Federal Reserve Bank of Minneapolis
Research Department Staff Report 277

Revised July 2001

Can Sticky Price Models Generate Volatile and Persistent Real Exchange Rates?

V. V. Chari*

University of Minnesota
and Federal Reserve Bank of Minneapolis

Patrick J. Kehoe*

Federal Reserve Bank of Minneapolis
and University of Minnesota

Ellen R. McGrattan*

Federal Reserve Bank of Minneapolis
and University of Minnesota

ABSTRACT

The central puzzle in international business cycles is that real exchange rates are volatile and persistent. We quantify the popular story for real exchange rate fluctuations: they are generated by monetary shocks interacting with sticky goods prices. When prices are held fixed for at least one year, risk aversion is high and preferences are separable in leisure, our quantitative model generates real exchange rates that are as volatile as in the data and quite persistent, but less so than in the data. The main discrepancy between the model and the data, the *consumption-real exchange rate anomaly*, is that the model generates a high correlation between real exchange rates and relative consumptions while the data show no clear pattern between these variables.

*This paper is a revised version of our 1996 paper entitled "Monetary Shocks and Real Exchange Rates in Sticky Price Models of International Business Cycles." A technical appendix, computer codes, and the data used in this paper are available at our website, http://minneapolisfed.org/research/sr/sr277.html. Chari and Kehoe thank the National Science Foundation for support. The views expressed herein are those of the authors and not necessarily those of the Federal Reserve Bank of Minneapolis or the Federal Reserve System.

The central puzzle in international business cycles is that real exchange rates are volatile and persistent. Ever since the work of Dornbusch (1976), the most popular story for exchange rate fluctuations is that they result from the interaction of monetary shocks and sticky prices. To date, however, few researchers have attempted to develop quantitative general equilibrium models of this story. In this paper, we do that with some success.

We develop a general equilibrium monetary model with sticky prices that builds on the pioneering work of Svensson and van Wijnbergen (1989) and Obstfeld and Rogoff (1995) to investigate the extent to which monetary shocks can account for the observed volatility and persistence of real exchange rates. We show that if risk aversion is high and preferences are separable in leisure, then the model can account for the volatility of real exchange rates. With price-stickiness of one year, the model also produces real exchange rates that are quite persistent, but less so than in the data. If monetary shocks are correlated across countries, then the comovements in aggregates across countries are broadly consistent with those in the data. The main discrepancy between the model and the data is that the model generates a high correlation between real exchange rates and relative consumptions while the data show no clear pattern of correlation between these variables.

In constructing our model, we need to choose whether to make real exchange rate fluctuations arise from deviations from the law of one price for traded goods across countries or from fluctuations in the relative prices of nontraded to traded goods across countries or from both. We choose to focus on fluctuations in real exchange rates arising solely from deviations from the law of one price for traded goods and to abstract from nontraded goods. This focus is guided by the data. We present evidence that fluctuations in the relative prices of nontraded to traded goods across countries account for essentially none of the volatility of real exchange rates. Using data for the United States and an aggregate of Europe (and our admittedly imperfect measures), we find that about 2 percent of the variance of real exchange rates is due to fluctuations in the relative prices of nontraded to traded goods. This evidence is consistent with studies which document that even at a very disaggregated level, the relative price of traded goods has large and persistent fluctuations. (See, for example, the work of

Engel (1993, 1999) and Knetter (1993).)

Our model with only traded goods is a version of Svensson and van Wijnbergen's (1989) model modified to allow for price discrimination, staggered price-setting, and capital accumulation. We introduce price-discriminating monopolists in order to get fluctuations in real exchange rates from fluctuations in the relative price of traded goods. (See the work of Dornbusch (1987), Krugman (1987), Knetter (1989), Marston (1990), and Goldberg and Knetter (1997).) We introduce staggered price-setting in order to get persistent real exchange rates. We introduce capital accumulation in order to generate the relative volatility of consumption and output observed in the data. In our model, this relative volatility is closely connected to the volatility of the real exchange rate relative to output.

In this benchmark model, the real exchange rate is the ratio of the marginal utilities of consumption of households in the two countries. Since the utility function is separable in leisure, the volatility of real exchange rates is essentially determined by the risk aversion parameter and the volatility of consumption, while the persistence of real exchange rates is essentially determined by the persistence of consumption. More precisely, we show that the volatility of real exchange rates is approximately equal to the product of the risk aversion parameter and the volatility of relative consumption in the two countries. We show that this calculation implies that a risk aversion parameter of about 5 produces the real exchange rate volatility in the data.

We also show that the persistence of real exchange rates is approximately the autocorrelation of relative consumptions in the two countries. If prices are set for a substantial length of time, then monetary shocks lead to persistent fluctuations in consumption and, hence, in real exchange rates. In our quantitative analysis, we assume that prices are set for one year at a time along the lines of the evidence summarized by Taylor (1999). We find that with this amount of price-stickiness, real exchange rates are persistent in our model, but somewhat less so than in the data. We refer to this discrepancy as the *persistence anomaly.*

To address the persistence anomaly we replace the model's frictionless labor markets with sticky wages. The idea is that with sticky wages, nominal marginal costs respond less to monetary shocks, so prices do too, thereby increasing persistence. While this avenue is conceptually promising, it does little to increase persistence.

Our model also displays a second anomaly. In the model the correlation between the real exchange rate and relative consumptions is high and positive. For the United States and Europe this correlation is somewhat negative while for other country pairs it ranges between small and positive to somewhat negative. We refer to this discrepancy as the *consumption-real exchange rate anomaly.*

In our model the real exchange rate and relative consumptions are tightly linked because we assume that asset markets are complete. We make this assumption because we are interested in isolating the role of a particular type of goods market friction, namely, price-stickiness and hence we abstract from asset market frictions. With complete markets the real exchange rate is equal to the ratio of marginal utilities of consumption in the model (up to a proportionality constant). We emphasize that this equality holds in *any* model with complete asset markets, regardless of the frictions in the goods and labor markets like sticky prices, sticky wages, shipping costs and so on.

This anomaly leads us to consider two asset market frictions to weaken the link between the real exchange rate and relative consumptions. We begin by replacing the model's complete international asset markets with incomplete markets that allow for trade only in an uncontingent nominal bond. This avenue is conceptually promising because it breaks the link between real exchange rates and the marginal utilities of consumption. It turns out, however, that the anomaly is as severe in the incomplete markets model it is as in the benchmark model.

We then explore if habit persistence in consumption can address this anomaly. This specification is appealing because habit persistence has been found to solve other anomalies in asset markets. (See Jermann (1998), Campbell and Cochrane (1999) and Boldrin, Christiano and Fisher (forthcoming).) We use some simple calculations to show that adding habit persistence to the model is unlikely to solve the anomaly.

Many researchers have investigated the economic effects of sticky prices. For some early work in a closed-economy setting, see the studies by Svensson (1986), Blanchard and Kiyotaki (1987), and Ball and Romer (1989). The international literature on sticky prices has three branches. The pioneering work laying out the general theoretical framework is by Svensson and van Wijnbergen (1989) and Obstfeld and Rogoff (1995). (See also the recent work by Corsetti, Pesenti, Roubini, and Tille (1999).) More closely related to our paper are those by Kollmann (1996) and Betts and Devereux (2000), who consider economies with price-discriminating monopolists who set prices as in the work of Calvo (1983). Kollmann considers a semi-small open-economy model without capital in which both prices and wages are sticky; he shows that the model generates volatile exchange rates. Betts and Devereux are primarily interested in replicating the vector autoregression evidence on monetary policy shocks and exchange rates. Finally, for some other work on the implications of sticky prices for monetary policy under fixed exchange rates, see the work of Ohanian and Stockman (1997).

1. DATA

Here we document properties of measures of bilateral exchange rates between the United States and individual European countries and a European aggregate. The series are constructed from data for individual countries collected by the International Monetary Fund (IMF) and the Organisation for Economic Co-operation and Development (OECD). (For details see Chari, Kehoe, McGrattan 2000.) The data are quarterly and cover the period from 1973:1 through 2000:1. The data clearly support the notion that real exchange rates between the United States and Europe are volatile and persistent. We then demonstrate, using disaggregated price data, that very little—about 2 percent—of the volatility in real exchange rates arises from fluctuations in the relative prices of nontraded to traded goods. This observation motivates our decision to exclude nontraded goods from the model.

A. *Volatility and persistence of exchange rates*

Our measure of the nominal exchange rate e_t between the United States and Europe is a trade-weighted average of the bilateral nominal exchange rates with individual European countries.[1]

We construct a price index for the European countries, denoted P_t^*, in an analogous way, using each country's consumer price index (CPI). The U.S. real exchange rate with Europe is $q_t = e_t P_t^*/P_t$, where P_t is the price index for the United States.

In Figure 1, we plot the U.S. nominal and real exchange rates with Europe and the ratio of the CPI for Europe to that for the United States. Our aggregate of Europe consists of the 11 countries for which we could get complete data: Austria, Denmark, Finland, France, Germany, Italy, the Netherlands, Norway, Spain, Switzerland, and the United Kingdom. Clearly, both the nominal and real exchange rates are highly volatile, especially when compared to the relative price level. The exchange rates are also highly persistent. (For an earlier analysis emphasizing these features of the data, see Mussa (1986).)

In Table 1, we present some statistics for exchange rates and CPIs for the United States and the European aggregate and for the 11 individual European countries. (The data reported in the table are logged and Hodrick-Prescott (H-P) filtered.) The standard deviation of the real exchange rate between the United States and Europe is 7.52.[2] That is about 4.6 times the volatility of U.S. output over the same time period (which is only 1.64 percent). Clearly, real exchange rates are very volatile.

We also see in Table 1 that both nominal and real exchange rates between the United States and Europe are highly persistent, with autocorrelations of .85 and .83, respectively, and nominal and real exchange rates are very highly correlated with each other, with a cross-correlation of .99. The data on the individual countries show that these patterns are also evident in bilateral comparisons between each European country and the United States.

B. *Decomposing real exchange rate fluctuations*

In the data, movements in real exchange rates arise from two sources: deviations from the law of one price for traded goods across countries and movements in the relative prices of nontraded to traded goods across countries. To investigate the relative magnitudes of these sources, define the traded goods real exchange rate as $q_T = eP_T^*/P_T$ where P_T and P_T^* are traded goods price indices in the two countries. Let $p = q/q_T$.

We refer to p as the *nontraded goods relative price* because of the following reasoning. Suppose, as an approximation, that the price indices in the two countries are given by $P = (P_T)^{1-\alpha}(P_N)^{\alpha}$ and $P^* = (P_T^*)^{1-\gamma}(P_N^*)^{\gamma}$, where P_N and P_N^* are nontraded goods price indices, and α and γ are the consumption shares of nontraded goods. Then p is equal to $(P_N^*/P_T^*)^{\gamma}/(P_N/P_T)^{\alpha}$, and its value depends on the relative prices of nontraded to traded goods in the two countries. Notice that if the law of one price holds, then q_T is constant and all the variance in q is attributable to the relative prices of nontraded to traded goods. Here, we use several measures of disaggregated price data to construct this decomposition.

One measure uses disaggregated CPI data. The Organisation for Economic Co-operation and Development (OECD) reports price index data in its *Main Economic Indicators,* where it disaggregates the consumer price index for all items into indices for food, all goods less food, rent, and services less rent. We construct a price index for traded goods as a weighted average of the price indices for food and for all goods less food. Since data on expenditure shares among traded goods by country are not readily available, we use U.S. weights obtained from the U.S. Department of Labor (1992) to construct this price index for each country in Europe which has disaggregated price data. These four countries are France, Italy, the Netherlands, and Norway. The period is 1973:1-1998:4. For the European aggregate, we use the trade-weighting procedure described above.

Figure 2 plots the real exchange rate, q; the traded goods real exchange rate, q_T; and the nontraded goods relative price, p. This figure shows that virtually none of the movement in real exchange rates is due to fluctuations in the relative prices of nontraded to traded goods across countries. The variance of the real exchange rate can be decomposed as $\text{var}(\log q) = \text{var}(\log q_T) + \text{var}(\log p) + 2\text{cov}(\log q_T, \log p)$. In the data, the variance decomposition becomes $(3.64) = (4.10) + (.076) + (-.54)$. Since the covariance between the two components is negative, the maximum portion of the variance of real exchange rates attributable to variability in the nontraded goods relative price is about 2 percent. (More precisely, the portion is 2.09 percent $= (.076/3.64) \times 100$ percent.)

C. *Alternative decompositions*

Table 2 gives some additional statistics on relative prices and nominal and real exchange rates for individual European countries as well as for the aggregate. Here, although there is some heterogeneity in the individual country statistics, the bilateral comparisons have the same basic patterns as the comparison of aggregates. For our European aggregate, the correlation between the traded goods real exchange rate and the all-goods real exchange rate is about 1. In other respects, the statistics in this table are similar to those in Table 1.

These measures provide evidence that the relative price of traded goods varies a great deal across countries. Since these measures are constructed from broad aggregates, the law of one price may hold for each traded good; and the volatility of the traded goods real exchange rate may arise from compositional effects among traded goods. But we doubt that composition effects account for much of the volatility of real exchange rates: European countries have consumption baskets similar to that of the United States, and these consumption baskets do not change much over time.

The OECD also reports nominal and real consumption expenditures for four categories: durable goods, semi-durable goods, nondurable goods, and services. We used these data to construct traded and nontraded goods price indices and found similar results. (For details, see Chari, Kehoe, and McGrattan (1998).)

Our measures of the price of traded goods are clearly imperfect in another way, however. They measure the price paid by the final user of the goods and, hence, incorporate the value of intermediate nontraded services, such as distribution and retailing. Thus, if the value of such nontraded services is volatile, we would expect the real exchange rate for traded goods to be volatile even if the law of one price held for goods net of the value of the nontraded services.

