 1 - L_t - H_t\right] \tag{1}$$

where E_0 is the expectation operator conditional on time 0 information, $\beta \in (0,1)$ is the subjective discount factor, L_t is hours worked supplied to the labor market in period t, and H_t is time spent in adjusting portfolio. The time endowment is normalized to unity. We use C_t^T and C_t^{NT} to denote the tradable and nontradable components of consumption, respectively. They are aggregated via a CES function $g(\cdot,\cdot)$. As will be discussed later, tradable consumption is in final goods, which itself results from aggregation of home and foreign produced tradable (intermediate) goods. The household is also engaged in the accumulation of physical capital. In period t the household purchases final goods in the amount I_t for investment purpose so that its capital stock evolves according to

$$K_{t+1} = (1-\delta) K_t + \Phi\left(\frac{I_t}{K_t}\right) K_t. \tag{2}$$

where δ is the rate of depreciation for capital. The function for gross capital formation per unit of existing capital stock, $\Phi\left(\cdot\right)$, is a strictly increasing function of the investment-capital ratio, with $\Phi\left(0\right) = 0$. If $\Phi\left(\cdot\right)$ is linear, then there is a constant rate of transformation from investment to capital formation. In contrast, if $\Phi\left(\cdot\right)$ is a concave function, then the transformation rate declines as investment increases. This corresponds to an adjustment cost for investment.

In addition to saving in physical capital, the household can also save by investing in financial assets. Let M_{ht} and M_{ft} denote the household's holdings of home currency (in home currency units) and foreign currency (in foreign currency units), respectively, at the beginning of period t. Define $M_t = M_{ht} + e_t M_{ft}$ as the household's total nominal wealth, where e_t is the nominal exchange rate expressed in units of home currency per unit of foreign currency. At the beginning of period t, the household allocates M_t to nominal savings S_t and cash balance N_t for transaction purposes in goods markets, with $M_t = S_t + N_t$. Following Christiano and Eichenbaum (1992), we assume that the household makes its portfolio decision (S_t, N_t) before observing the period t money shocks. Furthermore, in every period, the household spends some time in adjusting portfolio, with the needed time given by $H_t = H^h\left(S_{ht}, M_{ht}\right) + H^f\left(S_{ft}, M_{ft}\right) + J\left(S_{ft}, S_{ht}\right)$. The functions H^h represents costs associated with adjusting the allocation of home money balance to financial market (S_{ht}) and goods market $(M_{ht} - S_{ht})$. As is common in the liquidity effect literature, this term allows the model to generate a persistent liquidity effect for a money shock. The function H^f is a straightforward extension of the adjustment cost formulation to the open economy setting. It represents costs arising from changing the allocation of foreign currency holdings to financial markets (S_{ft}) and goods market ($M_{ft} - S_{ft}$ is exchanged into home currency at exchange rate e_t and goes to home country goods market). The function J is a novel feature of our model. It represents costs of changing the relative amount of home currency and foreign savings. Namely, disproportionately increasing savings in one of the two instruments entails some sacrificed leisure time. We refer to this term as "international portfolio adjustment cost". As will be demonstrated in the quantitative assessment of the model, the presence of this adjustment cost is important in resolving the "consumption-real exchange rate anomaly": it help lower the correlation between real exchange rate and relative consumption across countries effectively.

We assume that all goods purchases are subject to a cash-in-advance (CIA) constraint. Let P_t^{NT} denote the price of home produced nontradables, P_t^T denote the price of home country final goods, both in units of home currency. The CIA constraint is[4]

$$P_t^T\left(C_t^T + I_t\right) + P_t^{NT} C_t^{NT} \leq M_t - S_t \tag{3}$$

The household might allocate its savings S_t to both home and foreign financial markets. Denote the amount allocated to home and foreign financial markets by $S_{h,t}$ (in home currency units) and $S_{f,t}$ (in foreign currency units) respectively. We have $S_t = S_{ht} + e_t S_{ft}$. These savings yield $R_t S_{ht}$ and $R_t^* S_{ft}$ respectively at the end of period t, where R_t and R_t^* are the gross nominal interest rates prevalent in the home and foreign financial markets respectively. Within the period the household also receives wage income $W_t L_t$, rental income $V_t K_t$, and dividend payment Π_t from home country firms and financial intermediaries. It then carries these income as well as any unspent cash in the goods markets into the next period. Thus the household's holdings of home and foreign currency evolves according to

$$M_{h,t+1} = \left[M_t - S_t - P_t^T\left(C_t^T + I_t\right) - P_t^{NT} C_t^{NT}\right] + W_t L_t + V_t K_t + R_t S_{h,t} + \Pi_t \tag{4}$$

and

$$M_{f,t+1} = R_t^* S_{f,t} \tag{5}$$

where the bracketed term in (4) is the unspent cash when goods markets close.

Note that only risk-free claims are available in the model economy. That is, there do not exist complete contingent claim markets. Our departure from the complete market

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[4] Another way to look at the CIA constraint (3) is to write the right-hand side as $M_{ht} - e_t\left(S_{ft} - M_{ft}\right) - S_{ht}$, where $\left(S_{ft} - M_{ft}\right)$ is the intra-period adjustment of the household's foreign currency position. When the adjustment is upward, the household needs to exchange home currency in the amount $e_t\left(S_{ft} - M_{ft}\right)$ into foreign currency. When the adjustment is downward, the reduced amount of foreign currency is exchanged into home currency and adds to the household's holdings of home currency. The household then decides on the allocation of the resultant home currency holdings into domestic goods market and financial market.

setup is motivated by the observation that real exchange rates will be perfectly correlated with relative consumption across countries in such environments while these two variables show no clear correlation pattern in the data. Chari et al. refers to this observation as the "consumption-real exchange rate anomaly" (see their paper for a derivation of the perfect correlation in the complete market setup). To eliminate the perfect correlation between real exchange rates and relative consumption, some deviation from the complete contingent claim construct must be adopted.

The representative household's problem is then to maximize its discounted lifetime utility (1) subject to the cash-in-advance constraint (3), the wealth evolutions (4)-(5), the capital evolution (2), and the restrictions that $M_t = M_{ht} + e_t M_{ft}$ and $S_t = S_{ht} + e_t S_{ft}$, by choosing a sequence $\{C_t^T,\ C_t^{NT},\ I_t,\ L_t,\ S_{ht},\ S_{ft},\ M_{h,t+1},\ M_{f,t+1},\ K_{t+1}\}_{t=0}^{\infty}$. Let $\beta^t \lambda_t$, $\beta^t \mu_t$, $\beta^t \gamma_t$, and $\beta^t \eta_t$ be the Lagrangian multipliers associated with (3), (4), (5), and (2), respectively. The first order conditions with respect to C_t^T, C_t^{NT}, L_t, $M_{h,t+1}$, $M_{f,t+1}$, S_{ht}, S_{ft}, K_{t+1}, I_t are respectively

$$\begin{aligned} U_{1t} g_{1t} &= (\lambda_t + \mu_t) P_t^T \\ U_{1t} g_{2t} &= (\lambda_t + \mu_t) P_t^{NT} \\ U_{2t} &= \mu_t W_t \end{aligned}$$

$$\mu_t = E_t \left\{ \beta \left(\lambda_{t+1} + \mu_{t+1} \right) - \beta U_{2,t+1} H_{1,t+1}^h \right\}$$

$$\gamma_t = E_t \left\{ \beta \left(\lambda_{t+1} + \mu_{t+1} \right) e_{t+1} - \beta U_{2,t+1} H_{1,t+1}^f \right\}$$

$$E_{t-1} \left\{ \mu_t R_t - (\lambda_t + \mu_t) - U_{2t} \left(H_{1t}^h + J_{2t} \right) \right\} = 0$$

$$E_{t-1} \left\{ \gamma_t R_t^* - (\lambda_t + \mu_t) e_t - U_{2t} \left(H_{1t}^f + J_{1t} \right) \right\} = 0$$

$$E_t \eta_t = \beta E_t \left\{ \mu_{t+1} r_{t+1} + \eta_{t+1} \left[1 - \delta + \Phi \left(\frac{I_{t+1}}{K_{t+1}} \right) (1 - \omega) \right] \right\}$$

$$(\lambda_t + \mu_t) P_t^T = \eta_t \Phi' \left(\frac{I_t}{K_t} \right)$$

Here $U_{i,t}$, $i = 1, 2$, is the partial derivative of $U(\cdot)$ with respect to its i-th argument evaluated at period-t allocations. $g_{i,t}$, J_{it}, and $H_{i,t}^j$, $j = h, f$, $i = 1, 2$, are similarly defined. In addition, ω is the elasticity of the function Φ with respect to investment-capital ratio, which under the functional form we are going to adopt is constant. Note that the expectation operators relevant for the savings first order conditions are conditional on period $t-1$ information.

