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Euro-dollar real exchange rate dynamics in an estimated two-country model: An assessment ☆

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Several theoretical contributions using two-country models have combined alternative forms of pricing under nominal rigidities with different asset market structures to explain real exchange rate dynamics. We estimate a two-country model using data for the United States and the Euro Area, and study the importance of such alternative assumptions in fitting the data. A model with local currency pricing and incomplete markets does a good job in explaining real exchange rate volatility, and fits the dynamics of domestic variables well. The complete markets assumption delivers a similar fit only when the structure of shocks is rich enough.

1. Introduction

Most puzzles in international macroeconomics are related to real exchange rate dynamics. Fluctuations in real exchange rates are very large and persistent when compared to other real variables, while most models cannot account for this fact.[1] In addition, most models assume that financial markets are complete at the international level, while there is clear empirical evidence of lack of consumption risk-sharing across countries. In order to explain main features of real exchange rates and consumption behavior across countries, a newer generation of models known as the New Open Economy Macroeconomics (NOEM) literature, has incorporated either nominal rigidities, alternative structures of assets markets, or both. Some examples include Benigno (2009), Lane (2001) and Obstfeld and Rogoff (2000).

Why are these two extensions necessary? The real exchange rate between two countries is defined as the ratio of price levels expressed in a common currency. When all the components of the price level—namely domestically produced and imported goods—are sticky, it can be possible to explain real exchange rate volatility, as shown by Benigno (2004). It is also well known that under complete markets, the real exchange rate is equal to the ratio of the marginal utility of consumption across countries. In fact, a separable log utility function on consumption implies that the real exchange rate and the ratio of consumption levels across countries have a correlation of one. This relationship does not hold for many bilateral relationships in general, a fact originally labeled the Backus and Smith (1993) paradox. For the bilateral euro-U.S. dollar

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[1] See, for instance, Heathcote and Perri (2002).

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exchange rate in particular, the correlation between the real exchange rate and the ratio of consumption levels in both countries (taking logs and first differences) is −0.18. Hence, models that incorporate complete markets are bound to fail in explaining key features of the international dimension of the data, as shown by Chari, Kehoe and McGrattan (2002, CKM) in a model with several nominal and real rigidities but with monetary policy shocks only.

Motivated by the difficulties of most international macromodels in matching real exchange rate fluctuations and by the results in CKM, in this paper we use a Bayesian approach to estimate a two-country NOEM model under different assumptions of imports goods pricing and asset markets structures. We use data for the euro area and the United States. Our baseline model is a two-country extension of Smets and Wouters (2003, 2007), and Christiano et al. (2005), to which we include two additional features. First, we assume local currency pricing (LCP), meaning that prices are sticky in the currency of the destination market, and second, we assume incomplete financial markets. Hence, the baseline framework includes several nominal and real rigidities that improve the model's fit to the data in a closed economy context, and additional features that have been suggested to explain main facts of international business cycles and real exchange rates. Then, we conduct a model comparison exercise and analyze the implications of introducing the simplifying assumptions of producer currency pricing (PCP), where the law of one price holds for imported and exported goods, and complete international financial markets. It is well established that the assumption of complete markets is convenient to obtain theoretical analytically tractable solutions for the real exchange rate. Thus, we want to test the implications and possible limitations of this asset market structure and analyze possible benefits of an alternative incomplete markets structure to match the data. We believe this comparison is valuable since it factors to what extent financial markets integration affects both: (i) parameter estimates of the model; and (ii) the transmission mechanism of shocks in international business cycles models.

The main contributions of the current paper are on model comparison and the models' implications for the euro-dollar real exchange rate. Using the Bayes factor to compare between competing alternatives, we find that both features, LCP and incomplete markets are important to explain real exchange rate dynamics. We obtain a good fit to the data, both for domestic variables and for the real exchange rate. We find that it is easier to distinguish between competing asset markets structures when shocks to the risk sharing condition across countries, such as uncovered interest rate parity (UIP) shocks are removed from the estimation. This result makes sense if we think that these UIP shocks make up for the possible misspecification of the asset market structure in the model. We find that in our preferred model about 50 percent of the real exchange rate volatility is explained by the UIP shocks. We find that supply, demand and preference shocks explain roughly an equal share of the real exchange rate variance, while monetary policy shocks have had a negligible contribution to real exchange rate fluctuations.