One way to measure the volatility induced by distribution and retailing services is to examine wholesale price indices (WPIs). These data reflect prices received by producers and thus do not include many distribution and retailing costs. These price indices do, however, include the prices of exported goods and exclude the prices of imported goods; thus, they are imperfect measures of the real exchange rate. We report in Table 3 relative prices and exchange rates constructed using WPIs. The procedure we use to construct these indices is the same as that for the measures in Tables 1 and 2. For the period 1973:1-2000:1, WPI data are available for the 9 countries listed in Table 3. For the European aggregate relative to the United States, the standard deviation of the real exchange rate constructed using WPIs is 7.30, very close to the 7.52 standard deviation found using CPIs (Table 1). The closeness of these measures suggests that volatile distribution costs are unlikely to be a significant source of real exchange rate volatility.

2. THE WORLD ECONOMY

Here we develop a two-country model with infinitely lived consumers that we will use to confront the observations on exchange rates in Europe and the United States. In our model, competitive final goods producers in each country purchase intermediate goods from monopolistically competitive intermediate goods producers. Each intermediate goods producer can price-discriminate across countries and must set prices in the currency of the local market. Once prices are set, each intermediate goods producer must satisfy the forthcoming demand. The intermediate goods producers set prices in a staggered fashion.

Specifically, consider a two-country world economy consisting of a *home* country and a *foreign* country. Each country is populated by a large number of identical, infinitely lived consumers. In each period of time t, the economy experiences one of finitely many events s_t. We denote by $s^t = (s_0, \ldots, s_t)$ the history of events up through and including period t. The probability, as of period 0, of any particular history s^t is $\pi(s^t)$. The initial realization s_0 is given.

In each period t, the commodities in this economy are labor, a consumption-capital good, money, a continuum of intermediate goods indexed by $i \in [0, 1]$ produced in the home country, and a continuum of intermediate goods indexed by $i \in [0, 1]$ produced in the foreign country. In this economy, the intermediate goods are combined to form final goods which are country-specific. All trade between the countries is in intermediate goods that are produced by monopolists who can charge different prices in the two countries. We assume that all intermediate goods producers have the exclusive right to sell their own goods in the two countries. Thus, price differences in intermediate goods cannot be arbitraged away.

In terms of notation, goods produced in the home country are subscripted with an H, while those produced in the foreign country are subscripted with an F. In the home country, final goods are produced from intermediate goods according to a production function that combines features from the industrial organization literature (Dixit and Stiglitz (1977)) and the trade literature (Armington (1969)):

$$y(s^t) = \left[a_1 \left(\int_0^1 y_H(i, s^t)^\theta di\right)^{\rho/\theta} + a_2 \left(\int_0^1 y_F(i, s^t)^\theta di\right)^{\rho/\theta}\right]^{\frac{1}{\rho}}, \tag{1}$$

where $y(s^t)$ is the final good and $y_H(i, s^t)$ and $y_F(i, s^t)$ are intermediate goods produced in the home and foreign countries, respectively. This specification of technology will allow our model to be consistent with three features of the data. The parameter θ will determine the markup of price over marginal cost. The parameter ρ, along with θ, will determine the elasticity of substitution between home and foreign goods. And the parameters a_1 and a_2, together with ρ and θ, will determine the ratio of imports to output.

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

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

subject to (1), where $P(s^t)$ is the price of the final good in period t, $P_H(i, s^{t-1})$ is the price of the home intermediate good i in period t, and $P_F(i, s^{t-1})$ is the price of the foreign intermediate good i in period t. These prices are in units of the domestic currency. The intermediate goods prices can, at most, depend on s^{t-1} because producers set prices before the realization of the period t shocks. Solving the problem in (2) gives the input demand functions

$$y_H^d(i, s^t) = \frac{[a_1 P(s^t)]^{\frac{1}{1-\rho}}\, \bar{P}_H(s^{t-1})^{\frac{\rho-\theta}{(1-\rho)(\theta-1)}}}{P_H(i, s^{t-1})^{\frac{1}{1-\theta}}} y(s^t) \tag{3}$$

$$y_F^d(i, s^t) = \frac{[a_2 P(s^t)]^{\frac{1}{1-\rho}}\, \bar{P}_F(s^{t-1})^{\frac{\rho-\theta}{(1-\rho)(\theta-1)}}}{P_F(i, s^{t-1})^{\frac{1}{1-\theta}}} y(s^t), \tag{4}$$

where $\bar{P}_H(s^{t-1}) = \left(\int_0^1 P_H(i, s^{t-1})^{\frac{\theta}{\theta-1}} di\right)^{\frac{\theta-1}{\theta}}$ and $\bar{P}_F(s^{t-1}) = \left(\int_0^1 P_F(i, s^{t-1})^{\frac{\theta}{\theta-1}} di\right)^{\frac{\theta-1}{\theta}}$. Using the zero-profit condition, we have

$$P(s^t) = \left(a_1^{\frac{1}{1-\rho}} \bar{P}_H(s^{t-1})^{\frac{\rho}{\rho-1}} + a_2^{\frac{1}{1-\rho}} \bar{P}_F(s^{t-1})^{\frac{\rho}{\rho-1}}\right)^{\frac{\rho-1}{\rho}}.$$

Thus, in equilibrium, the price of the final good in period t does not depend on the period t shock.

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

$$y_H(i, s^t) + y_H^*(i, s^t) = F(k(i, s^{t-1}), l(i, s^t)), \tag{5}$$

where $k(i, s^{t-1})$ and $l(i, s^t)$ are the inputs of capital and labor, respectively, and $y_H(i, s^t)$ and $y_H^*(i, s^t)$ are the amounts of this intermediate good used in home and foreign production of the final good, respectively. The capital used in producing good i is augmented by investment of final goods $x(i, s^t)$ and is subject to adjustment costs. The law of motion for such capital is given by

$$k(i, s^t) = (1 - \delta)k(i, s^{t-1}) + x(i, s^t) - \phi\left(\frac{x(i, s^t)}{k(i, s^{t-1})}\right) k(i, s^{t-1}), \tag{6}$$

where δ is the depreciation rate and where the adjustment cost function ϕ is convex and satisfies $\phi(\delta) = 0$ and $\phi'(\delta) = 0$.

Intermediate goods producers behave as imperfect competitors. They set prices for N periods in a staggered way. In particular, in each period t, a fraction $1/N$ of the home country producers choose a home currency price $P_H(i, s^{t-1})$ for the home market and a foreign currency price $P_H^*(i, s^{t-1})$ for the foreign market before the realization of the event s_t. These prices are set for N periods, so for this group of intermediate goods producers, $P_H(i, s^{t+\tau-1}) = P_H(i, s^{t-1})$ and $P_H^*(i, s^{t+\tau-1}) = P_H^*(i, s^{t-1})$ for $\tau = 0, \ldots, N-1$. The intermediate goods producers are indexed so that those with $i \in [0, 1/N]$ set new prices in 0, N, $2N$, and so on, while those with $i \in [1/N, 2/N]$ set new prices in 1, $N+1$, $2N+1$, and so on, for the N cohorts of intermediate goods producers.

Consider, for example, producers in a particular cohort, namely $i \in [0, 1/N]$. These producers choose prices $P_H(i, s^{t-1}), P_H^*(i, s^{t-1})$, inputs of labor $l(i, s^t)$, capital $k(i, s^t)$, and investment $x(i, s^t)$ to solve

$$\begin{aligned} \max \ \textstyle\sum_{t=0}^{\infty} \sum_{s^t} Q(s^t)[P_H(i, s^{t-1}) y_H(i, s^t) + e(s^t) P_H^*(i, s^{t-1}) y_H^*(i, s^t) \\ -P(s^t) w(s^t) l(i, s^t) - P(s^t) x(i, s^t)] \end{aligned} \tag{7}$$

subject to (5), (6), and the constraints that their supplies to the home and foreign markets $y_H(i, s^t)$ and $y_H^*(i, s^t)$ must equal the amount demanded by home and foreign final goods producers, $y_H^d(i, s^t)$ from (3) and its analogue. In addition, the constraints that prices are set for N periods are $P_H(i, s^{t-1}) = P_H(i, s^{-1})$ for $t = 0, \ldots, N-1$, and $P_H(i, s^{t-1}) = P_H(i, s^{N-1})$ for $t = N, \ldots, 2N-1$ and so on, with similar constraints for $P_H^*(i, s^{t-1})$. Here $Q(s^t)$ is the price of one unit of home currency in s^t in an abstract unit of account, $e(s^t)$ is the nominal exchange rate, and $w(s^t)$ is the real wage. The initial capital stock $k(i, s^{-1})$ is given and is the same for all producers in this cohort.

The optimal prices for $t = 0,\ N,\ 2N$ are

$$P_H(i, s^{t-1}) = \frac{\sum_{\tau=t}^{t+N-1} \sum_{s^\tau} Q(s^\tau) P(s^\tau) v(i, s^\tau) \Lambda_H(s^\tau)}{\theta \sum_{\tau=t}^{t+N-1} \sum_{s^\tau} Q(s^\tau) \Lambda_H(s^\tau)}$$

$$P_H^*(i, s^{t-1}) = \frac{\sum_{\tau=t}^{t+N-1} \sum_{s^\tau} Q(s^\tau) P(s^\tau) v(i, s^\tau) \Lambda_H^*(s^\tau)}{\theta \sum_{\tau=t}^{t+N-1} \sum_{s^\tau} Q(s^\tau) e(s^\tau) \Lambda_H^*(s^\tau)}$$

where $v(i, s^t)$ is the real unit cost which is equal to the wage rate divided by the marginal product of labor, $w(s^t)/F_l(i, s^t)$, $\Lambda_H(s^t) = [a_1 P(s^t)]^{\frac{1}{1-\rho}} \bar{P}_H(s^{t-1})^{\frac{\rho-\theta}{(1-\rho)(\theta-1)}} y(s^t)$, and $\Lambda_H^*(s^t) = [a_2 P^*(s^t)]^{\frac{1}{1-\rho}} \bar{P}_H^*(s^{t-1})^{\frac{\rho-\theta}{(1-\rho)(\theta-1)}} y^*(s^t)$. Here, $F_l(i, s^t)$ denotes the derivative of the production function with respect to l. We use similar notation throughout the paper.

In a symmetric steady state, the real unit costs are equal across firms. Hence, in this steady state, these formulas reduce to $P_H(i) = eP_H^*(i) = Pv/\theta$, so that the law of one price holds for each good and prices are set as a markup $(1/\theta)$ over nominal costs Pv. Thus, in this model, all deviations from the law of one price are due to shocks which keep the economy out of the deterministic steady state.

In this economy, the markets for state-contingent money claims are complete. We represent the asset structure by having complete, contingent, one-period nominal bonds denominated in the home currency. We let $B(s^t, s_{t+1})$ denote the home consumers' holdings of such a bond purchased in period t and state s^t with payoffs contingent on some particular state s_{t+1} at $t+1$. Let $B^*(s^t, s_{t+1})$ denote the foreign consumers' holdings of this bond. One unit of this bond pays one unit of the home currency in period $t+1$ if the particular state s_{t+1} occurs and 0 otherwise. Let $Q(s^{t+1}|s^t)$ denote the price of this bond in units of the home currency in period t and state s^t. Clearly $Q(s^{t+1}|s^t) = Q(s^{t+1})/Q(s^t)$. (Notice that also including bonds denominated in the foreign currency would be redundant.) For notational simplicity, we assume that claims to the ownership of firms in each country are held by the residents of that country and cannot be traded.

In each period $t = 0, 1, \ldots$, consumers choose their period t allocations after the realization of the event s_t. Consumers in the home country face the sequence of budget constraints

$$\begin{aligned} &P(s^t)c(s^t) + M(s^t) + \textstyle\sum_{s_{t+1}} Q(s^{t+1}|s^t)B(s^{t+1}) \\ &\qquad \leq P(s^t)w(s^t)l(s^t) + M(s^{t-1}) + B(s^t) + \Pi(s^t) + T(s^t) \end{aligned} \tag{8}$$

and a borrowing constraint $B(s^{t+1}) \geq -P(s^t)\bar{b}$, where $c(s^t)$, $l(s^t)$, and $M(s^t)$ are consumption, labor, and nominal money balances, respectively, and $s^{t+1} = (s^t, s_{t+1})$. Here $\Pi(s^t)$ is the profits of the home country intermediate goods producers, $T(s^t)$ is transfers of home currency, and the positive constant $\bar{b}$ constrains the amount of real borrowing of the consumer. The initial conditions $M(s^{-1})$ and $B(s^0)$ are given.