To arrive at an explicit formula for the consumption price index (CPI), we assume that the utility function exhibits constant elasticity of substitution (CES) between tradable consumption and nontradable consumption:

$$g\left(C_t^T, C_t^{NT}\right) = \left[\gamma\left(C_t^T\right)^{\mu} + (1-\gamma)\left(C_t^{NT}\right)^{\mu}\right]^{\frac{1}{\mu}} \tag{6}$$

With this functional form the CPI, denoted by P_t, turns out to be a CES aggregate of P_t^T and P_t^{NT}:

$$P_t = \left[(\gamma)^{\frac{1}{1-\mu}}\left(P_t^T\right)^{\frac{\mu}{\mu-1}} + (1-\gamma)^{\frac{1}{1-\mu}}\left(P_t^{NT}\right)^{\frac{\mu}{\mu-1}}\right]^{\frac{\mu-1}{\mu}} \tag{7}$$

3.2 Firms

There are four types of producers in each country, including tradable goods producers, nontradable goods producers, distributors, and final goods producers. The tradable goods are regarded as intermediate goods. The final goods producers combine home and foreign produced tradables to generate a homogeneous final goods that can be used for domestic consumption and investment.

3.2.1 Intermediate Goods Producers

Firms in the tradable goods and nontradable goods sectors operate a constant returns-to-scale technology which transforms labor and capital input into tradable or nontradable goods according to the production function

$$Y_t^j = F\left(K_t^j, L_t^j, z_t\right), \qquad j = T, NT$$

where z_t is the period-t aggregate productivity, K_t, L_t, and Y_t are capital input, labor input, and output within the same period. The superscript "T" and "NT" are used to indicate the tradable goods and nontradable goods sector, respectively. The function $F(\cdot)$

is linearly homogeneous, increasing, and strictly concave in capital and labor. Nontradable goods are sold in a competitive domestic market at nominal price P_t^{NT}. Tradable goods are sold in a competitive world market at nominal price $\overline{P}_t^T$, which is denoted in units of home currency. Expressed in foreign currency units, the price is simply $\overline{P}_t^T/e_t$. Thus the Law of One Price holds at the producer price level.[5]

Firms hire labor from the competitive domestic labor market at nominal wage rate W_t. We assume that firms need to borrow domestic currency from financial intermediaries (banks) to finance their working capital at a gross nominal interest rate R_t. In line with Christiano and Eichenbaum (1992), the working capital is composed of wage bills, based on the assumption that wage bills have to be paid in advance of production. Given the portfolio adjustment costs, an expansionary monetary shock will cause firms to absorb a disproportionately large share of liquidity. The nominal interest rate must go down for firms to do so voluntarily.

Firms also rent capital from households at nominal rental rate V_t. For convenience, we allow firms to pay capital rental after production.

The profit of a representative firm in sector j is given by

$$\Pi_t^j = \overline{P}_t^j Y_t^j - R_t W_t L_t^j - V_t K_t^j, \qquad\qquad j = T, NT$$

and is distributed entirely as dividends to households. Profit maximization yields the following first order conditions

$$\begin{aligned} \overline{P}_t^j F_L\left(z_t, K_t^j, L_t^j\right) &= R_t W_t && (8) \\ \overline{P}_t^j F_K\left(z_t, K_t^j, L_t^j\right) &= V_t && (9) \end{aligned}$$

where F_K and F_L are the partial derivatives of $F(\cdot)$ with respect to K and L, respectively. Equations (8) states that firms equate marginal revenue product of labor to its marginal cost. Since firms need to borrow to finance wage bills, the marginal cost of labor is the wage rate W_t times the interest rate R_t.

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[5] Likewise, foreign produced tradables are sold in the competitive world market at nominal price $\overline{P}_t^{T*}$, which is denoted in units of foreign currency. Expressed in home currency units, the price is $e_t\overline{P}_t^{T*}$.

3.2.2 Distributors

Distribution services are necessary for intermediate goods to reach the final aggregation process. In particular, the usage of one unit of home (foreign) produced tradable goods requires $\phi\ \left(\widetilde{\phi}\right)$ units of domestic distribution services. We assume, as in Burstein, Neves, and Rebelo (2001), that the representative distributor transforms home produced nontradable goods to distribution services on a one-for-one basis. This formulation reflects the notion that distribution services are nontradables and that the production of distribution services requires local resources, just like the production of other nontradables.

Importantly, the presence of distribution costs create a wedge between the producer prices and the retail prices. Denote by P_{ht}^{T} and P_{ft}^{T} the retail prices of home and foreign produced tradables that are used in the home country, respectively, both specified in units of home currency. The distributor purchases home produced tradables at price $\overline{P}_{t}^{T}$ and incur distribution costs ϕP_{t}^{NT} for each unit purchased. It also purchases foreign produced tradables at foreign-currency price $\overline{P}_{t}^{T*}$, and incur distribution costs $\widetilde{\phi} P_{t}^{NT}$ per unit purchased. Via the distribution process, these goods are then sold to domestic aggregators at retail prices P_{ht}^{T} and P_{ft}^{T}. For competitive distributors to obtain bounded profits, the following relationships between retail prices and producer prices must hold.

$$\begin{aligned} P_{ht}^{T} &= \overline{P}_{t}^{T} + \phi P_{t}^{NT}, \\ P_{ft}^{T} &= e_t \overline{P}_{t}^{T*} + \widetilde{\phi} P_{t}^{NT}. \end{aligned}$$

3.2.3 Final Goods Producers

Our sole purpose of introducing final goods producers is to provide a way to aggregate home and foreign produced tradables into a homogeneous good that can be used for consumption and investment. The representative final goods producer purchases from distributors home produced tradables in the amount Y_{ht} at retail price P_{ht}^{T} and foreign produced tradables in the amount Y_{ft} at retail price P_{ft}^{T}. These goods are then aggregated according to the linearly homogeneous function $G\left(Y_{ht}, Y_{ft}\right)$ and sold to domestic households at price P_{t}^{T}.

The aggregator maximizes profit by solving the following problem.

$$\max_{Y_{ht},Y_{ft}} P_t^T G\left(Y_{ht}, Y_{ft}\right) - P_{ht}^T Y_{ht} - P_{ft}^T Y_{ft}$$

The first order conditions are

$$\begin{aligned} P_t^T G_1\left(Y_{ht}, Y_{ft}\right) &= P_{ht}^T \\ P_t^T G_2\left(Y_{ht}, Y_{ft}\right) &= P_{ft}^T \end{aligned}$$

To arrive at an explicit formula for the retail price index for tradables P_t^T, we assume that the aggregator function takes the constant elasticity of substitution (CES) form:

$$G\left(Y_{ht}, Y_{ft}\right) = \left[\psi Y_{ht}^{\theta} + (1-\psi) Y_{ft}^{\theta}\right]^{\frac{1}{\theta}} \tag{10}$$

With this functional form P_t^T turns out to be a CES aggregator of the retail prices of home and foreign tradables.

$$P_t^T = \left[(\psi)^{\frac{1}{1-\theta}} \left(P_{ht}^T\right)^{\frac{\theta}{\theta-1}} + (1-\psi)^{\frac{1}{1-\theta}} \left(P_{ft}^T\right)^{\frac{\theta}{\theta-1}}\right]^{\frac{\theta-1}{\theta}} \tag{11}$$

3.3 Financial Intermediaries

Financial intermediaries channel funds from households to firms. In each period there are three sources of funds for home country financial intermediaries: (1) home country households' nominal savings $S_{h,t}$, (2) foreign country households' nominal savings $S_{h,t}^*$ (also in home country currency), and (3) money injection X_t from the home country central bank. Let M_t^s denote the beginning-of-period-t aggregate money supply of the home country. Then $X_t = M_{t+1}^s - M_t^s$. The intermediaries are obligated to repay these deposits at gross nominal interest rate R_t. All of the funds are then lent to domestic firms, the total amount of bank lending being $S_{h,t} + S_{h,t}^* + X_t$. For the financial intermediaries' profits to be bounded, the lending rate of interest must equal R_t.