The literature on estimating NOEM models in the spirit of the models such as CKM and Galí and Monacelli (2005) has grown rapidly, with the adoption of the Bayesian methodology to an open economy setting already used in a closed economy environment. Lubik and Schorfheide (2007) estimate small open economy models with data for Australia, New Zealand, Canada and the U.K., focusing on whether the monetary policy rules of those countries have targeted the nominal exchange rate. Justiniano and Preston (2009) also estimate a small open economy model with an emphasis on the consequences of introducing imperfect pass-through on the international dimension of the data. Adolfson et al. (2007) estimate a medium-scale (15 variable) small open economy model for the euro area, and focus on the importance of several nominal and real frictions, as well as on which shocks are important to explain the data. Moving to a two-country model set up, Lubik and Schorfheide (2006), and De Walque et al. (2005) estimated models using U.S. and euro area data.

The rest of the paper is organized as follows. In the next section we outline the baseline model. In Section 3 we report the model's dynamics highlighting the role of LCP and incomplete markets. In Section 4 we document the data, priors and econometric strategy. The estimation results can be found in Section 5. In Section 6 we discuss several robustness exercises regarding the pricing of exports and asset market assumptions. In Section 7 we conclude.

2. The model

In this section we present the stochastic two country model that we will use to analyze real exchange rate dynamics. We estimate a two-country version of Christiano et al. (2005) and Smets and Wouters (2003, 2007). As in CKM, our benchmark model assumes that there is local currency pricing for goods that are shipped internationally. In addition, we assume that there is an incomplete asset market structure at the international level: agents only have access to one uncontingent bond that is denominated in foreign-country currency. The model incorporates 16 shocks because in the econometric section we are interested in explaining 15 variables.[2]

We assume that there are two countries, home and foreign, of equal size. Each country produces a continuum of intermediate goods, indexed by $h \in [0,1]$ in the home country and $f \in [0,1]$ in the foreign country, which are traded internationally. These intermediate goods are used in the production of the final good that is used for domestic final

[2] We include more shocks than observable variables since it helps to fit the data better and lowers misspecification problems as in Smets and Wouters (2003). In the robustness section below, we reestimate the model without the uncovered interest rate parity (UIP) shock, that affects the risk sharing condition across countries, and hence we will have the same number of shocks than variables.

consumption, investment, and government spending, and hence it is not traded across borders. In what follows, we present the problem for households, intermediate goods producers, and final goods producers in the home country. The expressions for the foreign country are analogous, and the convention we use is that variables and parameters with an asterisk denote the foreign country counterparts.

2.1. Households

In each country there is a continuum of infinitely lived households in the unit interval, that obtain utility from consuming the final good and disutility from supplying hours of labor. In the home country, households are indexed by $j \in [0,1]$ and their lifetime utility function is

$$U = E_0 \sum_{t=0}^{\infty} \beta^t D_{c,t} \left[\log(C_t^j - bC_{t-1}) - D_{n,t} \frac{(N_t^j)^{1+\eta}}{1+\eta} \right] \tag{1}$$

where E_0 denotes the rational expectations operator using information up to time $t=0$. $\beta \in [0,1]$ is the discount factor. Consumers obtain utility from consuming the final good, C_t^j, and the utility function displays external habit formation. $b \in [0,1]$ denotes the importance of the habit stock, which is last period's aggregate consumption (C_{t-1}). $\eta > 0$ is the inverse elasticity of labor supply with respect to the real wage, N_t^j, is the labor supply of the agent. $D_{c,t}$, and $D_{n,t}$ denote intertemporal and intratemporal preference shocks.[3] These shocks evolve as follows:

$$\log(D_{c,t}) = \rho_c \log(D_{c,t-1}) + \varepsilon_t^{c,d}$$

$$\log(D_{n,t}) = \rho_n \log(D_{n,t-1}) + \varepsilon_t^{n,d}$$

2.1.1. Incomplete international markets and the real exchange rate

Markets are complete within each country and incomplete at the international level. We introduce international incomplete markets in a simple and tractable way, following Benigno (2009). We assume that, in each country, domestic households have access to a nominal riskless bond that costs the inverse of the domestic nominal interest rate. Given the assumption of complete markets, this bond is redundant. In addition, there is an internationally traded bond that is denominated in foreign country currency, and that allows to engage in intertemporal international trade across countries.