Home consumers choose consumption, labor, money balances, and bond holdings to maximize their utility:

$$\sum_{t=0}^{\infty} \sum_{s^t} \beta^t \pi(s^t) U\big(c(s^t), l(s^t), M(s^t)/P(s^t)\big) \tag{9}$$

subject to the consumer budget constraints. Here β is the discount factor. The first-order conditions for the consumer can be written as

$$-\frac{U_l(s^t)}{U_c(s^t)} = w(s^t), \tag{10}$$

$$\frac{U_m(s^t)}{P(s^t)} - \frac{U_c(s^t)}{P(s^t)} + \beta \sum_{s_{t+1}} \pi(s^{t+1}|s^t) \frac{U_c(s^{t+1})}{P(s^{t+1})} = 0, \tag{11}$$

$$Q(s^t|s^{t-1}) = \beta\pi(s^t|s^{t-1}) \frac{U_c(s^t)}{U_c(s^{t-1})} \frac{P(s^{t-1})}{P(s^t)}. \tag{12}$$

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

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

Now let's develop a relationship between the real exchange rate and marginal utilities of consumption of the consumers in the two countries, which is implied by arbitrage. The budget constraint of a consumer in the foreign country is given by

$$\begin{aligned} &P^*(s^t)c^*(s^t) + M^*(s^t) + \textstyle\sum_{s_{t+1}} Q(s^{t+1}|s^t)B^*(s^{t+1})/e(s^t) \\ &\qquad \leq P^*(s^t)w^*(s^t)l^*(s^t) + M^*(s^{t-1}) + B^*(s^t)/e(s^t) + \Pi^*(s^t) + T^*(s^t), \end{aligned} \tag{13}$$

where $B^*(s^t)$ denotes the foreign consumer's holdings of the home country bonds at s^t. The first-order condition with respect to bond holdings for a foreign consumer is

$$Q(s^t|s^{t-1}) = \beta\pi(s^t|s^{t-1}) \frac{U_c^*(s^t)}{U_c^*(s^{t-1})} \frac{e(s^{t-1})}{e(s^t)} \frac{P^*(s^{t-1})}{P^*(s^t)}.$$

Substituting for the bond price in this equation from (12) and iterating, we obtain

$$\frac{U_c(s^t)}{U_c(s^0)} \frac{P(s^0)}{P(s^t)} = \frac{U_c^*(s^t)}{U_c^*(s^0)} \frac{e(s^0)}{e(s^t)} \frac{P^*(s^0)}{P^*(s^t)}.$$

Defining the real exchange rate as $q(s^t) = e(s^t)P^*(s^t)/P(s^t)$, we obtain

$$q(s^t) = \kappa \frac{U_c^*(s^t)}{U_c(s^t)}, \tag{14}$$

where the constant $\kappa = e(s^0)U_c(s^0)P^*(s^0)/U_c^*(s^0)P(s^0)$. We use this relationship between real exchange rates and marginal rates of substitution in developing intuition for our quantitative results.

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

An equilibrium requires several market-clearing conditions. The resource constraint in the home country is given by

$$y(s^t) = c(s^t) + \int_0^1 x(i, s^t)\, di$$

and the labor market-clearing condition is $l(s^t) = \int l(i, s^t)\, di$. Similar conditions hold for the foreign country. The market-clearing condition for contingent bonds is $B(s^t) + B^*(s^t) = 0$.

An *equilibrium* for this economy is a collection of allocations for home consumers $c(s^t)$, $l(s^t)$, $M(s^t)$, $B(s^{t+1})$; allocations for foreign consumers $c^*(s^t)$, $l^*(s^t)$, $M^*(s^t)$, $B^*(s^{t+1})$; allocations and prices for home intermediate goods producers $y_H(i, s^t)$, $y_H^*(i, s^t), l(i, s^t)$, $x(i, s^t)$, and $P_H(i, s^{t-1})$, $P_H^*(i, s^{t-1})$ for $i \in [0, 1]$; allocations and prices for foreign intermediate goods producers $y_F(i, s^t)$, $y_F^*(i, s^t), l^*(i, s^t)$, $x^*(i, s^t)$, and $P_F(i, s^{t-1})$, $P_F^*(i, s^{t-1})$ for $i \in [0, 1]$; and allocations for home and foreign final goods producers $y(s^t), y^*(s^t)$, final good prices $P(s^t)$, $P^*(s^t)$, real wages $w(s^t)$, $w^*(s^t)$, and bond prices $Q(s^{t+1}|s^t)$ that satisfy the following five conditions: (i) the consumer allocations solve the consumers' problem; (ii) the prices of intermediate goods producers solve their maximization problem; (iii) the final goods producers' allocations solve their problem; (iv) the market-clearing conditions hold; and (v) the money supply processes and transfers satisfy the specifications above.

We are interested in a stationary equilibrium and thus restrict the stochastic processes for the growth rates of the money supplies to be Markovian. To make the economy stationary, we deflate all nominal variables by the level of the relevant money supply. A stationary equilibrium for this economy consists of stationary decision rules and pricing rules that are functions of the state of the economy. The state of the economy when monopolists make their pricing decisions (that is, before the event s_t is realized) must record the capital stocks for a representative monopolist in each cohort in the two countries, the prices set by the other $N-1$ cohorts in the two countries, and the period $t-1$ monetary shocks. The shocks from period $t-1$ are needed because they help forecast the shocks in period t. The current shocks are also included in the state of the economy when the rest of the decisions are made (that is, after the event s_t is realized). We compute the equilibrium using standard methods to obtain linear decision rules (Chari, Kehoe, and McGrattan (2000)). For the benchmark preferences with one-quarter price-stickiness and $N = 2$, we checked the accuracy of the linear decision rules against nonlinear decision rules obtained by the finite element method. (For an introduction to the finite element method, see McGrattan (1996).)

3. PARAMETERIZATION

In this section we describe how we choose functional forms and benchmark parameter values. We report our choices in the top panel of Table 4. In later sections we do extensive sensitivity analyses.

We consider a benchmark utility function of the form

$$U(c, l, M/P) = \frac{1}{1-\sigma}\left[\left(\omega c^{\frac{\eta-1}{\eta}} + (1-\omega)\left(\frac{M}{P}\right)^{\frac{\eta-1}{\eta}}\right)^{\frac{\eta}{\eta-1}}\right]^{1-\sigma} + \psi\frac{(1-l)^{(1-\gamma)}}{1-\gamma} \tag{15}$$

and an intermediate goods production function of the form $F(k, l) = k^{\alpha}l^{1-\alpha}$. Notice that the utility function is separable between a consumption-money aggregate and leisure.

Consider first the preference parameters. The discount factor β is set to give an annual real return to capital of 4 percent. The literature has a wide range of estimates for the curvature parameter σ. We set it to 5 and show later that this value is critical for generating the right volatility in the real exchange rate. Balanced growth considerations lead us to set $\gamma = \sigma$.[3] We set ψ so that households devote 1/4 of their time to market activities. With these choices for γ, σ and ψ, the elasticity of labor supply, with marginal utility held constant, is 1/2.

To obtain η and ω, we draw on the money demand literature. Our model can be used to price a variety of assets, including a nominal bond which costs one dollar at s^t and pays $R(s^t)$ dollars in all states s^{t+1}. The first-order condition for this asset can be written as

$U_m(s^t) = U_c(s^t)[R(s^t) - 1]/R(s^t)$. When we use our benchmark specification of utility, the first-order condition can be rewritten as

$$\log \frac{M(s^t)}{P(s^t)} = -\eta \log \frac{\omega}{1-\omega} + \log c(s^t) - \eta \log \left(\frac{R(s^t) - 1}{R(s^t)} \right), \tag{16}$$

which has the form of a standard money demand function with consumption and interest rates. To obtain η, we ran a quarterly regression from 1960 to 1995 (inclusive) in which we used M1 for money; the GDP deflator for P; consumption of durables, nondurables, and services for c; and the three-month U.S. Treasury bill rate for R. Our estimate of the interest elasticity is $\eta = .39$, and the implied value for ω is .94.

Consider next the final goods technology parameters. In our model, the elasticity of substitution between home goods and foreign goods is $1/(1-\rho)$. Studies have estimated quite a range for this parameter. The most reliable studies seem to indicate that for the United States the elasticity is between 1 and 2, and values in this range are generally used in empirical trade models. (See, for example, the survey by Stern, Francis, and Schumacher (1976).)) We follow the work of Backus, Kehoe, and Kydland (1994) and use an elasticity of 1.5. To set a_1 and a_2, note that in a symmetric steady state, $y_H/y_F = [a_1/a_2]^{\frac{1}{1-\rho}}$. In U.S. data, imports from Europe are roughly 1.6 percent of GDP. This implies that $y_H/y_F = .984/.016$. Together with our normalization, this gives the values of a_1 and a_2 reported in Table 4.

For the intermediate goods technology parameters, we set the capital share parameter $\alpha = 1/3$ and the depreciation rate $\delta = .021$ which implies an annual depreciation rate of 10%., These are typical estimates for U.S. data. Based on the work of Basu and Fernald (1994, 1995), Basu and Kimball (1997), and Basu (1996), we choose $\theta = .9$, which implies a markup of 11 percent and an elasticity of demand of 10. We set $N = 4$, so that prices are set for four quarters based on the empirical studies summarized by Taylor (1999).

We consider an adjustment function of the form $\phi(x/k) = b(x/k - \delta)^2/2$. Notice that with this specification at the steady state, both the total and marginal costs of adjustment are 0. Uncertainty about the size of these adjustment costs is high. In all of our experiments, we choose the parameter b so that the standard deviation of consumption relative to the standard deviation of output is equal to that in the data. One measure of the adjustment costs is the resources used up in adjusting capital relative to investment given by $\phi(x/k)/x$. For our benchmark economy, the average resource cost in adjusting capital is .19 percent of investment.

The details of the monetary rules followed in the United States and Europe are extensively debated. For the benchmark economy we assume that all the monetary authorities follow a simple rule, namely, that the growth rate of the money stocks for both areas follows a process of the form

$$\begin{aligned} \log \mu_t &= \rho_\mu \log \mu_{t-1} + \varepsilon_{\mu t} \\ \log \mu_t^* &= \rho_\mu \log \mu_{t-1}^* + \varepsilon_{\mu t}^*, \end{aligned} \tag{17}$$

where $(\varepsilon_\mu, \varepsilon_\mu^*)$ is a normally distributed, mean-zero shock. (Notice that each period now has a continuum of states. Our earlier analysis with a finite number of states extends immediately to this case.) Each shock has a standard deviation of σ_μ, and the shocks have a positive cross-correlation. The stochastic process for money in the foreign country is the same. We choose $\rho_\mu = .68$ from the data by running a regression of the form (17) on quarterly U.S. data for M1 from 1959:2 through 2001:1 (obtained from the Board of Governors of the Federal Reserve System).

In our experiments, we choose the standard deviation of these shocks so that the volatility of output is the same as in the U.S. data. (For example, in the benchmark model we choose the standard deviation of $\log \mu$ to be 2.3% in order to produce a standard deviation of output of 1.82%. In the data the standard deviation of $\log \mu$ is 1.15%.) We also choose the cross-correlation of these shocks to produce a cross-correlation for outputs that is similar to that in the data. We choose the standard deviation and the cross-correlation of these shocks in this way because we want to investigate whether a model in which monetary shocks account for the observed movements in outputs can also account for the observed movements in exchange rates and other macroeconomic variables.

4. FINDINGS

We report on the H-P–filtered statistics for the data, the benchmark economy, and some variations on that economy in Tables 5 and 6. The statistics for the data are all computed with the United States as the home country and the aggregate of Europe as the foreign country for the period 1973:1-1994:4.[4] In these tables net exports are measured by bilateral real net exports from the United States to Europe. Unless otherwise noted, all other variables are from U.S. data.

Overall, we find that the benchmark model generates nominal and real exchange rates that match the data qualitatively: they are volatile, persistent, and highly cross-correlated. However, quantitatively, along some dimensions, the model does less well: while its volatility of exchange rates is about right, it generates too little persistence in exchange rates, too high a correlation between real exchanges rates and relative consumptions, too much volatility in the price ratio and employment, and too little volatility in investment.

In Table 5, we see that in the benchmark model, compared to output, the nominal exchange rate is 4.32 times as variable and the real exchange rate is 4.27 times as variable. These values are close to those in the data (4.67 and 4.36). The benchmark model also produces substantial persistence (autocorrelations) of nominal and real exchange rates (.69 and .62), but this persistence is less than that in the data (.86 and .83). Because these differences are substantial, we refer to this discrepancy as the persistence anomaly.

The high volatility of real exchange rates comes from our choice of a high curvature parameter σ, which corresponds to a choice of high risk aversion. To see the connection between volatility and σ, log-linearize the expression for real exchange rates, (14), to obtain

$$\hat{q} = A(\hat{c} - \hat{c}^*) + B(\hat{m} - \hat{m}^*) + D(\hat{l} - \hat{l}^*), \tag{18}$$

where a caret denotes the deviation from the steady state of the log of the variable and m, m^* denote real balances. The coefficients A, B, and D are given by

$$A = -\frac{cU_{cc}}{U_c},\ B = -\frac{mU_{cm}}{U_c},\ D = -\frac{lU_{cl}}{U_c},$$

evaluated at the steady state. For preferences of the form (15), the coefficient of relative risk aversion A is approximately equal to the curvature parameter $\sigma = 5$, B is unimportant, and $D = 0$. (The actual values are $A = 4.96$ and $B = .04$. Notice that A is only approximately equal to σ because of the nonseparability between consumption and money balances.) Thus, for our preferences,

$$\frac{\mathrm{std}(\hat{q})}{\mathrm{std}(\hat{y})} \cong \sigma \frac{\mathrm{std}(\hat{c} - \hat{c}^*)}{\mathrm{std}(\hat{y})}.$$

In Figure 3 we graph the benchmark model's volatility of the real exchange rates against the curvature parameter σ, where this volatility is measured as in Table 5. As we vary σ, we alter the adjustment cost parameter b to keep roughly unchanged the standard deviation of consumption relative to that of output.[5] We see that a curvature parameter of about 5 is needed to reproduce the data's volatility of real exchange rates relative to output (4.36). Note also in Figure 3 that as σ is varied, the autocorrelation of real exchange rates is essentially unchanged.

In terms of the persistence of real exchange rates, for our preferences the autocorrelation of real exchange rates can be written as

$$\mathrm{corr}(\hat{q}, \hat{q}_{-1}) \cong \mathrm{corr}(\hat{c} - \hat{c}^*, \hat{c}_{-1} - \hat{c}^*_{-1}).$$

This expression suggests that the autocorrelation of real exchange rates is essentially determined by the autocorrelation of consumption. In Table 6, we see that the autocorrelation of consumption in the model is high (.61) but less than that in the data (.89), which mirrors the feature (from Table 5) that the autocorrelation of real exchange rates is high in the model but less than that in the data.