At the end of period t, intermediaries receive repayment $R_t(S_{h,t}+ S_{h,t}^* +X_t)$ from firms, and pay $R_t S_{h,t}$ and $R_t S_{h,t}^*$ to home and foreign depositors, respectively. The profit of the representative financial intermediary is thus $\Pi_t^F = R_t X_t$. This is distributed as dividends to home country households at the end of the period t. Financial intermediaries in the foreign country adopts a similar operation.

3.4 Shock Processes

We use $x_t \equiv X_t/M_t$ and $x_t^* \equiv X_t^*/M_t^*$ to denote the growth rate of money supply in the home and foreign country, respectively, and assume that x_t and x_t^* jointly follow a bivariate $AR(1)$ process, which is given by

$$\begin{bmatrix} x_t \\ x_t^* \end{bmatrix} = A_x \begin{bmatrix} x_{t-1} \\ x_{t-1}^* \end{bmatrix} + \begin{bmatrix} \varepsilon_{x,t} \\ \varepsilon_{x,t}^* \end{bmatrix},$$

where A_x is a 2×2 coefficient matrix, and $\begin{bmatrix} \varepsilon_{x,t} & \varepsilon_{x,t}^* \end{bmatrix}'$ is a serially uncorrelated shock process with the variance-covariance matrix Ω_x.

The country-specific productivities also follow a bivariate $AR(1)$ process:

$$\begin{bmatrix} z_t \\ z_t^* \end{bmatrix} = A_z \begin{bmatrix} z_{t-1} \\ z_{t-1}^* \end{bmatrix} + \begin{bmatrix} \varepsilon_{z,t} \\ \varepsilon_{z,t}^* \end{bmatrix},$$

where A_z is a 2×2 matrix, and $\begin{bmatrix} \varepsilon_{z,t} & \varepsilon_{z,t}^* \end{bmatrix}'$ is a serially uncorrelated shock process with the variance-covariance matrix Ω_z.

3.5 Equilibrium

A competitive equilibrium of the world economy is defined as a sequence of allocation $\{Y_{ht}$, Y_{ft}, C_t^{NT},C_t^T, I_t, L_t, $S_{h,t}$, $S_{f,t}$, L_t^T, L_t^{NT}, K_t^T, K_t^{NT}, K_{t+1}, Y_{ft}^*, Y_{ht}^*, C_t^{NT*},C_t^{T*}, I_t^*, L_t^*, S_{ft}^*, S_{ht}^*, L_t^{T*}, L_t^{NT*}, K_t^{T*}, K_t^{NT*}, $K_{t+1}^*\}_{t=0}^{\infty}$ and a sequence of prices $\{\overline{P}_t^T$, P_{ht}^T, P_{ft}^T, P_t^T, P_t^{NT}, P_t, W_t, R_t, $\overline{P}_t^{T*}$, P_{ht}^{T*}, P_{ft}^{T*}, P_t^{NT*}, P_t^*, W_t^*, R_t^*, $e_t\}_{t=0}^{\infty}$, such that given the prices, the allocation solves the maximization problems of households, all types of producers, and financial intermediaries in each country, and the following market clearing conditions are satisfied for all t.

Labor market clearing conditions in the two countries are given by

$$\begin{aligned} L_t^T + L_t^{NT} &= L_t, \\ L_t^{T*} + L_t^{NT*} &= L_t^*. \end{aligned}$$

The markets for tradable (intermediate) goods clear when

$$\begin{aligned} Y_{h,t} + Y_{h,t}^* &= Y_t^T \\ Y_{ft}^* + Y_{ft} &= Y_t^{T*} \end{aligned}$$

In each country, nontradables are used up as consumption goods and as inputs to distribution service production. Thus nontradable goods markets clear when

$$\begin{aligned}
\phi Y_{ht} + \widetilde{\phi} Y_{ft} + C_t^{NT} &= Y_t^{NT} \\
\phi^* Y_{ft}^* + \widetilde{\phi}^* Y_{ht}^* + C_t^{NT*} &= Y_t^{NT*}
\end{aligned}$$

The final goods market clearing conditions are

$$\begin{aligned}
C_t^T + I_t &= G\left(Y_{ht}, Y_{ft}\right) \\
C_t^{T*} + I_t^* &= G\left(Y_{ft}^*, Y_{ht}^*\right)
\end{aligned}$$

The loan market clearing conditions are given by

$$\begin{aligned}
S_{h,t} + S_{h,t}^* + X_t &= W_t L_t, \\
S_{f,t}^* + S_{f,t} + X_t^* &= W_t^* L_t^*.
\end{aligned}$$

The demand for loans, which consists of firms' wage bills, equals the supply of loanable funds, which consists of nominal savings of households in both countries and money injection from the central banks.

The money market clearing conditions are

$$\begin{aligned}
M_t^s &= M_{ht} + M_{ht}^* \\
M_t^{s*} &= M_{ft}^* + M_{ft}
\end{aligned}$$

Lastly, the foreign exchange market clearing condition is

$$e_t \overline{P}_t^{T*} Y_{ft} + e_t \left(S_{ft} - M_{ft}\right) = \overline{P}_t^T Y_{ht}^* + \left(S_{ht}^* - M_{ht}^*\right) \tag{12}$$

The foreign exchange market opens at the beginning of each period. The demand for foreign currency, denoted in units of home currency, consists of two parts. The first part is home country distributors' purchase of foreign produced tradables $e_t \overline{P}_t^{T*} Y_{ft}$, and the second part is home country households' adjustment of foreign currency holdings in the beginning of period t, $e_t \left(S_{ft} - M_{ft}\right)$.

The demand for home currency, also denoted in units of home currency, includes foreign country distributors' purchase of home produced tradables $\overline{P}_t^T Y_{ht}^*$, and foreign country households' adjustment of holdings of home country currency in the beginning of period t, $S_{ht}^* - M_{ht}^*$. Thus, the beginning-of-period foreign exchange market clears when holds (12), that is, the home demand for foreign currency equals the foreign demand for home currency, both measured in units of home currency.

The real exchange rate is defined as

$$RER_t = e_t \frac{P_t^*}{P_t}.$$

4 Quantitative Assessment

We now turn to a quantitative assessment of the model laid out in the previous section. To ensure the existence of a steady state, we adopt the normalization by dividing each country's nominal variables by the money stock in that country. Lowercase letters are then used to represent the normalized variables. In interpreting the simulation results, we emphasize the role played by distribution costs in replicating the cyclical properties of exchange rates.

Two distinguishing features of our results stand out. First, money shocks generate large volatility for real exchange rates despite that prices are perfectly flexible in our model. Second, productivity shocks generate significant volatilities of both nominal and real exchange rates, a feature absent in the literature. These will be explained in our discussion of results.

4.1 Calibration

We parameterize the model economy following standard practices in the business cycle literature. A period in the model corresponds to a quarter. The two countries are entirely symmetric so that all parameters have the same values for both countries. The utility function takes the following form

$$
\begin{aligned}
U\left(C^T, C^{NT}, 1-L-H\right) &= \log\left\{\left[\gamma\left(C^T\right)^{\mu} + (1-\gamma)\left(C^{NT}\right)^{\mu}\right]^{\frac{1}{\mu}}\right\} \\
&\quad +\nu\left(1-L-H\right).
\end{aligned}
$$

We follow Hansen (1985) to assume that utility is linear in leisure. The constant ν in the utility function is chosen to ensure that the steady state level of hours worked is 1/3. The discount factor β is set to be 0.99, implying a 4% annual real rate of interest. We choose μ such that the elasticity of substitution between C^T and C^{NT} equals 0.44, the value that Stockman and Tesar (1995) obtained from their estimation. The share parameter of C^T in aggregate consumption, γ, is set to 0.7.

The Armington aggregator for final goods production take the forms:

$$
G\left(Y_h, Y_f\right) = \left[\psi Y_h^{\theta} + (1-\psi)\, Y_f^{\theta}\right]^{\frac{1}{\theta}}
$$

The elasticity of substitution between domestically and foreign produced tradables, $\frac{1}{1-\theta}$, is set to 1.5, as in Backus, Kehoe, and Kydland (1995). The share parameter ψ is set such that the steady-state ratio of imports to GDP equals 0.15.