The budget constraint of home-country households is given by

$$P_t(C_t^j + I_t^j) + \frac{B_t^j}{R_t} + \frac{S_t D_t^j}{R_t^* \Psi\left(\frac{S_t D_t}{Y_t P_t}\right)} + T_t = B_{t-1}^j + S_t D_{t-1}^j + W_t^j N_t^j + P_t R_t^K K_{t-1}^j + \Pi_t^j + \xi_t^j \tag{2}$$

where B_t^j and D_t^j denote holdings of the domestic and foreign currency denominated bonds, R_t is the home country gross nominal interest rate and R_t^* is the foreign country gross nominal interest rate. S_t is the nominal exchange rate expressed in units of domestic currency needed to buy one unit of foreign currency and P_t is the price level of the final good (to be defined below). ξ_t^j denotes the payoff from engaging in trade of state-contingent securities.[4] T_t are lump-sum taxes that are used to finance government spending.

Home-country households face a cost of undertaking positions in the foreign bonds market. The $\Psi(\cdot)$ function captures this cost and depends on the aggregate real holdings of the foreign assets in the entire economy, and therefore is taken as given by individual households.[5] Consumers obtain labor income from supplying labor to intermediate goods producers, for which they receive a nominal wage, W_t^j, and receive profits from intermediate and wholesale final goods producers Π_t^j. The model includes sticky wages, and hence the wage received by each household is specific and depends on the last time wages were reoptimized. The assumption of complete markets within each country allows to separate the consumption/saving decisions from the labor supply decision (see Erceg, Henderson, and Levin, 2001; henceforth EHL).

Households rent capital to the firms that produce intermediate goods. K_{t-1}^j and I_t^j denotes holdings of capital stock and investment purchases, respectively. The real rental rate of capital is denoted by R_t^K. The capital accumulation dynamics is given by the following expression:

$$K_t^j = (1-\delta)K_{t-1}^j + V_t \left[1 - S\left(\frac{I_t^j}{I_{t-1}^j} \right) \right] I_t^j \tag{3}$$

[3] See Primiceri et al. (2006).

[4] In order to keep notation simple, we do not make the structure of the complete domestic asset markets explicit.

[5] This cost induces stationarity in the net foreign asset position. See Schmitt-Grohé and Uribe (2003) for applications in small open economy models, and Benigno (2009) in two-country models. In order to achieve stationarity $\Psi(\cdot)$ has to be differentiable and decreasing in the neighborhood of zero. We further assume that $\Psi(0) = 1$, such that there is balanced trade in the steady state.

here δ denotes the rate of depreciation and the adjustment cost function, $S(\cdot)$, is an increasing and convex function (i.e. $S'()$, $S''()>0$). Furthermore, in the steady state $\overline{S}=\overline{S}'=0$ and $\overline{S}''>0$. The $S(\cdot)$ function summarizes the technology that transforms current and past investment into installed capital for use in the following period.[6] This expression also includes an investment-specific technology shock (V_t) that evolves as

$$\log(V_t)=\rho_v \log(V_{t-1})+\varepsilon_t^v$$

The first order conditions for holding domestic and foreign bonds, capital and investment are

$$1=\beta R_t E_t\left(\frac{C_t-bC_{t-1}}{C_{t+1}-bC_t}\frac{D_{c,t+1}}{D_{c,t}}\frac{P_t}{P_{t+1}}\right) \tag{4}$$

$$1=\beta R_t^* \Psi\left(\frac{S_t D_t}{P_t Y_t}\right) E_t\left(\frac{C_t-bC_{t-1}}{C_{t+1}-bC_t}\frac{D_{c,t+1}}{D_{c,t}}\frac{S_{t+1}P_t}{S_t P_{t+1}}\right) \tag{5}$$

$$Q_t=\beta E_t\left\{\left(\frac{C_t-bC_{t-1}}{C_{t+1}-bC_t}\frac{D_{c,t+1}}{D_{c,t}}\right)[R_{t+1}^K+Q_{t+1}(1-\delta)]\right\} \tag{6}$$

$$1-Q_t V_t\left(1-S\left(\frac{I_t}{I_{t-1}}\right)-\frac{I_t}{I_{t-1}}S'\left(\frac{I_t}{I_{t-1}}\right)\right)=\beta E_t\left(\frac{C_t-bC_{t-1}}{C_{t+1}-bC_t}\frac{D_{c,t+1}}{D_{c,t}}\right)Q_{t+1}V_{t+1}\left[S'\left(\frac{I_{t+1}}{I_t}\right)\left(\frac{I_{t+1}}{I_t}\right)^2\right] \tag{7}$$

where Q_t is the shadow price of investment in terms of consumption goods, and where we have dropped all the superscripts, since by using the complete markets assumption, all households in one country take the same decision.