Note that without substantial price-stickiness, neither consumption nor real exchange rates would have much persistence. To see this, consider Figure 4 in which we graph the autocorrelation of consumption, the autocorrelations of real and nominal exchange rates, and the volatility of the price ratio relative to that of output against the number of periods that prices are held fixed, N. Notice that the autocorrelations of consumption and the real exchange rate match almost exactly. When $N = 1$, consumption is negatively autocorrelated, as is the real exchange rate. As N increases, so do the autocorrelations of consumption and the real exchange rate. Notice also that as the number of periods of price-stickiness increases, the volatility of the price ratio declines and the behavior of the real exchange rate comes to mirror that of the nominal exchange rate.

Our model has a tight link between real exchange rates and the ratio of marginal utilities given by (18). This link implies a high correlation between real exchange rates and relative consumptions. In Table 6 we see that in the data this correlation is $-.35$ while in the model it is about 1. We address this discrepancy in Section 7.

Consider now the rest of the statistics for the benchmark economy in Tables 5 and 6. In Table 5, we see that the price ratio is substantially more volatile in the model (3.00) than in the data (.71) while real and nominal exchange rates are less correlated in the model (.76) than in the data (.99). These differences occur because prices move to offset nominal exchange rate movements more in the model than in the data. In Table 6, we see that real exchange rates and output are more correlated in the model than in the data (.51 vs. .08), while real exchange rates and net exports are slightly negatively correlated in the model ($-.04$) and slightly positively correlated in the data (.14).[6]

In Table 6, we see that investment is a little over a half as volatile in the model as in the data (1.59 vs. 2.78), while employment is more than twice as volatile in the model as in the data (1.51 vs. .67). Investment is less volatile in the model because when $\sigma = 5$, we need to use a relatively high adjustment cost parameter to make consumption have the right volatility. With that level of adjustment costs, investment is not very volatile. If we used a sufficiently low adjustment cost parameter, investment would be as volatile as in the data, but consumption would be significantly less volatile. (For example, when we choose the adjustment cost parameter so that investment has a volatility of about 2.78, the volatility of consumption is only .50 while in the data it is .83)

Employment is more rather than less volatile than output in the model because almost all of the movement in output comes from variations in the labor input. Specifically, note that log-deviations in output can be written as $\hat{y} = \alpha\hat{k} + (1-\alpha)\hat{l}$. Since investment is only a small percentage of the capital stock, this stock moves only a small amount at business cycle frequencies, and we roughly have that $\text{std}(\hat{y}) \cong (1-\alpha)\text{std}(\hat{l})$. With $\alpha = 1/3$, this gives

$\text{std}(\hat{l})/\text{std}(\hat{y}) \cong 1.5$. So, in a sticky price model like ours, we should expect employment to be much more volatile than output. This feature does not arise in standard real business cycle models because in them the technology shock accounts for much of the movement in output.[7] (A related problem of sticky price models more generally is that labor productivity is countercyclical in the model but procyclical in the data.)

In Table 6, we also see that in the model, the cross-country correlation of output is the same as that of consumption (.49 in both) while in the data, the cross-correlation of output is higher than that of consumption (.60 vs. .38). While the cross-correlation of consumption in our model is higher than that in the data, the model does much better on this dimension than does the standard real business cycle model (see Backus, Kehoe, and Kydland (1994)). In the standard real business cycle model the law of one price holds for all traded goods and the real exchange rate does not vary as much as it does in our model. Since an equation like (14) holds in both models, the lower variability of real exchange rates in the real business cycle model leads to a higher correlation of the marginal utilities of consumption and, thus, to a higher cross-country correlation of consumption. A minor discrepancy between the benchmark model and the data is that in the data, net exports are somewhat countercyclical ($-.41$) while in the model they are essentially acyclical (.04).

5. SENSITIVITY ANALYSIS

Here we examine the findings of our benchmark model by varying assumptions about four of the model's features. We raise the export share and find little change. We consider nonseparable preferences and find a dramatic reduction in the volatility of real exchange rates. We add technology and government consumption shocks and find little change. Finally, we model monetary policy as an interest rate rule and a find some reduction in the persistence of real exchange rates.

A. *Export share*

We have chosen parameters so that the export share of output is 1.6 percent, which is similar to the share that the United States has in its bilateral trade with Europe. More open economies have much larger shares than this. To see what difference a larger share might make, we consider a variation of the model with an export share of 15 percent (by adjusting a_1 and a_2 accordingly). To put this number in perspective, note that it is similar to the share that the United States has with the rest of the world.

In Tables 5 and 6, the columns labeled “High Exports” list the model's predictions with the 15 percent export share. Having a high export share worsens the performance of net exports by making them more procyclical and by slightly lowering their correlation with real exchange rates. But it produces little change overall.

B. *Nonseparable Preferences*

One concern with our benchmark preferences is that balanced growth considerations impose a very tight restriction between γ, a parameter that determines the labor supply elasticity, and σ, a parameter that determines risk aversion. If these parameters do not satisfy this restriction growth is unbalanced. A commonly used class of preferences yields balanced growth with no such restrictions. A typical specification of such preferences is

$$U(c,l,M/P) = \left[\left(\omega c^{\frac{\eta-1}{\eta}} + (1-\omega)(M/P)^{\frac{\eta-1}{\eta}}\right)^{\frac{\eta}{\eta-1}} (1-l)^{\xi}\right]^{1-\sigma} /(1-\sigma). \tag{19}$$

It is easy to verify that these preferences are consistent with balanced growth.

Unfortunately, these preferences do not generate volatile exchange rates. To see this we set the parameters η, σ, and ω as in the benchmark model. We set $\xi = 2.25$, as is typical in the business cycle literature (for example, Chari, Christiano, and Kehoe (1991)), and we display the resulting statistics in the columns labeled “Nonseparable Preferences” in Tables 5 and 6. Now real exchange rates vary hardly at all.

To understand this finding, recall that the real exchange rate is the ratio of the marginal utility of consumption in the two countries. In this model monetary shocks lead to small changes in the marginal utility of consumption because movements in employment tend to offset the effects of movements in consumption. Here an increase in the money growth rate in the home country increases both consumption and employment in that country. The increase in consumption decreases the marginal utility of home consumption. With our nonseparable preferences and $\sigma > 1, U_{cl} > 0$ so that the increase in employment increases the marginal utility of home consumption and hence tends to offset the effects of marginal utility arising from consumption. This offsetting effect is not present when preferences are separable in leisure since $U_{cl} = 0$.

To get a quantitative feel for the magnitude of the offsetting effects from employment consider the expression for log-linearized real exchange rates

$$\hat{q} = A(\hat{c} - \hat{c}^*) + B(\hat{m} - \hat{m}^*) + D(\hat{l} - \hat{l}^*), \tag{20}$$

where the coefficients are $A = -cU_{cc}/U_c$, $B = -mU_{cm}/U_c$, and $D = -lU_{cl}/U_c$. In our quantitative model $A = 4.96$, $B = .04$, and $D = -3.02$. Since B is essentially zero, the flucuations in real balances are quantitatively unimportant in determining the variance of real exchange rates. To gain intuition we suppose that B is exactly zero so that

$$\begin{array}{ccccccc} \dfrac{\operatorname{var}\hat{q}}{\operatorname{var}\hat{y}} & \cong & A^2\dfrac{\operatorname{var}(\hat{c}-\hat{c}^*)}{\operatorname{var}\hat{y}} & + D^2 & \dfrac{\operatorname{var}(\hat{l}-\hat{l}^*)}{\operatorname{var}\hat{y}} & + 2AD & \dfrac{\operatorname{cov}(\hat{c}-\hat{c}^*,\hat{l}-\hat{l}^*)}{\operatorname{var}\hat{y}} \\ & & 21.16 & + & 20.98 & - & 42.24 \end{array} \tag{21}$$

where the numbers below the equation are the values of each of the three terms for the model economy with nonseparable preferences. Here we have used the values for the model's statistics given by $\operatorname{var}(\hat{c} - \hat{c}^*)/\operatorname{var}\hat{y} = .86$, $\operatorname{var}(\hat{l} - \hat{l}^*)/\operatorname{var}\hat{y} = 2.30$, and $\operatorname{cov}(\hat{c} - \hat{c}^*, \hat{l} - \hat{l}^*)/\operatorname{var}\hat{y} = 1.41$. The numbers below (21) demonstrate the importance of the covariance between relative consumption and relative employment in the two countries. Notice that if D were equal to zero, then the variance of the real exchange relative to output is simply the first term in (21) and the standard deviation relative to output would be 4.6. Thus, if it were not for the offsetting effects from employment, the model with nonseparable preferences could easily generate the volatility of exchange rates seen in the data.

It is worth pointing out that the offsetting effects from employment are higher in the model than in the data. In the data $\operatorname{var}(\hat{c} - \hat{c}^*)/\operatorname{var}\hat{y} = .62$, $\operatorname{var}(\hat{l} - \hat{l}^*)/\operatorname{var}\hat{y} = .40$, and $\operatorname{cov}(\hat{c} - \hat{c}^*, \hat{l} - \hat{l}^*)/\operatorname{var}\hat{y} = .37$. Substituting these values into (21) and using $A = 4.96$ and $D = -3.02$ gives that $\operatorname{std}\hat{q}/\operatorname{std}\hat{y} = 2.8$. Thus, the main problem with nonseparable preferences is that in the model the covariance between relative consumption and relative employment is much larger than in the data (1.41 vs. .37). Of course, if the model could generate the type of comovements between relative consumption and relative employment seen in the data, it would also generate a substantial amount of the variability of real exchange rates seen in the data.

In our benchmark model we assume that preferences are separable between consumption and leisure. Thus, $D = 0$, there are no offsetting effects from employment and the model can generate the volatility of real exchange rates seen in the data if A is sufficiently large, regardless of the comovements between relative consumption and relative employment. Indeed, for the benchmark model $\text{cov}(\hat{c} - \hat{c}^*, \hat{l} - \hat{l}^*)/\ \text{var}\,\hat{y} = 1.33$, so that the model misses the data in terms of this statistic, but with $D = 0$, that problem does not affect the volatility of real exchange rates.

C. *Real shocks*

So far the only shocks in the model are monetary shocks. Now we add real shocks of two types: shocks to technology and to government consumption. Here we primarily want to examine whether adding these shocks improves the model's performance on business cycle statistics. As noted above, employment is too volatile in our model because variation in labor input is the primary source of variation in output at business cycle frequencies. Adding other shocks will add other sources of variation in output.

We allow for country-specific technology shocks which are common across all intermediate goods producers. The technology for producing intermediate goods in the home country and foreign countries is now $F(k_t, A_t l_t)$ and $F(k_t^*, A_t^* l_t^*)$. Here the technology shocks A_t and A_t^* are common across all intermediate goods and follow a stochastic process given by $\log A_{t+1} = \rho_A \log A_t + \varepsilon_{At+1}$ and $\log A_{t+1}^* = \rho_A \log A_t + \varepsilon_{At+1}^*$, where the technology innovations ε_A and ε_A^* have zero means, are serially uncorrelated, and are uncorrelated with shocks to money and government consumption. We follow Kehoe and Perri (2000) and use $\rho_A = .95$, $\text{var}(\varepsilon_A) = \text{var}(\varepsilon_A^*) = (.007)^2$, and $\text{corr}(\varepsilon_A, \varepsilon_A^*) = .25$.

We add government consumption shocks as follows. The final good is now used for government consumption as well as private consumption and investment. The resource constraint for the home country is now

$$y_t = c_t + g_t + \int_0^1 x_t(i)\, di,$$

where home government consumption g_t follows a stochastic process $\log g_{t+1} = (1-\rho_g)\mu_g + \rho_g \log g_t + \varepsilon_{gt+1}$. To obtain estimates for this autoregressive process, we ran a regression with data on real government purchases for the United States over the period 1947:1 through 1998:4. Our estimates from this regression are as follows: $\mu_g = .13$, $\rho_g = .97$, and $\text{var}(\varepsilon_g) = (.01)^2$. We assume that the shock ε_g is serially uncorrelated and uncorrelated with shocks to money and technology and to the shock to government consumption in the foreign country. We model government consumption in the foreign country symmetrically. In each period, first the technology and government consumption shocks are realized, then prices are set, and then the monetary shock is realized. (Alternative timing assumptions lead to similar results.)

We report the results for this economy in the columns labeled "Real Shocks" in Tables 5 and 6. Again, most of the statistics change little. However, the relative volatility of employment actually increases slightly (from 1.51 in the benchmark model to 1.56 in the model with real shocks). To understand this finding note that here the log-deviations in output are approximately given by $\hat{y} \cong (1-\alpha)(\hat{A}+\hat{l})$ so that

$$\frac{\mathrm{var}\,\hat{\mathrm{l}}}{\mathrm{var}\,\hat{\mathrm{y}}} \cong \frac{1}{(1-\alpha)^2} - \frac{\mathrm{var}\,\hat{\mathrm{A}}}{\mathrm{var}\,\hat{\mathrm{y}}} - \frac{2\mathrm{cov}(\hat{\mathrm{A}},\hat{\mathrm{l}})}{\mathrm{var}\,\hat{\mathrm{y}}}.$$

From this expression we see that introducing technology shocks can increase the variability of employment if technology shocks and employment are sufficiently negatively correlated. In the model, on impact a positive technology shock leads to a fall in employment since firms can meet the same demand with fewer workers. This feature of the model makes technology shocks and employment negatively correlated enough to raise the relative volatility of employment. Government consumption shocks, meanwhile, have a quantitatively insignificant role.

D. *Taylor rule*

There is a lively debate over the most appropriate way to model monetary policy. A recently popular way to do so has been with an interest rate rule. Here we discuss how our money growth rule can be interpreted as an interest rate rule, and we describe the properties of our model economy under several interest rate rules that stem from the work of Taylor (1993).