The production functions are assumed to be Cobb-Douglas:

$$
\begin{aligned}
F\left(, K^T, L^T, z\right) &= \exp(z)\left(K^T\right)^{\alpha}\left(L^T\right)^{1-\alpha}, \\
F\left(K^{NT}, L^{NT}, z\right) &= \exp(z)\left(K^{NT}\right)^{\alpha}\left(L^{NT}\right)^{1-\alpha}.
\end{aligned}
$$

The share of capital income, α, is 0.36. The capital depreciation rate, δ, is chosen to be 0.02. In the benchmark model, we set the unit distribution cost $\phi = \widetilde{\phi} = \phi^* = \widetilde{\phi}^*$ to be 1.13. This corresponds to a distribution margin of about 53%. The distribution margin is defined as the excess of retail price over producer price, measured as percentages of the retail price. Burstein *et al.* reports that the distribution margin is about 60% for Argentina and 46% for the U.S. data. For our benchmark specification we take the average which is 53%.

The portfolio adjustment cost functions H^h and H^f take a simple quadratic form:

$$
H_t^j = a\left[\frac{\left(M_{jt} - S_{jt}\right)/M_{jt}}{\left(M_j - S_j\right)/M_j} - 1\right]^2, \quad j = h, f,
$$

where $(M_j - S_j)/M_j$ is the steady state value of $(M_{jt} - S_{jt})/M_{jt}$. There is little guidance for setting the value of the scale parameter a. In our benchmark specification we set $a = 10$. At this value we are not able to generate the persistence of exchange rates observed in the data. Unfortunately, further increasing the value for a does not help generate more persistence of exchange rates. That is, beyond a certain range, the persistence of exchange rates is robust against the value of a.

The "international portfolio adjustment cost" function is also quadratic:

$$J_t = \kappa \left(\frac{e_t S_{ft}/S_{ht}}{e S_f/S_h} - 1 \right)^2 ,$$

where eS_f/S_h is the steady state value of $e_t S_{ft}/S_{ht}$. Again, there is little guidance for the choice of the value for the scale parameter κ. And, this value turns out to be important for exchange rate volatilities and the correlation between real exchange rate and cross-country consumption ratio. In our benchmark specification, we set $\kappa = 0.01$. We then perform sensitivity analysis by varying the value of κ.

We assume that the function for gross capital formation per unit of outstanding capital stock is given by

$$\Phi\left(\frac{I}{K}\right) = \xi \left(\frac{I}{K}\right)^{\omega}, \quad 0 < \omega \leq 1.$$

Following a strategy adopted by Bernanke, Gertler, and Gilchrist (1999), we normalize the function $\Phi(\cdot)$ so that $1/\Phi'$ is unity in the nonstochastic steady state. Note that $1 - \omega$ represents the elasticity of the price of capital with respect to the investment-capital ratio. There is no firm consensus in the literature about what this parameter value should be. In the benchmark case we set $\omega = 1$ which corresponds to the situation of no capital adjustment costs. The coefficient ξ can be determined given the value of ω and the normalization that $1/\Phi'$ is unity in the steady state.

Following Backus *et al.*, we set the autocorrelation matrix of the bivariate process of country-specific technology shocks to be

$$A_z = \begin{pmatrix} 0.906 & 0.088 \\ 0.088 & 0.906 \end{pmatrix}.$$

The standard deviations of the innovations $\varepsilon_{z,t}$ and $\varepsilon^*_{z,t}$ are set to 0.00852 for both countries. The correlation between these innovations is 0.258.

We estimate the stochastic process of money growth using data on the 14 countries listed in Table 1, except Switzerland. We follow a three-step procedure. First, for each of the non-US countries, we form a pair of the country in question with the US. We then fit a bivariate $AR(1)$ on the country-specific money growth rates for each pair of countries to obtain pairwise parameters. Second, we take the mean of these pairwise parameters to obtain an average bivariate $AR(1)$ process. Finally, we symmetrize this bivariate process by taking averages. In the first step, we find that there does not exist a systematic pattern for the cross-country correlation of money growth shocks, with the correlation ranging from -0.15 to 0.08. The average of these cross-country correlations turn out to be close to zero (-0.02). Based on these findings, we set the cross-country correlation of shocks to be zero in our simulation. In the final process that we obtain, the autocorrelation matrix is

$$A_x = \begin{pmatrix} 0.5 & 0.067 \\ 0.067 & 0.5 \end{pmatrix}.$$

The unconditional mean of money growth rate is about 0.016. The standard deviation of both $\varepsilon_{x,t}$ and $\varepsilon^*_{x,t}$ is about 0.015.

4.2 Results

We report the simulation results in Table 3 – 5. Entries in the tables are averages over 100 simulations of length 300 with the first 200 observations truncated, along with standard deviations of these simulations in parentheses. Column (1) in Table 3a presents statistics on exchange rates, price ratios, and cross-country correlations obtained from the data. The cross-country correlations, as well as the correlation of real exchange rate and relative consumption are taken from Chari *et al.*. Other statistics are based on our calculation.

4.2.1 Benchmark Model

Column (2) in Table 3a pertains to the benchmark model with the presence of distribution costs. In particular, $\phi = \widetilde{\phi} = \phi^* = \widetilde{\phi}^* = 1.13$, implying a distribution margin of 53% for both domestically produced goods and imported goods.

The results indicate that our model is quite successful in reproducing the volatilities of exchange rates observed in the data, but not as successful in generating the observed persistence. The model also generates high contemporaneous correlation between nominal and real exchange rates. The standard deviations for nominal and real exchange rates are about 8.52% and 8.15%, respectively, in the data. The corresponding statistics are 9.28% and 6.48%, respectively, in our benchmark model. The model produces autocorrelations for nominal and real exchange rates of 0.53 and 0.40 respectively. Their empirical counterparts are 0.84 and 0.83. Furthermore, the correlation between nominal and real exchange rates generated by the model is 0.90 while in the data this correlation is 0.98. Thus our model is consistent with the comovement of nominal and real exchange rates.

As for the price ratio, the benchmark model produces a standard deviation of 4.49%, which is larger than its empirical counterpart — a value of 1.70%. This is not surprising given that prices in our model have no stickiness. The price ratio's autocorrelation is about 0.83 in the model, while in the data this statistic is about 0.88.

In our benchmark model, the correlation between real exchange rate and the cross-country consumption ratio is about 0.76. This value is closer to the data as compared to the perfect correlation obtained by Chari *et al* (2001). They refer to the discrepancy between their model and the data in terms of the exchange rate-consumption ratio correlation as the "consumption-real exchange rate anomaly" (The data show no clear comovement pattern between these two variables).

Our model generates positive cross-country correlations for output, investment, and consumption. Employment, however, turns out to exhibit little cross-country comovement in the model. It is well know that the series of output, employment, investment, and consumption are all positively correlated across countries. The original international real business cycle model (Backus et al. 1995) is inconsistent with this fact. Such inconsistency is known as the "international comovement puzzle". This is partially resolved in our model.

As there are two types of shocks in the model economy, namely, money shocks and productivity shocks, it is interesting to look at the roles played by each type of shock separately. This is accomplished by subjecting the world economy to only money shocks or productivity shocks once at a time and simulating the model accordingly. The results for money shocks are displayed in Table 3b while those for productivity shocks are presented in Table 3c.

In our model money shocks generate large volatilities of exchange rates and high correlation between nominal and real exchange rates. The standard deviations for nominal and real exchange rates are about 8.23% and 5.20% respectively when the world economy is disturbed by money shocks only. Their contemporaneous correlation takes the value of 0.87. The persistence of nominal and real exchange rates, however, appear to be low compared to the data. Their autocorrelations are 0.52 and 0.30 respectively. In addition, the correlation between real exchange rate and relative consumption is 0.66.

Note that these high exchange rate volatilities are obtained within a flexible-price framework. The literature has found that real exchange rate volatility is very small when prices are flexible (see, for example, Kollman 2001). In contrast, we generate large volatility for real exchange rates by simply adding a distribution sector into a flexible-price model. The contrast between our results and those of the literature stems from the difference in mechanisms that are used to generate deviations from the Law of One Price. In conventional views, the large volatility of real exchange rates is the result of the interplay between money shocks and sticky prices: Money shocks generate highly volatile nominal exchange rates. Price stickiness the lead to low pass through from changes in nominal exchange rates to consumer prices and allow nominal exchange rate volatility to be translated into real exchange rate volatility. Without price stickiness, real exchange rates remain to be smooth series. To the contrary, distribution costs are sufficient to generate low exchange rate pass through so that price stickiness is not a necessary condition for the model to generate high real exchange rate volatility. Quantitatively, a distribution margin of 53% turns out to imply exchange rate volatilities that are quite large.