Combining Eq. (5) with the analogous to (4) in the foreign country delivers the following risk-sharing condition, which forms the basis of the real exchange rate determination under incomplete markets:

$$E_t\left(\frac{C_t^*-b^*C_{t-1}^*}{C_{t+1}^*-bC_t^*}\frac{D_{c,t+1}^*}{D_{c,t}^*}\frac{P_t^*}{P_{t+1}^*}\right)=E_t\left(\frac{C_t-bC_{t-1}}{C_{t+1}-bC_t}\frac{D_{c,t+1}}{D_{c,t}}\frac{S_{t+1}P_t}{S_t P_{t+1}}\right)\Psi\left(\frac{S_t D_t}{Y_t P_t}\right) \tag{8}$$

We define the real exchange rate as the ratio of final goods prices, expressed in common currency:

$$RER_t=\frac{S_t P_t^*}{P_t} \tag{9}$$

2.1.2. The wage decision

As in EHL, we assume that the household is a monopoly supplier of differentiated labor service, N_t^j. It sells this service to a competitive firm that transforms it into an aggregate labor input that is used by the intermediate goods producers. Thus, one effective unit of labor that an intermediate goods producer firm, h, uses for production is given by

$$N_t(h)=\left\{\int_0^1 [N_t^j(h)]^{(\varepsilon_w-1)/\varepsilon_w}dj\right\}^{\varepsilon_w/(\varepsilon_w-1)} \tag{10}$$

where $N_t^j(h)$ is the amount of labor supplied by household j to firm h.

As shown by EHL, the demand curve for each type of labor is given by

$$N_t^j=\left(\frac{W_t^j}{W_t}\right)^{-\varepsilon_w}N_t \quad \text{for } j\in[0,1] \tag{11}$$

where W_t and N_t are aggregate labor and wage indices as follows:

$$W_t=\left[\int_0^1 (W_t^j)^{1-\varepsilon_w}dj\right]^{1/(1-\varepsilon_w)}$$

$N_t^j=\int_0^1 N_t^j(h)\,dh$, and $N_t=\int_0^1 N_t(h)\,dh$.

Households set wages in a staggered way with a Calvo-type restriction. In each period, a fraction $1-\theta_w$ of households can re-optimize their posted nominal wage. Consider a household resetting its wage in period t, and let W_t^* the newly set wage. The household will choose W_t^* in order to maximize

$$\underset{W_t^*}{Max}\,E_t\sum_{k=0}^{\infty}(\beta\theta_w)^k D_{c,t+k}\left[\log(C_{t+k}-bC_{t+k-1})-D_{n,t+k}\frac{(N_{t+k|t})^{1+\eta}}{1+\eta}\right] \tag{12}$$

where $N_{t+k|t}$ denotes labor supply in period $t+k$ of a household that last reset its wage in period t.

[6] The assumption that household j makes the capital accumulation decision is a matter of simplicity. At the cost of more complicated notation we could have outline an alternative descentralization scheme. See Christiano et al. (2005).

Households maximize (12) subject to (2) and (11). The first order condition associated with the problem above can be expressed as follows:

$$E_t \sum_{k=0}^{\infty} (\beta\theta_w)^k \frac{D_{c,t+k} N_{t+k|t}}{(C_{t+k} - bC_{t+k-1})} \left\{ \frac{W_t^*}{P_{t+k}} - \frac{\varepsilon_w}{\varepsilon_w - 1} D_{n,t+k} N_{t+k|t}^{\eta} (C_{t+k} - bC_{t+k-1}) \right\} = 0 \tag{13}$$

where $N_{t+k|t} = (W_t^*/W_{t+k})^{-\varepsilon_w} N_{t+k}$.