Logically, any interest rate rule can be interpreted as a money growth rule and vice versa. To see this, posit an interest rate rule and work out the equilibrium of the economy. This equilibrium has a corresponding money growth process associated with it. Clearly, if one views this money growth process as the policy, then the equilibrium for this economy with this money growth is the same as that for an economy with the interest rate rule. Of course, if there are multiple equilibria under the interest rule, then for each equilibrium, there is a different money growth process that implements it. The converse also holds. (Of course, such rules can be represented either as a function of both past endogenous variables and exogenous shocks or as a function solely of the history of exogenous shocks.) Moreover, there is empirical evidence in support of our choice for the money growth rule. In particular, Christiano, Eichenbaum, and Evans (1998) have shown with vector autoregression analysis that a money growth process of the kind considered here is a good approximation to a process that implements their estimated interest rate rule.

As a practical matter, however, some simple interest rate rule might be a better approximation to the policy in the data than is our simple money growth rule. Thus, we consider the implications of replacing our simple rule for money growth rates with an interest rate rule similar to those studied by Taylor (1993) and Clarida, Gali, and Gertler (2000).

In particular, we assume that nominal interest rates r_t are set as a function of lagged nominal rates, expected inflation rates, and output according to

$$r_t = \rho_r r_{t-1} + (1 - \rho_r)\left(\alpha_\pi E_t \pi_{t+1} + \alpha_y [\ln \mathrm{gdp}_t]/4\right) + \varepsilon_{rt}, \tag{22}$$

where we have dropped the constant and converted units to quarterly rates. In (22) π_{t+1} is the inflation rate from t to $t+1$, gdp_t is real gross domestic product at t, and ε_{rt} is a normally distributed, mean-zero shock. We set $\rho_r = .79$, $\alpha_\pi = 2.15$, and $\alpha_y = .93$. (The numbers are taken from Clarida, Gali, and Gertler (2000), Table II.) We choose the volatility of the shocks to match the volatility of output, and we choose the correlation of the home shock ε_{rt} and the foreign shock to match the cross-correlation of output.

When we use this Taylor rule in our benchmark model, we are unable to generate reasonable business cycle behavior. Briefly, for low values of the adjustment cost parameter the relative volatility of consumption is tiny. For high values of the adjustment cost parameter the relative volatility of consumption increases but the correlation between consumption and output is negative. On closer investigation, we found that these features of the model were driven by the nonseparability of consumption and money balances. Since we do not view this nonseparability as a crucial feature of our model, we investigate a version with the Taylor rule and with preferences of the form

$$\frac{c^{1-\sigma}}{1-\sigma} + \omega\frac{(M/P)^{1-\sigma}}{1-\sigma} + \psi(1-l)^{(1-\gamma)}/(1-\gamma).$$

We set the parameters σ, ψ and γ as before. (The parameter ω is not relevant since money demand is determined residually.) In Tables 5 and 6, we report the results for this exercise in the columns labeled "Taylor Rule." This model moves the volatilities of the price ratio and the exchange rates closer to those in the data. Unfortunately, however, the model's nominal and real exchange rates, with autocorrelations of .46 and .48, are much less persistent than those in either the data or the benchmark model.

We also investigated the properties of the economy using a Taylor rule estimated by Rotemberg and Woodford (1997). Their estimated Taylor rule uses three lags of nominal interest rates and inflation together with current output and two of its lags. When we use this rule we obtain essentially the same results as we did with the one estimated by Clarida, Gali, and Gertler (2000). For example, the autocorrelations of nominal and real exchange rates are .40 and .43.

Nominal exchange rates are less persistent in the Taylor rule model than in the benchmark model because the endogenous policy reaction tends to offset the exogenous shocks. For example, a negative shock to interest rates in (22) raises the quantity of money and leads to a rise in inflation in subsequent periods. This rise in inflation leads to an endogenous increase in interest rates that offsets the initial shock. As a result, interest rates are not very persistent and, hence, neither are movements in consumption or real exchange rates. We confirmed this intuition by analyzing the properties of the model for higher values of ρ_r. For example, when we raised ρ_r from .66 to .95, the autocorrelations of nominal and real exchange rates increased from .46 and .48 to .63 and .60, while for $\rho_r = .99$, these autocorrelations increased even further, to .64 and .63.

6. ADDRESSING THE PERSISTENCE ANOMALY

Our benchmark model displays a persistence anomaly in that the model generates somewhat less persistence in real exchange rates than is present in the data. One avenue for increasing persistence seems promising: adding labor frictions by making wages sticky. However, this change leads to only a marginal improvement in the benchmark model's persistence performance.

Our logic for using sticky wages to increase persistence is as follows. In the benchmark model wages immediately rise after a monetary shock. This rise in wages leads intermediate goods producers to increase their prices as soon as they can. Thus, the benchmark model generates little endogenous price-stickiness, that is, price-stickiness beyond that exogenously imposed. Preset nominal wages cannot rise after a monetary shock. If they do not, intermediate goods producers may choose not to raise prices much when they can. Hence the model may lead to some endogenous price-stickiness and, consequently, more persistence in exchange rates.

We extend the benchmark model to include sticky wages by letting labor be differentiated and having monopolistically competitive unions that set wages in a staggered way for M periods.

The final goods producers in the model remain as before, while the problems of the intermediate goods producers and the consumers are altered. The only change in technology is that the labor input $l(i, s^t)$ of intermediate goods producer i is now a composite of a continuum of differentiated labor inputs $j \in [0,1]$ and is produced according to

$$l(i,s^t) = \left[\int l(i,j,s^t)^{\vartheta}\, dj\right]^{1/\vartheta}, \tag{23}$$

where $l(i,j,s^t)$ denotes the amount of differentiated labor input j used by intermediate goods producer i in date t.

The problem of the intermediate goods producer is the same as before except that now we have a sub-problem of determining the cost-minimizing composition of the different types of labor. The term $w(s^t)l(i,s^t)$ in the intermediate goods producers' problem (7) is now replaced by

$$w(s^t)l(i,s^t) = \min_{\{l(i,j,s^t)\},j\in[0,1]} \int \frac{W(j,s^{t-1})}{P(s^t)}\, l(i,j,s^t)\, dj \tag{24}$$

subject to (23) where $W(j,s^{t-1})$ is the nominal wage for the jth type of labor in date t and where the dependence of this wage on s^{t-1} reflects our timing assumption on the setting of wages discussed below. The solution to this problem is the demand for labor of type j by intermediate goods producer i, namely

$$l(i,j,s^t) = \left(\frac{\bar{W}(s^t)}{W(j,s^{t-1})}\right)^{\frac{1}{1-\vartheta}} l(i,s^t),$$

where $\bar{W}(s^t) = \left[\int W(j,s^{t-1})^{\frac{\vartheta}{\vartheta-1}}\, dj\right]^{\frac{\vartheta-1}{\vartheta}}$ is the nominal wage index. Substitution of the demand into (24) implies that the real wage index is given by $w(s^t) = \bar{W}(s^t)/P(s^t)$.

The consumer side of the labor market can be thought of as being organized into a continuum of unions indexed by j. Each union consists of all the consumers in the economy with labor of type j. Each union realizes that it faces a downward-sloping demand for its type of labor. The total demand for labor of type j is obtained by integrating across the demand of the intermediate goods producers and is given by

$$l^d(j,s^t) = \left(\frac{\bar{W}(s^t)}{W(j,s^{t-1})}\right)^{\frac{1}{1-\vartheta}} \int l(i,s^t)\, di. \tag{25}$$

We assume that a fraction $1/M$ of unions set their wages in a given period and hold them fixed for M subsequent periods. The unions are indexed so that those with $j \in [0,1/M]$ set new wages in 0, M, $2M$, and so on, while those with $j \in [1/M, 2/M]$ set new wages in 1,

$M+1$, $2M+1$, and so on, for the M cohorts of unions. In each period these new wages are set before the realization of the current money shocks. Notice that the wage-setting arrangement is analogous to the price-setting arrangement for intermediate goods producers.

The problem of the jth union, for say $j \in [0, 1/M]$, is to maximize

$$\sum_{t=0}^{\infty} \sum_{s^t} \beta^t \pi(s^t)\, U\left(c(j, s^t), l^d(j, s^t), M(j, s^t)/P(s^t)\right) \tag{26}$$

subject to the labor demand schedule (25), the budget constraints

$$\begin{aligned} P(s^t)c(j, s^t) + M(j, s^t) + \textstyle\sum_{s_{t+1}} Q(s^{t+1}|s^t)B(j, s^{t+1}) \\ \leq W(j, s^{t-1})l^d(j, s^t) + M(j, s^{t-1}) + B(j, s^t) + \Pi(s^t) + T(s^t), \end{aligned} \tag{27}$$

and the constraints that wages are set for M periods, $W(j, s^{t-1}) = W(j, s^{-1})$ for $t = 0, \ldots, M-1$, and $W(j, s^{t-1}) = W(j, s^{M-1})$ for $t = M, \ldots, 2M-1$ and so on. We choose the initial bond holdings of the unions so that each union has the same present discounted value of income.

In this problem, the union chooses the wage and agrees to supply whatever is demanded at that wage. The first-order conditions are changed from those in the benchmark economy as follows. The condition for the labor choice (10) is replaced by the condition for nominal wages

$$W(j, s^{t-1}) = -\frac{\sum_{\tau=t}^{t+M-1} \sum_{s^\tau} Q(s^\tau)P(s^\tau)U_l(j, s^\tau)/U_c(j, s^\tau)l^d(j, s^\tau)}{\vartheta \sum_{\tau=t}^{t+M-1} \sum_{s^\tau} Q(s^\tau)l^d(j, s^\tau)}. \tag{28}$$

Notice that in a steady state, this condition reduces to $W/P = (1/\vartheta)(-U_l/U_c)$, so that real wages are set as a markup over the marginal rate of substitution between labor and consumption. The conditions (11) and (12) are now indexed by j. These conditions, together with our assumption on initial bond holdings, imply that $U_c(j, s^t)$ and $U_m(j, s^t)$ are equated across unions.

The new parameters in the model are the number of periods of wage-setting M and the markup parameter ϑ. Following Taylor's (1999) discussion of the evidence, we set $M = 4$. We set $\vartheta = .87$ so that the markup is about 15 percent. This markup is consistent with estimates of the markup of union wages over non-union wages. (See Lewis 1986.)

In Tables 5 and 6, in the columns labeled "Sticky Wages," we see that the sticky wage model improves upon the benchmark model only slightly. The sticky wage model decreases the volatility of the price ratio (from 3.00 to 2.11) and increases the volatility of real exchange rates (from 4.27 to 4.35). The sticky wage model also slightly increases the persistence of real exchange rates (from .62 to .69) and the cross-correlation of real and nominal exchange rates (from .76 to .88). The business cycle statistics remain basically unchanged, except for the correlations of real exchange rates with GDP and net exports, which worsen slightly.

7. ADDRESSING THE CONSUMPTION-EXCHANGE RATE ANOMALY

Here we address the consumption-real exchange rate anomaly. To do this, we restrict the set of assets that can be traded across countries, thereby making markets incomplete. This avenue weakens the link between real exchange rates and relative consumptions. Another avenue we explore is allowing for habit persistence in preferences. We find that neither avenue is successful in solving the consumption-real exchange rate anomaly.

With incomplete markets, the simple static relationship between the real exchange rate and the ratio of the marginal utilities given in (18) is replaced by one that holds only in expected first-differences. Furthermore, with incomplete markets monetary shocks can lead to wealth redistributions across countries and can increase the persistence of real exchange rates. Unfortunately, making markets incomplete has little quantitative effect. Both the correlation between real exchange rates and relative consumptions and the persistence of real exchange rates are essentially the same as in the benchmark model.

We introduce market incompleteness into the benchmark model by replacing the complete set of contingent bonds traded across countries by a single uncontingent nominal bond. This bond is denominated in units of the home currency. The home consumer's budget constraint is now

$$\begin{aligned}&P(s^t)c(s^t) + M(s^t) + \bar{Q}(s^t)D(s^t)\\ &\qquad \leq P(s^t)w(s^t)l(s^t) + M(s^{t-1}) + D(s^{t-1}) + \Pi(s^t) + T(s^t),\end{aligned} \tag{29}$$

where D is the consumer's bond holdings. The real value of these bonds $D(s^t)/P(s^t)$ is bounded below. Here each unit of $D(s^t)$ is a claim on one unit of the home currency in all states s^{t+1} that can occur at $t+1$, and $\bar{Q}(s^t)$ is the corresponding price. The foreign consumer's budget constraint is modified similarly.

The first-order condition for bond-holding in the home country is now given by

$$\bar{Q}(s^t) = \sum_{s_{t+1}} \beta\pi(s^{t+1}|s^t) \frac{U_c(s^{t+1})}{U_c(s^t)} \frac{P(s^t)}{P(s^{t+1})}, \tag{30}$$

while that in the foreign country is given by

$$\bar{Q}(s^t) = \sum_{s_{t+1}} \beta\pi(s^{t+1}|s^t) \frac{U_c^*(s^{t+1})}{U_c^*(s^t)} \frac{e(s^t)}{e(s^{t+1})} \frac{P^*(s^t)}{P^*(s^{t+1})}. \tag{31}$$

Equating (30) and (31) and log-linearizing the resulting equations gives

$$E_t\left[\hat{U}_{ct+1} - \hat{U}_{ct} + \hat{P}_t - \hat{P}_{t+1}\right] = E_t\left[\hat{U}^*_{ct+1} - \hat{U}^*_{ct} + \hat{e}_t + \hat{P}^*_t - \hat{e}_{t+1} - \hat{P}^*_{t+1}\right], \tag{32}$$

where carets denote log-deviations from a steady state with $D = 0$. Noting that $\hat{q}_t = \hat{e}_t + \hat{P}^*_t - \hat{P}_t$, we can rewrite (23) as

$$E_t\left[\hat{q}_{t+1} - \hat{q}_t\right] = E_t\left[(\hat{U}^*_{ct+1} - \hat{U}_{ct+1}) - (\hat{U}^*_{ct} - \hat{U}_{ct})\right]. \tag{33}$$

Thus, with incomplete markets, the relation between real exchange rates and marginal utilities only holds in expected first-differences.