When the economy is subject to productivity shocks only, nominal and real exchange rates exhibit perfect correlation and both series are volatile to some extent, with standard deviations of 3.76% and 3.51% respectively. These exchange rate series are also quite persistent, both autocorrelations being 0.62. In addition, the correlation between real exchange rate and the relative consumption is close to unity (0.97). It is also interesting to note that the cross-country correlations are quite large for output, employment, investment, and consumption under productivity shocks.

It should be emphasized that these exchange rate volatilities are remarkable considering that it is real shocks that are disturbing the economy in the current experiment. Our finding that real shocks, such as productivity shocks, play a quantitatively significant role in generating exchange rate volatilities is new to the literature. Productivity shocks here are important for the volatilities of both nominal and real exchange rates. In sharp contrast, productivity shocks have almost no effect on exchange rate volatilities in models of Backus *et al.* and Chari *et al.*.

Again, this contrast between our results and those of the existing literature stems from the difference in the exchange rate volatility generating mechanisms employed. To the extent that productivity shocks have little effect on nominal exchange rate volatility, their presence hardly affect real exchange rate volatility in conventional models. Productivity shocks affect real exchange rate volatility through two channels in our model. First, given the behavior of nominal exchange rates, there is low pass through from nominal exchange rates to prices due to the presence of distribution costs. Thus large nominal exchange rate volatility is translated into large real exchange rate volatility. Second, productivity shocks are capable of generating significant volatility for nominal exchange rates. Section 4.2.3 provides more discussion on nominal exchange rate volatilities.

Next we discuss on why and how distribution costs contribute to explaining the cyclical properties of exchange rates. Understanding the real exchange rate behavior hinges on understanding two related observations. First, why do nominal exchange rate variations lead to deviations from the Law of One Price? Second, why are nominal exchange rates volatile? We take up the first question first.

4.2.2 Deviations from the Law of One Price

To gain insight into the role distribution costs play in shaping the behavior of real exchange rates, in this subsection we first analyze the relationship among nominal exchange rate, real exchange rate, and distribution costs. Then we conduct numerical experiments to quantify the importance of these costs.

We first note that the presence of nontradable goods itself can cause deviations from the Law of One Price. Empirical evidence, however, suggests that it is not an important source of deviations from the said law. It is therefore suitable to ask whether our model does not overpredict its importance. To proceed, suppose that the aggregators for tradables and nontradables (g and g^*) are Cobb-Douglas ($\mu = 0$). Then, as shown in Section 2, the real exchange rate can be written as

$$RER = RER^T \cdot Q,$$

where RER^T is the tradable goods real exchange rate and Q is the nontradable goods relative price. As shown in Table 2, variations in Q contributes little to the volatility of RER, while the volatility of RER^T is the dominant component in the total real exchange rate volatility. This observation is confirmed by the simulation results of our model.

In particular, we perform a series of numerical experiments and report the results in Table 5, where the variance of RER is decomposed into the variances of RER^T and Q, and the covariance between these two variables. We list two cases, where $\phi = 0$ and 1.13 respectively. For all these cases, the covariance of RER^T and Q are very small compared to the standard deviation of the real exchange rate. The standard deviation of Q varies from 0.25% to 0.77% as the unit distribution cost ϕ increases from 0 to 1.13. In contrast, the tradable-goods real exchange rate becomes significantly more volatile as ϕ increases: the standard deviation of RER^T rises sharply from 1.11% to 5.71%. Concomitantly, the standard deviation of real exchange rate, RER, rises from 1.36% to 6.45%. It is evident that the sharp increase in the volatility of the tradable-goods real exchange rate is the predominant force underlying the sharp increase in the volatility of the real exchange rate in response to the increased unit distribution costs. When the unit distribution cost takes an empirically plausible value, the volatility of Q indeed contributes little to explaining deviations from the Law of One Price, while the volatility of RER^T accounts for the bulk.

The preceding discussion leads us to focus on the tradable goods real exchange rate

$RER^T \equiv eP^{T*}/P^T$. In Appendix B we show that if there are no distribution costs, then the Purchasing Power Parity holds and $RER^T = 1$. This is because if there is ever a movement in the (log of) nominal exchange rate e, then there must be a corresponding movement in the (log of) cross-country price ratio, $\log\left(\overline{P}^{T*}\right) - \log\left(\overline{P}^{T*}\right) - \log(e)$, the latter exactly offsetting the former. We also show that if there are distribution costs associated with imported goods ($\widetilde{\phi} > 0$, $\widetilde{\phi}^* > 0$), then the elasticity of RER^T with respect to e is positive. In contrast, if the distribution costs associated with imported goods are zero ($\widetilde{\phi} = \widetilde{\phi}^* = 0$), then the elasticity of RER^T with respect to e is identically zero. This implies that holding the prices fixed, variations in the nominal exchange rate will result in variations in the tradable goods real exchange rate only if there are distribution costs associated with imported goods. Because of these costs, changes in the nominal exchange rate are not translated into exactly offsetting changes in the cross-country price ratio. Furthermore, the elasticity of RER^T with respect to e gets larger when the unit distribution costs on imported goods increase. These observations pinpoint the special importance of the distribution costs on imported goods in causing and magnifying deviations from the Law of One Price and the Purchasing Power Parity.

To partial out the contribution of distribution costs to exchange rate volatilities, consider the polar situation where all distribution costs are eliminated. The simulation results for $\phi = \widetilde{\phi} = \phi^* = \widetilde{\phi}^* = 0$ are summarized in Column (3) of Table 3a-c. In the sequel we shall focus on the case where the economy is subject to both money and productivity shocks (Table 3a). Compared to the benchmark case, both nominal and real exchange rates are much less volatile: their standard deviations are now only 4.31% and 1.36%, respectively. In addition, the contemporaneous correlation between real and nominal exchange rates falls sharply from 0.90 to 0.12.

Our previous analysis suggests that contributions to real exchange rate volatility by distribution costs are likely to be asymmetric in that distribution costs associated with imported goods should have more importance. We now examine whether differential effects will arise if we introduce heterogeneity in the unit distribution costs for domestically produced goods and imported goods. We shall, however, still maintain the symmetry across countries. In Column (4) of Table 3a-c, the simulation results for the case where $\phi = \phi^* = 1.13$ and $\widetilde{\phi} = \widetilde{\phi}^* = 0$ are reported. This corresponds to the situation where there are no distribution costs associated with imported goods. Results for the case where $\phi = \phi^* = 0$ and $\widetilde{\phi} = \widetilde{\phi}^* = 1.13$, implying that there are no distribution costs associated with domestically produced goods, are reported in Column (5) of the same tables. A noticeable difference arises with regard to exchange rate volatilities. In Column (4) of Table 3a where distribution costs exist only for domestically produced goods, the standard deviations of nominal and real exchange rates are 3.97% and 1.22% respectively when the economy is subject to both money and technology shocks. The same statistics rise to 9.52% and 6.48% respectively if distribution costs exist only for imported goods, as shown in Column (5) of the same table. These results indicate that in accounting for exchange rate volatility, distribution costs on imported goods are indeed the dominant factor.

4.2.3 Nominal Exchange Rate Variations: Quantities versus Prices

In the previous subsection we decompose the real exchange rate into a tradable goods real exchange rate (RER^T) component and a nontradable goods relative price component Q. An alternative decomposition is to write the real exchange rate as

$$RER = e\frac{P^*}{P}.$$

And by ignoring the terms of households' financial adjustment, the nominal exchange rate can be written as

$$e = \frac{\overline{P}^T}{\overline{P}^{T*}}\frac{Y_h^*}{Y_f}$$

We shall show that the ratio of export quantity Y_h^* to import quantity Y_f plays a special role in determining the real exchange rate volatility. We do this by the following two steps.

First, we decompose the variance of RER into the variance of the nominal exchange rate e, the variance of the price ratio P^*/P, and the covariance between these two variables. The results are reported in Part a of Table 6. The standard deviation of P^*/P is stable across different values of unit distribution costs (again we let $\phi = \phi^* = \widetilde{\phi} = \widetilde{\phi}^*$), while the standard deviation of the nominal exchange rate rises sharply with unit distribution costs. Their covariance contributes little to the volatility of the real exchange rate.