The evolution of the aggregate wage index is given by

$$W_t = [\theta_w W_{t-1}^{1-\varepsilon_w} + (1-\theta_w)(W_t^*)^{1-\varepsilon_w}]^{1/(1-\varepsilon_w)} \tag{14}$$

2.2. Firms

2.2.1. Final good producers

We assume that the production of the final good is performed in two stages. First, a continuum of wholesale firms purchase a composite of intermediate home goods, $Y_{H,t}$, and a composite of intermediate foreign-produced goods, $Y_{F,t}$, to produce a differentiated final good product, $Y_t(i)$ in the unit interval:

$$Y_t(i) = \left[\omega^{1/\theta} Y_{H,t}^{(\theta-1)/\theta} + (1-\omega)^{1/\theta} Y_{F,t}^{(\theta-1)/\theta}\right]^{\theta/(\theta-1)}, \quad i \in [0,1] \tag{15}$$

where ω denotes the fraction of home-produced goods that are used for the production of the final good, and θ denotes the elasticity of substitution between domestically produced and imported intermediate goods in both countries. Since both countries are of equal size, if $\omega > 1/2$ then the model exhibits *home bias* in the production of the intermediate good.

The composite intermediate goods are

$$Y_{H,t} = \left[\int_0^1 Y_{H,t}(h)^{\varepsilon_p/(\varepsilon_p-1)} dh\right]^{(\varepsilon_p-1)/\varepsilon_p}, \quad Y_{F,t} = \left[\int_0^1 Y_{F,t}(f)^{\varepsilon_p/(\varepsilon_p-1)} df\right]^{(\varepsilon_p-1)/\varepsilon_p}$$

where $\varepsilon_p > 1$ denotes is the elasticity of substitution between types of intermediate goods. Note that $Y_{H,t}(h)$ denotes home intermediate goods and $Y_{F,t}(f)$ denotes foreign intermediate goods used by a home wholesale firm.[7]

Second, retail firms purchase the differentiated final goods from wholesale firms, and produce a homogeneous final good that is used for consumption, investment, and government spending purposes:

$$Y_t = \left[\int_0^1 Y_t(i)^{\varepsilon_{f,t}/(\varepsilon_{f,t}-1)} di\right]^{(\varepsilon_{f,t}-1)/\varepsilon_{f,t}} \tag{16}$$

Both wholesale and retail firms operate under flexible prices, but the price of the final good (P_t) can fluctuate over its real marginal cost due to the presence of exogenous mark-up fluctuations, $\mu_{f,t} = \varepsilon_{f,t}/(\varepsilon_{f,t} - 1)$.

Optimal choices by retail and final good producers deliver the following demand and pricing equations. First, the demand functions and price levels for the home country intermediate goods producers are

$$Y_{H,t}(h) = \left[\frac{P_{H,t}(h)}{P_{H,t}}\right]^{-\varepsilon_p} Y_{H,t} \quad \text{for all } h \in [0,1] \tag{17}$$

$$Y_{F,t}(f) = \left[\frac{P_{F,t}(f)}{P_{F,t}}\right]^{-\varepsilon_p} Y_{F,t} \quad \text{for all } f \in [0,1] \tag{18}$$

where

$$Y_{H,t} = \omega \left(\frac{P_{H,t}}{MC_t^Y}\right)^{-\theta} Y_t, \quad Y_{F,t} = (1-\omega)\left(\frac{P_{F,t}}{MC_t^Y}\right)^{-\theta} Y_t \tag{19}$$

and

$$P_{H,t}^{1-\varepsilon_p} = \int_0^1 P_{H,t}^{1-\varepsilon_p}(h)\, dh; \quad P_{F,t}^{1-\varepsilon_p} = \int_0^1 P_{F,t}^{1-\varepsilon_p}(h)\, dh \tag{20}$$

Finally, the final goods price level, which we also refer to as the Consumer Price Index (P_t), is a time-varying markup over the marginal cost of production of the final good (MC_t^Y) which is a composite of home and foreign intermediate goods prices:

$$P_t = \mu_{f,t} MC_t^Y$$

$$MC_t^Y = [\omega(P_{H,t})^{1-\theta} + (1-\omega)(P_{F,t})^{1-\theta}]^{1/(1-\theta)} \tag{21}$$

[7] In the foreign country, $Y_{H,t}^*(h)$ denotes home intermediate goods used by a foreign firm, and $Y_{F,t}^*(f)$ denotes foreign intermediate goods used by a foreign firm.