In Tables 5 and 6, we report statistics for an incomplete market economy which has the same parameters as does the benchmark economy, but has the asset structure just discussed. In the columns labeled "Incomplete Markets," the statistics in both tables are virtually identical to those for the benchmark economy with complete markets. Thus, while adding incomplete markets theoretically could help solve the consumption-real exchange rate and persistence anomalies, quantitatively it does not.

In our benchmark model the tight link between real exchange rates and marginal utilities arises because of consumers' abilities to trade in asset markets. This observation suggests that the consumption-real exchange rate anomaly might be addressed with specifications of utility functions used to analyze other asset market anomalies. One such specification has external habit persistence in that lagged aggregate consumption enters each household's period utility function. In our context we can add habit persistence by replacing c_t in (15) with $c_t - d\bar{c}_{t-1}$ where $\bar{c}_{t-1}$ is lagged aggregate consumption and d is the habit persistence parameter. With this formulation, using the equilibrium conditions that $c_t = \bar{c}_t$ and $c_t^* = \bar{c}_t^*$, (18) becomes

$$\hat{q}_t = \frac{A}{1-d}[(\hat{c}_t - \hat{c}_t^*) - d(\hat{c}_{t-1} - \hat{c}_{t-1}^*)] + B(\hat{m} - \hat{m}^*), \tag{34}$$

where $A = -cU_{cc}/U_c$ and $B = -mU_{cm}/U_c$. In what follows, we set B to 0 since it is quantitatively small.

We can use the data to see whether the habit persistence approach is promising. Using filtered data for the United States and Europe, we compute the correlation between real exchange rates and the right-hand side of (34). We experimented with values for d between -1 and 1 and found that this correlation attains its maximum value of $-.19$ at d arbitrarily close to 1. If the theory is correct, this correlation will be 1. We conclude that this popular version of the habit persistence approach is not particularly promising.

Given that a number of models cannot produce the negative correlation between real exchange rates and relative consumption in U.S.-European data, we ask whether this negative correlation is pervasive across different sets of countries. In Table 7 we report the correlation between bilateral real exchange rates and bilateral relative consumptions for a number of countries. This correlation varies between $-.48$ and .14. This observation suggests that there is no tight link in the data. Clearly, we need models with asset market frictions to break the tight link between real exchange rates and marginal utililities and thus between real exchange rates and relative consumptions.

8. CONCLUSION

The central puzzle in international business cycles is the large and persistent fluctuations in real exchange rates. In this paper, we have taken a step toward solving that puzzle. We have developed a general equilibrium sticky price model which can generate fluctuations in real exchange rates that are appropriately volatile and quite persistent, though not quite persistent enough. We have found that for monetary shocks to generate these data, the model needs to have separable preferences, high risk aversion, and price-stickiness of at least one year. We have also found that if monetary shocks are correlated across countries, then the comovements in aggregates across countries in the model are broadly consistent with those in the data.

We have seen that without substantial price-stickiness, real exchange rates are not persistent. We have assumed that prices are exogenously fixed for one year. While this assumption generates movements in prices that are consistent with the evidence in Taylor (1999), it is somewhat unappealing to simply assume that firms cannot change their prices for a year. A major challenge in this line of research is to find a mechanism that generates substantial amounts of endogenous price-stickiness from small frictions. By this, we mean a mechanism that leads firms to optimally choose not to change prices much even when they can freely do so.

The main failing of our model is the consumption-real exchange rate anomaly: the model predicts a high correlation between the real exchange rate and relative consumptions while none exists in the data. We have shown that complete asset markets give rise to a tight link the real exchange rate and relative consumption which generates the anomaly. In particular, such frictions as sticky prices, sticky wages, and trading frictions in goods markets play no role in breaking this link. We have also shown that the most widely used forms of asset market incompleteness and habit persistence do not dispel the anomaly.

Essentially all of the models in the international business cycle literature, real or nominal, have either complete markets or the type of incomplete markets considered here. Our analysis suggests that all of these models will display this anomaly. Future research should focus on richer forms of asset market frictions to address this anomaly.

Acknowledgments. This paper is a revised version of our 1996 paper entitled "Monetary Shocks and Real Exchange Rates in Sticky Price Models of International Business Cycles." A technical appendix, computer codes, and the data used in this paper are available at our website, http://minneapolisfed.org/research/sr/sr277.html. Chari and Kehoe thank the National Science Foundation for support. The views expressed herein are those of the authors and not necessarily those of the Federal Reserve Bank of Minneapolis or the Federal Reserve System.

Notes

[1]In particular, our constructed index is $e_t = \sum_{i \in \mathcal{I}} \omega_i e_{it}/e_{i0}$, where e_{it} is the exchange rate for country i in period t, e_{i0} is the exchange rate for country i in the first quarter of 1973, and the weight ω_i is the time series average of the ratio of the dollar value of exports plus imports between country i and the United States to the total dollar value of all exports plus imports between the European countries included in set $\mathcal{I}$ and the United States. The countries (trade weights) included in our data set are: Austria (1.2), Denmark (1.8), Finland (1.2), France (13.8), Germany (25.7), Italy (11.6), the Netherlands (10.5), Norway (2.2), Spain (2.7), Switzerland (5.8), and the United Kingdom (23.5).

[2]Our real exchange rate measure is substantially more volatile than another measure of the real exchange rate between the United States and the rest of the world. The IMF's *International Financial Statistics* reports the effective real exchange rate for the United States, based on weights derived from the multilateral exchange rate model (MERM). For the period 1980:1-2000:1 this exchange rate has a standard deviation of 4.63 and an autocorrelation of .82. The MERM measure is less volatile presumably because shocks affecting bilateral exchange rates are not perfectly correlated across countries, and the MERM measure averages across more countries than our measure does.

[3]To derive our benchmark model's implications for growth paths, we suppress uncertainty and add equal rates of productivity growth to both the market and nonmarket sectors. In the market sector, suppose that the technology for each intermediate goods producer is given by $F(k_t, z_t l_t)$, where z_t grows at a constant rate z. In the nonmarket sector, in the spirit of Becker (1993), suppose that technical progress raises the productivity of time allocated to nonmarket activities, so that an input of $(1 - l_t)$ units of time outside the market produces $z_t(1 - l_t)$ units of leisure services. With our benchmark preferences if c_t and m_t grow at the same rate as z_t and if l_t is a constant, then $-\frac{U_{lt}}{U_{ct}} = \kappa \frac{(1+z)^{(1-\gamma)t}}{(1+z)^{-\sigma t}}$ where κ is a constant. Along a balanced growth path, wages grow at the same rate as z_t, so that in order for the economy to have a balanced growth path, it must have $\sigma = \gamma$.

[4]Our series for the foreign country are aggregates for France, Italy, the United Kingdom and Germany obtained from the OECD. Our choices of countries and time period are dictated by data availability. We convert these series into dollars using the OECD's 1990 purchasing power parity exchange rate and add the results to obtain our aggregates for Europe. Exports and imports are reported in U.S. dollars.

[5]If we keep the adjustment cost parameter unchanged, then as we increase σ, the relative volatility of consumption and output decreases somewhat. Hence, the volatility of the real

exchange rate increases with σ, but at a somewhat slower rate. For example, with b held fixed, the volatility of the real exchange rate at $\sigma = 1.01$ and 10 is 1.21 and 6.39, while when b is adjusted, these volatilities are .87 and 8.75.

[6]It is worth noting that, across countries, there is greater heterogeneity in the correlations between real exchange rates and various aggregates, like output, net exports and relative consumptions than for other statistics, like the volatility and persistence of real exchange rates or the cross-correlation of real and nominal exchange rates.

[7]One extension that might help sticky price models in this dimension is to have cyclical variations in the intensity that measured capital and labor are worked.

References

ARMINGTON, P. S. (1969), "A Theory of Demand for Products Distinguished by Place of Production", *International Monetary Fund Staff Papers,* **16**, 159–178.

BACKUS, D. K.; KEHOE, P. J.; and KYDLAND, F. E. (1994), "Dynamics of the Trade Balance and the Terms of Trade: The J-Curve?", *American Economic Review,* **84**, 84–103.

BALL, L., and ROMER, D. (1989), "Are Prices Too Sticky?", *Quarterly Journal of Economics,* **104**, 507–524.

BASU, S. (1996), "Procyclical Productivity: Increasing Returns or Cyclical Utilization?" *Quarterly Journal of Economics,* **111**, 719–751.

BASU, S., and FERNALD, J. G. (1994), "Constant Returns and Small Markups in U.S. Manufacturing," (International Finance Discussion Paper 483, Board of Governors of the Federal Reserve System).

__________. (1995), "Are Apparent Productive Spillovers a Figment of Specification Error?" *Journal of Monetary Economics,* **36**, 165–188.

BASU, S., and KIMBALL, M. S. (1997), "Cyclical Productivity With Unobserved Input Variation," (Working Paper 5915, National Bureau of Economic Research).

BECKER, G. S. (1993), *Human Capital: A Theoretical and Empirical Analysis, With Special Reference to Education,* 3rd ed. (Chicago: University of Chicago Press).

BETTS, C., and DEVEREUX, M. B. (2000), "Exchange Rate Dynamics in a Model of Pricing-to-Market", *Journal of International Economics,* **50**, 215–244.

BLANCHARD, O. J., and KIYOTAKI, N. (1987), "Monopolistic Competition and the Effects of Aggregate Demand," *American Economic Review,* **77**, 647–666.

BOLDRIN, M.B., CHRISTIANO, L.J., and FISHER J. "Habit Peristence, Asset Returns and the Business Cycle," *American Economic Review,* forthcoming.

CALVO, G. A. (1983), "Staggered Prices in a Utility-Maximizing Framework", *Journal of Monetary Economics,* **12**, 383–398.

CAMPBELL, J.Y. and COCHRANE, J.Y. (1999), "By Force of Habit: A Consumption-Based Explanation of Aggregate Stock Market Behavior," *Journal of Political Economy,* **107**, 205–251.

CHARI, V. V.; CHRISTIANO, L. J.; and KEHOE, P. J. (1991), "Optimal Fiscal and Monetary Policy: Some Recent Results", *Journal of Money, Credit, and Banking,* **23**, 519–539.

CHARI, V. V.; KEHOE, P. J.; and MCGRATTAN, E. R. (1998), "Can Sticky Price Models Generate Volatile and Persistent Real Exchange Rates?" (Staff Report 223, Federal

Reserve Bank of Minneapolis, http://minneapolisfed.org/research/sr/sr223.html).

CHARI, V. V.; KEHOE, P. J.; and MCGRATTAN, E. R. (2000), "Appendix: 'Can Sticky Price Models Generate Volatile and Persistent Real Exchange Rates?'" (Federal Reserve Bank of Minneapolis, http://minneapolisfed.org/research/sr/sr277.html).

CHRISTIANO, L. J.; EICHENBAUM, M.; and EVANS, C. L. (1998), "Modeling Money" (Working Paper 6371, National Bureau of Economic Research).

CLARIDA, R.; GALI, J.; and GERTLER, M. (2000), "Monetary Policy Rules and Macroeconomic Stability: Evidence and Some Theory" *Quarterly Journal of Economics*, **115**, 147-180.

CORSETTI, G.; PESENTI, P.; ROUBINI, N.; and TILLE, C. (1999), "Competitive Devaluations: A Welfare-Based Approach" (Working Paper 6889, National Bureau of Economic Research).

DEARDORFF, A. V., and STERN, R. M. (1990), *Computational Analysis of Global Trading Arrangements* (Ann Arbor: University of Michigan Press).

DIXIT, A. K., and STIGLITZ, J. E. (1977), "Monopolistic Competition and Optimum Product Diversity", *American Economic Review,* **67**, 297–308.

DOMOWITZ, I.; HUBBARD, R. G.; and PETERSEN, B. C. (1986), "Business Cycles and the Relationship Between Concentration and Price-Cost Margins", *Rand Journal of Economics,* **17**, 1–17.

DORNBUSCH, R. (1976), "Expectations and Exchange Rate Dynamics", *Journal of Political Economy,* **84**, 1161–1176.

__________. (1987), "Exchange Rates and Prices", *American Economic Review,* **77**, 93–106.

ENGEL, C. (1993), "Real Exchange Rates and Relative Prices: An Empirical Investigation", *Journal of Monetary Economics,* **32**, 35–50.

__________. (1999), "Accounting for U.S. Real Exchange Rate Changes", *Journal of Political Economy,* **107**, 507–538.

GOLDBERG, P. K., and KNETTER, M. M. (1997), "Goods Prices and Exchange Rates: What Have We Learned?", *Journal of Economic Literature,* **35**, 1243–1272.

JERMANN, U. (1998), "Asset Pricing in Production Economies," *Journal of Monetary Economics,* **41(2)**, 257–275.

KEHOE, P. J., and PERRI, F. (2000), "International Business Cycles With Endogenous Incomplete Markets" (Staff Report 265, Federal Reserve Bank of Minneapolis).

KNETTER, M. M. (1989), "Price Discrimination by U.S. and German Exporters", *American Economic Review,* **79**, 198–210.

__________. (1993), "International Comparisons of Price-to-Market Behavior", *American Economic Review,* **83**, 473–486.