Second, the variance of the nominal exchange rate e is further decomposed into the variance of the export-import quantity ratio Y_h^*/Y_f, the variance of the export-import price ratio $\overline{P}^T/\overline{P}^{T*}$, and their covariance. It is evident that the high volatility of nominal exchange rate is mainly due to the high volatility of the quantity ratio. Its importance rises sharply with unit distribution costs. As the unit distribution costs increase, the standard deviation of the price ratio hardly changes, while the standard deviation of the quantity ratio, as well as that of the nominal exchange rate, rises sharply. To a large extent, the volatility of exchange rate corresponds to the export-import quantity ratio. In contrast, the price ratio plays only a minor role. We conclude that the export-import quantity ratio, rather than the price ratios, is the dominant source of variations for both nominal and real exchange rates.

To check the empirical plausibility of this result, we calculate the export-import quantity ratios as well as price ratios for 14 countries using IMF's International Financial Statistics dataset. From Table 7, one observes that on average the quantity ratio is significantly more volatile than the price ratio. Their standard deviations are 7.21% and 3.09%, respectively. Furthermore, the volatility of the quantity ratio is close to the prediction of our model.

4.2.4 International Portfolio Adjustment and the Consumption-Real Exchange Rate Anomaly

The main discrepancy between Chari *et al.* and the data is that their model generates a high correlation between real exchange rates and the ratio of consumption across countries, while the data show no clear pattern between these variables. This is referred to as the "consumption-real exchange rate anomaly". Note that this anomaly is an unavoidable consequence of consumption-based asset pricing in complete contingent claim markets setup. That is, real exchange rates will be perfectly correlated with relative consumption in such environments. This observation motivates departures from the complete-markets paradigm. One natural approach is to assume that only risk-free claims are available in the economy, as in some variations of Chari *et al.* and in the present paper. This approach, however, does not deliver quantitative significant departure from the unit correlation benchmark.

Here we offer an attempt to resolve the consumption-real exchange rate anomaly. We add an international portfolio adjustment cost to households' problem where the parameter κ governs the magnitude of such adjustment costs. The idea is that such adjustment costs prevent international arbitrage in the financial market and might break the tight link between asset prices and consumption that is inherent in consumption-based asset pricing models. Table 4 reports simulation results (with distribution costs for all tradables) for $\kappa = 0$, 0.01, and 0.02 respectively. When $\kappa = 0$, i.e., international portfolio adjustment cost is absent, the correlation between real exchange rate and relative consumption is close to unity. When κ increases to 0.02, this correlation falls drastically to 0.14. Real exchange rates and relative consumption are almost uncorrelated. Interestingly and importantly, the volatilities of nominal and real exchange rates both increase significantly. The standard deviation of real exchange rate is as large as 8.27%—almost the same as in the data. Also note that exchange rates become more persistent and that the correlation between nominal and real exchange rates gets larger. These results are particularly encouraging because they indicate that success in resolving the real exchange rate-consumption anomaly also brings forth success in generating large volatilities and persistence of exchange rates.

5 Conclusions

This paper develops a quantitative dynamic general equilibrium model to explain several key features of exchange rate behavior. Our model differs from previous studies by introducing distribution services into tradable goods transactions in a flexible price environment. The presence of distribution costs drives a natural wedge between retail prices in different countries, leading to deviations from the Law of One Price for traded goods.

Simulation results show that our model is capable of generating the high volatility of both nominal and real exchange rates as well as the high correlation between nominal and real exchange rates. The distribution costs that are associated with imported goods account for the bulk of the exchange rate variations. In addition, our model does not exhibit systematic relations between the real exchange rate and relative consumption across countries. These results suggest that it is possible to generate realistic exchange rate movements within a flexible price framework, if relevant factors, such as distribution costs, are introduced. We view our framework as complementary to those that emphasize the role of sticky prices.

Appendix A. Data

Nominal exchange rates are quarterly averages of market exchange rates or official rates of the U.S. dollar per national currency unit from IMF's *International Financial Statistics*. Real exchange rates are calculated based on relative consumer price indices.

The set of countries in Table 2 is determined by the data availability of tradable and nontradable goods prices in OECD's *Main Economic Indicators*. Following Engel (1999), we take price data on all items (AL), food (FD), energy (EN), all goods less food less energy $(ALFE)$, service less rent (SLR), and rent (RT). The weights in the tradeable and nontradable goods price indices are constructed from the regression[6]

$$\Delta\left(al-rt\right)=a_1\Delta\left(alfe-rt\right)+a_2\Delta\left(fd-rt\right)+a_3\Delta\left(en-rt\right)+a_4\Delta\left(slr-rt\right)+\varepsilon$$

where Δ is the first-difference operator, and lowercase letters are used to denote natural logarithms. Then the tradeable and nontradable goods price indices are constructed as follows:

$$P^T=\left(\frac{a_1}{a_1+a_2+a_3}\right)alfe+\left(\frac{a_2}{a_1+a_2+a_3}\right)fd+\left(\frac{a_3}{a_1+a_2+a_3}\right)en$$

and

$$P^{NT}=\left(\frac{a_4}{1-a_1-a_2-a_3}\right)slr+\left(\frac{1-a_1-a_2-a_3-a_4}{1-a_1-a_2-a_3}\right)rt.$$

Since price series on "service less rent" and "rent" in U.S. start in December 1982, the starting point for each country's (except Germany) series is the first quarter of 1983.

Money stock is from OECD's *Main Economic Indicators*. We use M1 for non-UK countries and M2 for UK.

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[6] Engel doesn't separate "energy" from "all items". He takes price data on all items, food, all goods less food, service less rent, and rent.

Appendix B. Deviations from the Law of One Price

We focus on the tradable goods real exchange rate $RER^T \equiv eP^{T*}/P^T$. To simplify discussion, suppose that the aggregators for tradables (the function G) is Cobb-Douglas ($\theta = 0$), then

$$\begin{aligned} P^{T*} &= \left(P_f^{T*}\right)^{\psi}\left(P_h^{T*}\right)^{(1-\psi)} \\ P^{T} &= \left(P_h^{T}\right)^{\psi}\left(P_f^{T}\right)^{(1-\psi)} \end{aligned}$$

and

$$RER^T = e\left(\frac{P_f^{T*}}{P_h^T}\right)^{\psi}\left(\frac{P_h^{T*}}{P_f^T}\right)^{(1-\psi)}$$

Note that if $\psi > 1/2$, then consumer preferences are biased toward domestically produced goods, therefore P^{T*} and P^T are not the price indices for the same basket of goods (the usual kind of index number problems arise). In this case RER^T will deviate from 1 even if the Law of One Price hold for all goods, the bias being

$$\left(\frac{P_f^{T*}}{P_h^T}\right)^{\psi-\frac{1}{2}}\left(\frac{P_h^{T*}}{P_f^T}\right)^{(1-\psi)-\frac{1}{2}} - 1$$

Empirical evidence suggests that the bias is not large compared to the volatility of the tradable goods real exchange rate, because of the small volatility of price ratios. To purge away this bias, set $\psi = 1/2$ and write RER^T as

$$RER^T = e\left(\frac{P_f^{T*}}{P_f^T}\right)^{\frac{1}{2}}\left(\frac{P_h^{T*}}{P_h^T}\right)^{\frac{1}{2}}$$

Using the relations between retail prices and producer prices and taking log, we obtain

$$\begin{aligned} \log RER^T &= \frac{1}{2}\left[\log e + \log\left(\overline{P}^{T*} + \phi^* P^{NT*}\right) - \log\left(e\overline{P}^{T*} + \widetilde{\phi} P^{NT}\right)\right] \\ &\quad + \frac{1}{2}\left[\log\left(\overline{P}^{T} + e\widetilde{\phi}^* P^{NT*}\right) - \log\left(\overline{P}^{T} + \phi P^{NT}\right)\right] \end{aligned}$$

It is easy to see that if there are no distribution costs, then the Purchasing Power Parity holds and $RER^T = 1$. This is because if there is ever a movement in the (log of) nominal exchange rate e, then there must be a corresponding movement in the (log of) cross-country price ratio, $\log\left(\overline{P}^{T*}\right) - \log\left(\overline{P}^{T*}\right) - \log(e)$, the latter exactly offsetting the former. Given the high volatility of e, the price ratio will also be highly volatile, and these two variables must be negatively correlated.

If, to the contrary, distribution costs are present, then deviations from the Purchasing Power Parity will occur even if the Law of One Price holds on the producer level. To shed light on the role of distribution costs in causing and magnifying such deviations, we perform some comparative statics analysis. Differentiating with respect to $\log e$, we have

$$\frac{\partial \log RER^T}{\partial \log e} = \frac{1}{2}\left(\zeta_1 + \zeta_2\right),$$

where

$$\begin{aligned} \zeta_1 &\equiv 1 - \left[1 + \widetilde{\phi}\frac{P^{NT}}{e\overline{P}^{T*}}\right]^{-1} \\ \zeta_2 &\equiv \left[1 + \frac{\left(1/\widetilde{\phi}^*\right)}{P^{NT*}/\left(\overline{P}^T/e\right)}\right]^{-1}. \end{aligned}$$

It is important to note that if the distribution costs associated with imported goods are zero ($\widetilde{\phi} = \widetilde{\phi}^* = 0$), then $\zeta_1 = \zeta_2 = 0$, and the elasticity of RER^T with respect to e is identically zero. If there are indeed distribution costs associated with imported goods ($\widetilde{\phi} > 0, \widetilde{\phi}^* > 0$), then the elasticity of RER^T with respect to e is positive. This implies that holding the prices fixed, variations in the nominal exchange rate will result in variations in the tradable goods real exchange rate only if there are distribution costs associated with imported goods. Because of these costs, changes in the nominal exchange rate are not translated into exactly offsetting changes in the cross-country price ratio. Furthermore,

$$\frac{\partial}{\widetilde{\phi}}\left(\frac{\partial \log RER^T}{\partial \log e}\right) = \frac{1}{2}\left[e\overline{P}^{T*}/P^{NT} + 2\widetilde{\phi} + \widetilde{\phi}^2\left(P^{NT}/e\overline{P}^{T*}\right)\right]^{-1} > 0,$$

and

$$\frac{\partial}{\widetilde{\phi}^*}\left(\frac{\partial \log RER^T}{\partial \log e}\right) = \frac{1}{2}\left[\left(\overline{P}^T/e\right)/P^{NT*} + 2\widetilde{\phi}^* + \widetilde{\phi}^{*2}P^{NT*}/\left(\overline{P}^T/e\right)\right]^{-1} > 0,$$

which means that the elasticity of RER^T with respect to e gets larger when the unit distribution costs on imported goods increase. These observations pinpoint the special importance of the distribution costs on imported goods in causing and magnifying deviations from the Law of One Price and the Purchasing Power Parity.

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Table 1: **Properties of Exchange Rates and Relative Consumer Price Indices**

	standard deviations (%)			auto-correlations			cross-correlations
	Price Ratios	exchange rates		Price ratio	exchange rates		exchange rates
		Nominal	Real		Nominal	Real	Real and Nominal
Austria	1.62	8.39	8.13	0.89	0.83	0.82	0.98
Belgium	2.09	9.13	8.51	0.95	0.86	0.85	0.97
Denmark	1.27	8.26	8.17	0.74	0.84	0.83	0.99
Finland	1.84	8.44	7.86	0.92	0.86	0.84	0.98
France	1.20	8.72	8.13	0.92	0.86	0.84	0.99
Germany	1.45	8.54	8.22	0.90	0.84	0.82	0.99
Italy	1.71	8.68	7.93	0.87	0.86	0.83	0.98
Japan	1.80	9.17	9.17	0.87	0.84	0.83	0.98
Netherlands	1.66	8.51	8.19	0.93	0.84	0.83	0.98
Norway	1.85	6.37	6.23	0.90	0.79	0.77	0.96
Spain	2.32	9.07	8.61	0.91	0.87	0.86	0.97
Sweden	1.73	8.34	7.81	0.85	0.84	0.83	0.98
Switzerland	1.53	9.33	9.07	0.90	0.83	0.82	0.99
U.K.	1.77	8.35	8.01	0.79	0.84	0.81	0.98
Average	1.70	**8.52**	**8.15**	0.88	**0.84**	**0.83**	**0.98**

Data source: IMF's *International Financial Statistics*

The statistics are based on logged and H-P-filtered quarterly data for the period 1973:1–1998:4.

Table 2: Decomposition of Real Exchange Rate Variance
(standard deviations %)

	Belgium	France	Germany	Italy	Japan	Norway
all goods real exchange rate	8.41	7.94	6.01	8.38	9.39	6.59
tradable goods real exchange rate	8.37	7.84	6.01	8.35	9.34	6.57
nontradable goods relative price	0.11	0.16	0.05	0.09	0.08	0.10

Data source: IMF's *International Financial Statistics*
OECD *Main Economic Indicator*
The statistics are based on logged and H-P-filtered quarterly data

Belgium	1983Q1–1998Q4
France	1983Q1–1998Q4
Germany	1991Q1–1998Q4
Italy	1983Q1–1998Q4
Japan	1983Q1–2001Q2
Norway	1983Q1–2001Q4

Table 3a. Model Predictions on Exchange Rates, Prices, and Cross-Country Correlations

Statistics	Data	Benchmark Model $\phi(\phi^*) = \widetilde{\phi}\left(\widetilde{\phi}^*\right) = 1.13$	$\phi(\phi^*) = 0$ $\widetilde{\phi}\left(\widetilde{\phi}^*\right) = 0$	$\phi(\phi^*) = 1.13$ $\widetilde{\phi}\left(\widetilde{\phi}^*\right) = 0$	$\phi(\phi^*) = 0$ $\widetilde{\phi}\left(\widetilde{\phi}^*\right) = 1.13$
	(1)	(2)	(3)	(4)	(5)
Standard Deviations (%)					
GDP	1.70	1.75 (0.001)	1.98 (0.001)	1.96 (0.001)	1.68 (0.001)
Nominal exchange rate	8.52	9.28 (0.008)	4.31 (0.004)	3.97 (0.003)	9.52 (0.009)
Real exchange rate	8.15	6.48 (0.004)	1.36 (0.007)	1.22 (0.001)	6.48 (0.009)
Price ratio	1.70	4.49 (0.006)	4.36 (0.008)	4.03 (0.003)	4.45 (0.006)
Autocorrelations					
Nominal exchange rate	0.84	0.53 (0.072)	0.89 (0.016)	0.87 (0.019)	0.56 (0.043)
Real exchange rate	0.83	0.40 (0.072)	0.46 (0.060)	0.38 (0.076)	0.40 (0.068)
Price ratio	0.88	0.83 (0.084)	0.86 (0.059)	0.83 (0.031)	0.85 (0.018)
Cross-Correlations					
Nominal & real exchange rates	0.98	0.90 (0.077)	0.12 (0.077)	0.10 (0.080)	0.88 (0.027)
Real exchange rate & relative consumption	-0.35	0.76 (0.048)	0.77 (0.050)	0.66 (0.063)	0.82 (0.022)
Cross-Country Correlations					
Output	0.60	0.36 (0.060)	0.12 (0.150)	0.18 (0.089)	0.33 (0.070)
Employment	0.39	0.03 (0.105)	-0.18 (0.116)	-0.19 (0.057)	-0.03 (0.110)
Investment	0.33	0.59 (0.031)	0.15 (0.147)	0.16 (0.081)	0.47 (0.008)
Consumption	0.38	0.59 (0.088)	0.82 (0.044)	0.88 (0.020)	0.39 (0.103)

Table 3b. Model Predictions on Exchange Rates, Prices, and Cross-Country Correlations (Money Shocks)