KOLLMANN, R. (1996), "The Exchange Rate in a Dynamic-Optimizing Current Account Model with Nominal Rigidities: A Quantitative Investigation" (Working Paper 319, University of Montreal).

KRUGMAN, P. R. (1987), "Pricing to Market When the Exchange Rate Changes", in S. W. Arndt and J. D. Richardson (eds.), *Real-Financial Linkages Among Open Economies,* pp. 49–70 (Cambridge, Mass.: MIT Press).

LEWIS, H. G. (1986), "Union Relative Wage Effects," in O. Ashenfelter and R. Layard (eds.), *Handbook of Labor Economics*, Vol. II, Chap. 20, pp. 1139-1181 (Amsterdam: Elsevier/North-Holland).

MARSTON, R. C. (1990), "Pricing to Market in Japanese Manufacturing", *Journal of International Economics,* **29**, 217–236.

MCGRATTAN, E. R. (1996), "Solving the Stochastic Growth Model With a Finite Element Method", *Journal of Economic Dynamics and Control,* **20**, 19–42.

MUSSA, M. (1986), "Nominal Exchange Rate Regimes and the Behavior of Real Exchange Rates: Evidence and Implications", *Carnegie-Rochester Conference Series on Public Policy,* **25**, 117–213.

OBSTFELD, M., and ROGOFF, K. (1995), "Exchange Rate Dynamics Redux", *Journal of Political Economy,* **103**, 624–660.

OHANIAN, L. E., and STOCKMAN, A. C. (1997), "Short-Run Independence of Monetary Policy Under Pegged Exchange Rates and Effects of Money on Exchange Rates and Interest Rates", *Journal of Money, Credit, and Banking,* **29**, 783–806.

ROTEMBERG J. J., and WOODFORD, M. (1997), "An Optimization-Based Econometric Framework for the Evaluation of Monetary Policy," *NBER Macroeconomics Annual* (Cambridge, Mass.: MIT Press).

STERN, R. M.; FRANCIS, J.; and SCHUMACHER, B. (1976), *Price Elasticities in International Trade: An Annotated Bibliography* (Toronto: Macmillan).

SVENSSON, L. E. O. (1986), "Sticky Goods Prices, Flexible Asset Prices, Monopolistic Competition, and Monetary Policy", *Review of Economic Studies,* **53**, 385–405.

SVENSSON, L. E. O., and VAN WIJNBERGEN, S. (1989), "Excess Capacity, Monopolistic Competition, and International Transmission of Monetary Disturbances", *Economic Journal,* **99**, 785–805.

TAYLOR, J. B. (1993), "Discretion versus Policy Rules in Practice", *Carnegie-Rochester Conference Series on Public Policy,* **39**, 195–214.

__________. (1999), "Staggered Price and Wage Setting in Macroeconomics", in J. B. Taylor and M. Woodford (eds.), *Handbook of Macroeconomics,* Vol. 1B, Chap. 15, pp. 1009–1050 (Amsterdam: Elsevier/North-Holland).

U.S. DEPARTMENT OF LABOR, Bureau of Labor Statistics (1992), *BLS Handbook of Methods,* Bulletin 2414, September (Washington, D.C.: U.S. Bureau of Labor Statistics).

WHALLEY, J. (1985), *Trade Liberalization Among Major World Trading Areas* (Cambridge, Mass.: MIT Press).

Table 1

Properties of exchange rates and consumer price indices

Statistic	Country Relative to U.S.											Europe Relative to U.S.
	Austria	Denmark	Finland	France	Germany	Italy	Netherlands	Norway	Spain	Switzerland	UK	
Standard Deviations												
Price ratio	1.59	1.23	1.80	1.17	1.42	1.67	1.62	1.80	2.29	1.49	1.74	1.18
Exchange rate												
Nominal	8.19	8.08	8.28	8.52	8.37	8.51	8.30	6.23	8.88	9.08	8.20	7.95
Real	7.93	8.00	7.71	7.95	8.06	7.80	7.99	6.08	8.42	8.83	7.89	7.52
Autocorrelations												
Price ratio	0.89	0.74	0.92	0.92	0.90	0.87	0.93	0.90	0.90	0.90	0.79	0.90
Exchange rate												
Nominal	0.83	0.84	0.85	0.86	0.83	0.85	0.84	0.78	0.87	0.82	0.84	0.85
Real	0.82	0.83	0.83	0.84	0.82	0.83	0.82	0.77	0.86	0.82	0.81	0.83
Cross-Correlations												
Real and nominal exchange rates	0.98	0.99	0.98	0.99	0.99	0.98	0.98	0.96	0.97	0.99	0.98	0.99

See notes at the end of the Tables.

Table 2

Properties of exchange rates and disaggregated consumer price indices

Statistic	Country Relative to U.S.				Europe Relative to U.S.
	France	Italy	Netherlands	Norway	
Standard Deviations					
Price ratio					
All goods	1.01	1.57	1.44	1.82	1.24
Traded goods	1.42	2.00	1.97	2.13	1.65
Exchange rate					
Nominal	8.72	8.68	8.50	6.39	8.25
All goods real	8.25	8.10	8.24	6.14	7.78
Traded goods real	8.05	8.12	8.05	6.34	7.76
Autocorrelations					
Price ratio					
All goods	0.90	0.83	0.88	0.91	0.91
Traded goods	0.90	0.85	0.84	0.90	0.89
Exchange rate					
Nominal	0.86	0.86	0.84	0.79	0.85
All goods real	0.84	0.83	0.83	0.76	0.83
Traded goods real	0.84	0.83	0.82	0.79	0.83
Cross-Correlations of Exchange Rates					
Real and nominal					
All goods	0.99	0.98	0.99	0.96	0.99
Traded goods	0.99	0.97	0.97	0.94	0.94
All and traded goods real	1.00	0.99	0.99	0.99	1.00

See notes at the end of the Tables.

Table 3

Properties of exchange rates and wholesale price indices

Statistics	Country Relative to U.S.									Europe Relative to U.S.
	Austria	Denmark	Finland	Germany	Italy	Netherlands	Spain	Switzerland	UK	
Standard Deviations										
Price ratio	2.19	2.25	1.92	2.04	2.86	2.59	2.85	1.99	2.52	2.08
Exchange rate										
Nominal	8.19	8.08	8.28	8.37	8.51	8.30	8.88	9.08	8.20	7.98
Real	7.45	6.52	7.29	7.74	7.35	7.59	7.79	8.71	7.25	7.30
Autocorrelations										
Price ratio	0.76	0.86	0.83	0.88	0.83	0.90	0.87	0.85	0.85	0.87
Exchange rate										
Nominal	0.83	0.84	0.85	0.83	0.85	0.84	0.87	0.82	0.84	0.85
Real	0.79	0.80	0.82	0.81	0.82	0.82	0.84	0.80	0.79	0.82
Cross-Correlations										
Real and nominal exchange rates	0.97	0.97	0.98	0.97	0.95	0.95	0.95	0.98	0.95	0.97

See notes at the end of the Tables.

Table 4

Parameter values

Benchmark Model	
Preferences	$\beta = .99$, $\psi = 10$, $\gamma = 5$, $\sigma = 5$, $\eta = .39$, $\omega = .94$
Final good technology	$\rho = 1/3$, $a_1 = .9397$, $a_2 = .0603$
Intermediate good technology	$\alpha = 1/3$, $\delta = .021$, $\theta = .9$, $N = 4$
Money growth process	$\rho_\mu = .683$, $\text{corr}(\varepsilon_\mu, \varepsilon^*_\mu) = .5$
Variations[a]	
High exports	$a_1 = .7607$, $a_2 = .2393$
Real shocks	
Technology	$\rho_A = .95$, $\text{var}(\varepsilon_A) = \text{var}(\varepsilon^*_A) = (.007)^2$, $\text{corr}(\varepsilon_A, \varepsilon^*_A) = .25$
Government consumption	$\mu_g = .13$, $\rho_g = .97$, $\text{var}(\varepsilon_g) = \text{var}(\varepsilon^*_g) = (.01)^2$
Taylor rule	$\rho_r = .79$, $\alpha_\pi = 2.15$, $\alpha_y = .93/4$, $\text{corr}(\varepsilon_r, \varepsilon^*_r) = .5$
Incomplete markets	No changes
Sticky wages	$\vartheta = .87$, $M = 4$
Nonseparable preferences	$\xi = 2.25$

See notes at the end of the Tables.

Table 5

Exchange rates and prices for the models

Statistic	Data[b]	Benchmark Economy	Variations on the Benchmark Economy[a]: High Exports	Nonseparable Preferences	Real Shocks	Taylor Rule	Sticky Wages	Incomplete Markets
Standard Deviations Relative to GDP[c]								
Price ratio	.71	3.00	3.26	.02	2.98	1.35	2.11	2.98
		(.75)	(.77)	(.00)	(.74)	(.33)	(.59)	(.75)
Exchange rate								
Nominal	4.67	4.32	4.27	.07	4.27	4.66	4.14	4.22
		(.80)	(.79)	(.01)	(.80)	(.66)	(.80)	(.78)
Real	4.36	4.27	4.09	.05	4.26	4.98	4.35	4.19
		(.72)	(.67)	(.01)	(.71)	(.72)	(.83)	(.71)
Autocorrelations								
Price ratio	.87	.93	.92	.81	.93	.92	.95	.93
		(.02)	(.02)	(.06)	(.02)	(.02)	(.02)	(.02)
Exchange rate								
Nominal	.86	.69	.69	.83	.69	.46	.69	.69
		(.08)	(.08)	(.05)	(.08)	(.10)	(.08)	(.08)
Real	.83	.62	.58	.77	.62	.48	.69	.62
		(.08)	(.08)	(.06)	(.08)	(.09)	(.08)	(.08)
Cross-Correlations								
Real and nominal exchange rates	.99	.76	.70	.98	.76	.96	.88	.75
		(.06)	(.07)	(.00)	(.06)	(.01)	(.04)	(.06)

See notes at the end of the Tables.

Table 6
Business cycle statistics for the models

			Variations on the Benchmark Economy					
Statistics	Data[a]	Benchmark Economy	High Exports	Nonseparable Preferences	Real Shocks	Taylor Rule	Sticky Wages	Incomplete Markets
Standard Deviations Relative to GDP								
Consumption	.83	.83 (.01)	.83 (.04)	.92 (.00)	.83 (.02)	.83 (.01)	.83 (.02)	.83 (.01)
Investment	2.78	1.59 (.01)	1.70 (.08)	1.32 (.01)	2.34 (.05)	1.62 (.01)	1.49 (.03)	1.59 (.01)
Employment	.67	1.51 (.01)	1.49 (.03)	1.51 (.00)	1.56 (.09)	1.51 (.00)	1.50 (.01)	1.50 (.01)
Net exports	.11	.09 (.01)	.69 (.08)	.04 (.00)	.11 (.02)	.09 (.01)	.19 (.03)	.09 (.01)
Autocorrelations								
GDP	.88	.62 (.08)	.65 (.07)	.03 (.10)	.61 (.08)	.49 (.09)	.70 (.07)	.62 (.08)
Consumption	.89	.61 (.08)	.60 (.08)	.03 (.10)	.61 (.08)	.48 (.09)	.67 (.07)	.61 (.08)
Investment	.91	.60 (.08)	.59 (.08)	.03 (.10)	.60 (.08)	.47 (.09)	.68 (.07)	.60 (.08)
Employment	.90	.61 (.08)	.63 (.07)	.03 (.10)	.61 (.08)	.48 (.09)	.69 (.07)	.61 (.08)
Net exports	.82	.72 (.05)	.53 (.07)	.12 (.11)	.77 (.05)	.68 (.06)	.84 (.04)	.71 (.05)
Cross-Correlations								
Between foreign and domestic								
GDP	.60	.49 (.14)	.58 (.14)	.50 (.09)	.47 (.14)	.51 (.12)	.43 (.18)	.49 (.14)
Consumption	.38	.49 (.14)	.52 (.13)	.50 (.09)	.48 (.14)	.50 (.12)	.49 (.16)	.49 (.14)
Investment	.33	.49 (.14)	.52 (.13)	.41 (.10)	.48 (.14)	.50 (.12)	.48 (.16)	.49 (.14)
Employment	.39	.49 (.14)	.60 (.13)	.50 (.09)	.48 (.14)	.51 (.12)	.44 (.18)	.49 (.14)
Between net exports and GDP	−.41	.04 (.16)	.11 (.15)	−.50 (.09)	.05 (.17)	−.04 (.15)	.26 (.18)	.04 (.16)
Between real exchange rates and								
GDP	.08	.51 (.13)	.34 (.15)	.17 (.09)	.51 (.13)	.49 (.11)	.52 (.15)	.51 (.13)
Net exports	.14	−.04 (.13)	−.47 (.09)	−.26 (.06)	.03 (.16)	−.20 (.13)	.30 (.13)	−.04 (.13)
Relative consumptions	−.35	1.00 (.00)	1.00 (.00)	.32 (.04)	1.00 (.00)	1.00 (.00)	1.00 (.00)	1.00 (.00)

See notes at the end of the Tables.

Table 7
The Correlation Between the Real Exchange Rate and Relative Consumptions

	France	Germany	Italy	U.K.
U.S.	−.06	−.15	−.35	−.48
France		.24	−.17	.05
Germany			−.08	.17
Italy				.14

See notes at the end of the Tables.

Footnotes to the Tables

Table 1.

The statistics are based on logged and H-P-filtered quarterly data for the period 1973:1–2000:1. The statistics for Europe are trade-weighted aggregates of countries in the table. (See the text for details on construction of the data for Europe.)

Table 2.

The statistics are based on logged and H-P-filtered quarterly data for the period 1973:1–1998:4. The statistics for Europe are trade-weighted aggregates of countries in the table. (See the text for details.)