Statistics	Data	Benchmark Model $\phi(\phi^*) = \widetilde{\phi}\left(\widetilde{\phi}^*\right) = 1.13$	$\phi(\phi^*) = 0$ $\widetilde{\phi}\left(\widetilde{\phi}^*\right) = 0$	$\phi(\phi^*) = 1.13$ $\widetilde{\phi}\left(\widetilde{\phi}^*\right) = 0$	$\phi(\phi^*) = 0$ $\widetilde{\phi}\left(\widetilde{\phi}^*\right) = 1.13$
	(1)	(2)	(3)	(4)	(5)
Standard Deviations (%)					
GDP	1.70	0.96 (0.001)	1.27 (0.001)	1.31 (0.001)	1.04 (0.001)
Nominal exchange rate	8.52	8.23 (0.022)	4.21 (0.004)	4.11 (0.005)	8.33 (0.008)
Real exchange rate	8.15	5.20 (0.017)	1.01 (0.001)	0.95 (0.001)	5.28 (0.003)
Price ratio	1.70	4.38 (0.007)	4.05 (0.004)	3.98 (0.004)	4.36 (0.006)
Autocorrelations					
Nominal exchange rate	0.84	0.52 (0.077)	0.88 (0.015)	0.88 (0.018)	0.51 (0.060)
Real exchange rate	0.83	0.30 (0.099)	0.28 (0.063)	0.27 (0.057)	0.29 (0.068)
Price ratio	0.88	0.84 (0.069)	0.87 (0.018)	0.87 (0.022)	0.84 (0.028)
Cross-Correlations					
Nominal & real exchange rates	0.98	0.87 (0.012)	0.28 (0.008)	0.26 (0.015)	0.87 (0.015)
Real exchange rate & relative consumption	-0.35	0.66 (0.019)	0.66 (0.049)	0.47 (0.085)	0.76 (0.038)
Cross-Country Correlations					
Output	0.60	-0.15 (0.146)	-0.31 (0.093)	-0.29 (0.099)	-0.11 (0.140)
Employment	0.39	-0.14 (0.146)	-0.31 (0.093)	-0.29 (0.097)	-0.10 (0.138)
Investment	0.33	0.35 (0.122)	-0.13 (0.099)	-0.15 (0.097)	0.26 (0.122)
Consumption	0.38	-0.64 (0.126)	0.42 (0.123)	0.62 (0.101)	-0.71 (0.102)

Table 3c. Model Predictions on Exchange Rates, Prices, and Cross-Country Correlations (Technology Shocks)

Statistics	Data	Benchmark Model $\phi\left(\phi^*\right)=\widetilde{\phi}\left(\widetilde{\phi}^*\right)=1.13$	$\phi\left(\phi^*\right)=0$ $\widetilde{\phi}\left(\widetilde{\phi}^*\right)=0$	$\phi\left(\phi^*\right)=1.13$ $\widetilde{\phi}\left(\widetilde{\phi}^*\right)=0$	$\phi\left(\phi^*\right)=0$ $\widetilde{\phi}\left(\widetilde{\phi}^*\right)=1.13$
	(1)	(2)	(3)	(4)	(5)
Standard Deviations (%)					
GDP	1.70	1.36 (0.001)	1.54 (0.002)	1.55 (0.001)	1.28 (0.001)
Nominal exchange rate	8.52	3.76 (0.003)	0.54 (0.002)	0.53 (0.000)	3.87 (0.007)
Real exchange rate	8.15	3.51 (0.003)	0.88 (0.002)	0.74 (0.000)	3.63 (0.007)
Price ratio	1.70	0.25 (0.000)	1.41 (0.001)	0.13 (0.001)	0.25 (0.001)
Autocorrelations					
Nominal exchange rate	0.84	0.62 (0.059)	0.63 (0.148)	0.62 (0.058)	0.64 (0.060)
Real exchange rate	0.83	0.62 (0.059)	0.63 (0.068)	0.62 (0.054)	0.64 (0.058)
Price ratio	0.88	0.59 (0.070)	0.63 (0.062)	0.62 (0.052)	0.60 (0.060)
Cross-Correlations					
Nominal & real exchange rates	0.98	1.00 (0.000)	-0.99 (0.126)	-0.99 (0.007)	1.00 (0.001)
Real exchange rate & relative consumption	-0.35	0.97 (0.053)	0.91 (0.312)	0.89 (0.089)	0.98 (0.057)
Cross-Country Correlations					
Output	0.60	0.72 (0.064)	0.37 (0.111)	0.58 (0.091)	0.66 (0.070)
Employment	0.39	0.95 (0.032)	0.53 (0.039)	0.68 (0.015)	0.91 (0.002)
Investment	0.33	0.80 (0.047)	0.39 (0.060)	0.57 (0.025)	0.69 (0.003)
Consumption	0.38	0.87 (0.048)	0.83 (0.064)	0.92 (0.027)	0.75 (0.075)

Table 4. Model Predictions: The Role of International Portfolio Adjustment Costs

Statistics	Data	$\kappa = 0$	$\kappa = 0.01$	$\kappa = 0.02$
	(1)	(2)	(3)	(4)
Standard Deviations (%)				
GDP	1.70	1.66 (0.001)	1.75 (0.001)	1.98 (0.002)
Nominal exchange rate	8.52	7.66 (0.006)	9.28 (0.008)	11.81 (0.010)
Real exchange rate	8.15	5.50 (0.003)	6.48 (0.004)	8.27 (0.006)
Price ratio	1.70	4.41 (0.005)	4.49 (0.006)	4.72 (0.005)
Autocorrelations				
Nominal exchange rate	0.84	0.49 (0.074)	0.53 (0.072)	0.58 (0.064)
Real exchange rate	0.83	0.38 (0.067)	0.40 (0.072)	0.47 (0.069)
Price ratio	0.88	0.84 (0.031)	0.83 (0.084)	0.83 (0.031)
Cross-Correlations				
Nominal & real exchange rates	0.98	0.82 (0.035)	0.90 (0.077)	0.95 (0.010)
Real exchange rate & relative consumption	-0.35	0.95 (0.011)	0.76 (0.048)	0.14 (0.095)
Cross-Country Correlations				
Output	0.60	0.47 (0.081)	0.36 (0.060)	0.24 (0.126)
Employment	0.39	0.16 (0.090)	0.03 (0.105)	-0.04 (0.131)
Investment	0.33	0.64 (0.057)	0.59 (0.031)	0.63 (0.086)
Consumption	0.38	0.56 (0.083)	0.59 (0.088)	0.52 (0.116)

Table 5. Decomposition of Real Exchange Rate Variations

Real Exchange Rate: $RER = RER^T \cdot Q$

	RER	RER^T	Q	$corr\left(RER^T, Q\right)$
$\phi = 1.13$	6.48 (0.004)	5.71 (0.004)	0.77 (0.000)	1.00 (0.000)
$\phi = 0$	1.36 (0.001)	1.11 (0.001)	0.25 (0.000)	1.00 (0.000)

Standard deviations of RER, RER^T, and Q are in percentage terms.

Table 6. Sources of Exchange Rate Variations

a. Real Exchange Rate: $RER = e\frac{P^*}{P}$

	RER	e	P^*/P	$corr\,(e, P^*/P)$
$\phi = 1.13$	6.48 (0.004)	9.28 (0.008)	4.49 (0.006)	-0.77 (0.041)
$\phi = 0$	1.36 (0.001)	4.31 (0.004)	4.36 (0.004)	-0.95 (0.009)

Standard deviations of RER, e, and P^*/P are in percentage terms.

b. Nominal Exchange Rate: $e \approx \frac{\overline{p}^T}{\overline{p}^{T*}}\frac{Y_h^*}{Y_f}$

	e	$\frac{Y_h^*}{Y_f}$	$\frac{\overline{p}^T}{\overline{p}^{T*}}$	$corr\left(\frac{Y_h^*}{Y_f}, \frac{\overline{p}^T}{\overline{p}^{T*}}\right)$
$\phi = 1.13$	9.28 (0.008)	8.94 (0.006)	4.54 (0.005)	-0.16 (0.101)
$\phi = 0$	4.31 (0.004)	1.86 (0.001)	4.70 (0.005)	-0.32 (0.060)

Standard deviations of e, Y_h^*/Y_f, and $\overline{p}^T/\overline{p}^{T*}$ are in percentage terms.

Table 7. Quantity and Price Ratios for Exports and Imports

	Standard Deviations (%)	
	Export-Import Quantity Ratio	Export-Import Price Ratio
Belgium	1.84	1.13
Denmark	5.29	2.66
Finland	9.73	3.09
France	4.97	1.09
Germany	5.45	3.06
Italy	7.94	3.68
Japan	8.99	6.32
Netherlands	3.60	1.64
Norway	14.69	6.01
Spain	16.99	5.16
Sweden	5.96	2.25
Switzerland	3.32	1.59
U.K.	4.22	2.94
U.S.	7.95	2.67
Average	7.21	3.09

Data source: IMF's *International Financial Statistics*
The statistics are based on logged and H-P-filtered quarterly data