Table 3.

The statistics are based on logged and H-P-filtered quarterly data for the period 1973:1–2000:1. The statistics for Europe are trade-weighted aggregates of countries in the table. (See the text for details.)

Table 4.

[a] Other parameters in the variations are the same as in the benchmark model, except for two parameters. The adjustment cost parameter is chosen to keep the relative volatility of consumption and output the same as in the data. The innovations to the monetary policy are chosen to keep the volatility of output the same as in the data.

Table 5.

The statistics are based on logged and H-P filtered data. For each economy the standard deviation of monetary shocks are chosen so that the standard deviation of GDP is the same as it is in the data from 1973:1-1994:4, namely, 1.82 percent. Numbers in parentheses are standard deviations of the statistic across 100 simulations.

[a] See Table 4 for specifications of the variations of the benchmark economy.

[b] The statistics are based on a European aggregate with France, Italy, the U.K., and West Germany over the sample period 1973:1-1994:4.

[c] The standard deviations of the variables are divided by the standard deviation of GDP.

Table 6.

Notes *a* and *c* of Table 5 also apply here. With the exception of net exports, the standard deviation of each variable is divided by the standard deviation of output. Throughout the table we measure net exports as the H-P-filtered ratio of real net exports to real gross domestic product. Thus, the standard deviation of net exports is simply the standard deviation of this ratio.

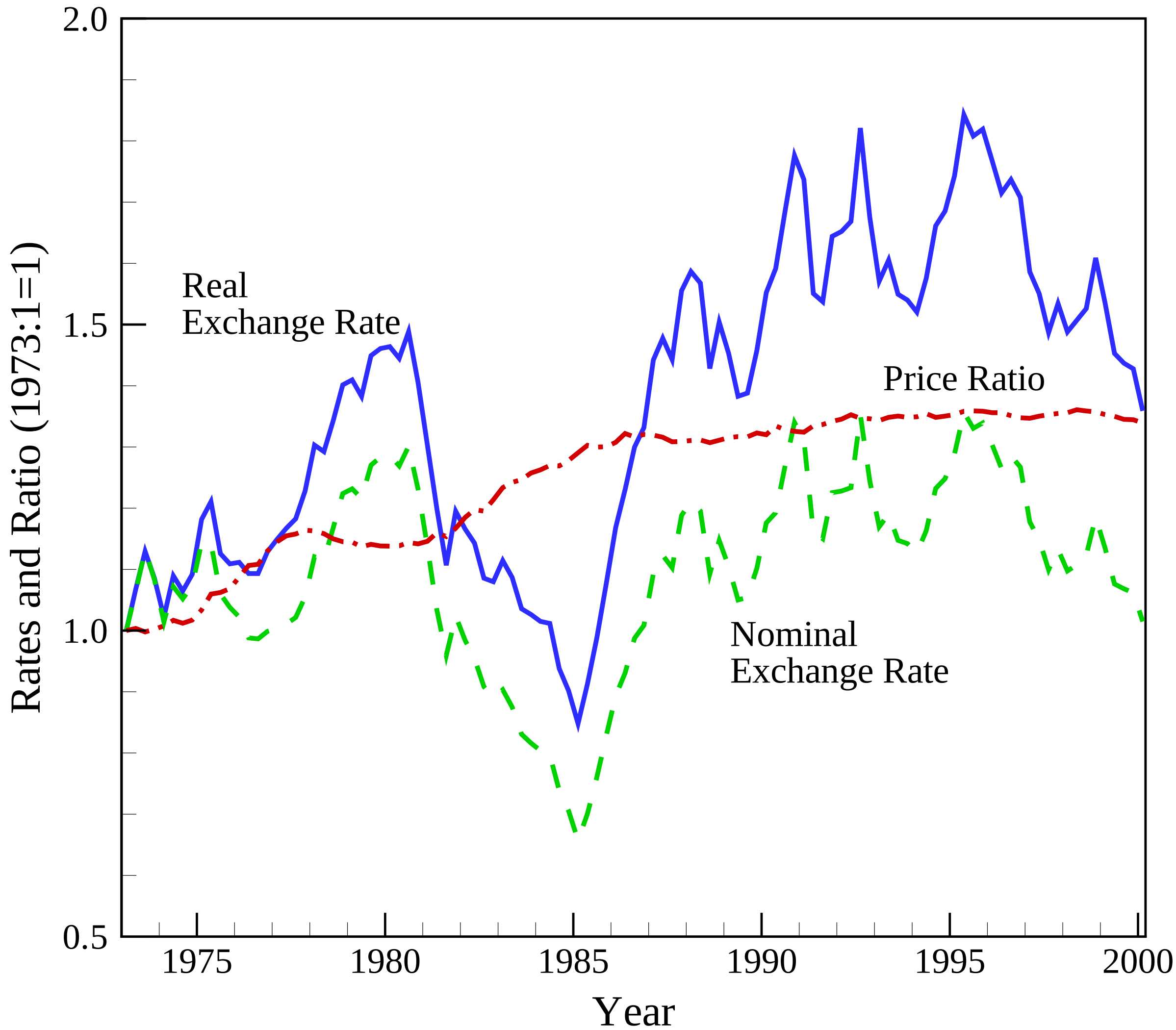
[a] With the exception of net exports, the standard deviations and autocorrelations in the data column are based on logged and H-P-filtered U.S. quarterly data for the period 1973:1–1994:4. The cross-correlations between domestic and foreign variables are based on the U.S. and a European aggregate of France, Italy, the U.K., and West Germany.

Table 7.

The table reports the correlation between bilateral real exchange rates, $\hat{q}_t$, and relative consumptions, $\hat{c}_t - \hat{c}_t^*$.

Figure 1

Exchange rates and price ratio
between the United States and Europe

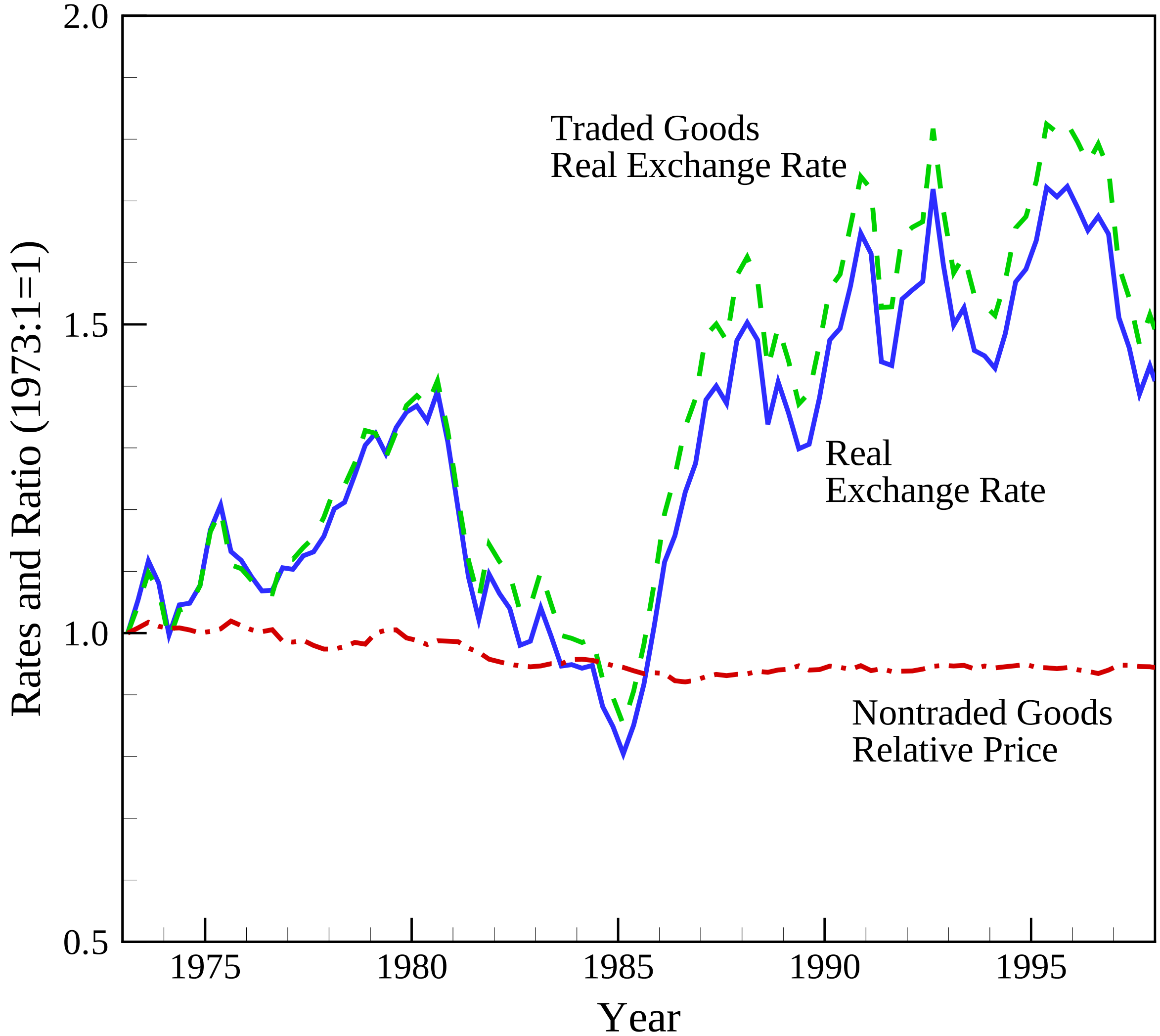


Source of basic data: IMF and OECD

NOTE: The real exchange rate is eP^*/P, where the nominal exchange rate e is the U.S. dollar price of a basket of European currencies, P^* is an aggregate of European CPIs, and P is the U.S. CPI. The price ratio is P^*/P.

Figure 2

Decomposing real exchange rates



Source of basic data: OECD and U.S. Department of Labor

Figure 3

The benchmark model's real exchange rate properties
vs. Its curvature parameter

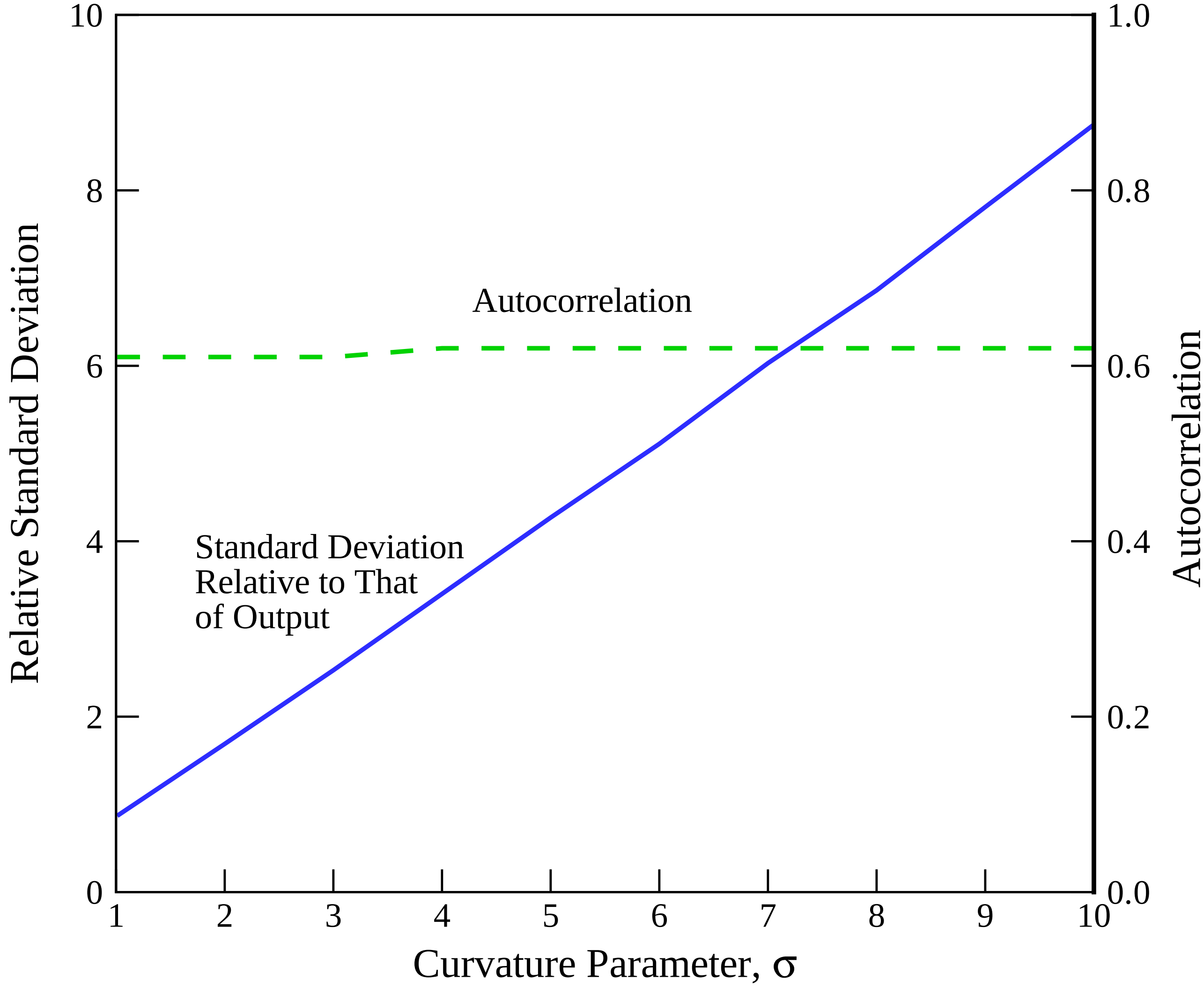


Figure 4

Measures of persistence vs. Price-stickiness