In the empirical part, the time-varying i.i.d. mark-up shock is helpful to pick up high-frequency fluctuations in price indices, and can help overcome identification problems, as in Iskrev (2008).[8]

2.2.2. Intermediate goods producers

In each country, there is a continuum of intermediate goods producers, each producing a type of good that is an imperfect substitute of the others. These differentiated goods are sold to the wholesale final goods producers. Intermediate goods are traded internationally, while final goods are not.

Technology: The production function of each intermediate good in the home country is given by

$$Y_{H,t}(h)+Y^*_{H,t}(h)=[K_{t-1}(h)]^{\alpha}[A_tN_t(h)X_t]^{1-\alpha} \tag{22}$$

where α is the share of capital in the production function. The above production function has two technology shocks. The first one, X_t, is a world technology shock, that affects the two countries the same way: it has a unit root, as in Galí and Rabanal (2005) and Lubik and Schorfheide (2006). In addition, there is a labor-augmenting country specific technology shock, A_t, that evolves as an $AR(1)$ process. The evolution of technology shocks is as follows:

$$\log(X_t)=\log(X_{t-1})+\varepsilon_t^x$$

$$\log(A_t)=\rho_a\log(A_{t-1})+\varepsilon_t^a$$

From cost minimization the real marginal cost of production is given by

$$MC_t(h)=\frac{(R_t^K)^{\alpha}\left(\frac{W_t/P_t}{A_t}\right)^{1-\alpha}}{X_t^{1-\alpha}\alpha^{\alpha}(1-\alpha)^{(1-\alpha)}}=MC_t$$

Note that the marginal cost is not firm-specific but rather depends on aggregate variables: all firms receive the same technology shock and all firms rent inputs at the same price. The optimal capital–output ratio is also not firm-specific and given by

$$\frac{N_t(h)}{K_{t-1}(h)}=\frac{N_t}{K_{t-1}}=\frac{(1-\alpha)}{\alpha}\left(\frac{R_t^K}{W_t/P_t}\right) \tag{23}$$

Local currency pricing: In the second stage, intermediate good producers choose the price that maximizes discounted profits subject to a Calvo (1983)-type restriction. In our baseline model, we assume local currency pricing (LCP) for goods that are shipped internationally: a firm chooses a price for the domestic market and a price for the foreign market, each price quoted in the destination market currency. Hence, there is price stickiness in each country's imports prices in terms of local currency, and there are deviations from the law of one price.

In each period, a fraction $1-\theta_H$ of firms that set prices in the domestic market change their prices. Additionally, we assume that the prices of each firm that cannot reoptimize in a given period are adjusted according to the indexation rules:

$$\frac{P_{H,t}(h)}{P_{H,t-1}(h)}=(\Pi_{H,t-1})^{\lambda_H} \quad \text{and} \quad \frac{P^*_{H,t}(h)}{P^*_{H,t-1}(h)}=(\Pi^*_{H,t-1})^{\lambda_H} \tag{24}$$

where $0<\lambda_H<1$. Therefore, conditioned on a fixed price from period t, the present discounted value of firm h profits is

$$Max_{P_{H,t}(h),P^*_{H,t}(h)}E_t\left\{\begin{array}{l}\sum_{k=0}^{\infty}(\beta\theta_H)^k\Lambda_{t,t+k}\left[\frac{P_{H,t}(h)}{P_{t+k}}\left(\frac{P_{H,t+k-1}}{P_{H,t-1}}\right)^{\lambda_H}-MC_{t+k}\right]Y_{H,t+k|t}(h)+\\ \sum_{k=0}^{\infty}(\beta\theta_H)^k\Lambda_{t,t+k}\left[\frac{S_tP^*_{H,t}(h)}{P_{t+k}}\left(\frac{P^*_{H,t+k-1}}{P^*_{H,t-1}}\right)^{\lambda_H}-MC_{t+k}\right]Y^*_{H,t+k|t}(h)\end{array}\right\} \tag{25}$$

where $P_{H,t}(h)$ and $P^*_{H,t}(h)$ are prices of good h in the home and foreign markets, and whose evolution depends on the indexation rules, and $Y_{H,t+k|t}(h)$ and $Y^*_{H,t+k|t}(h)$ are the associated demands for intermediate good h in each country.

The first order conditions to the home intermediate goods producers firms for the home and foreign market are

$$\frac{\hat{P}_{H,t}(h)}{P_{H,t}}=\frac{\varepsilon_p}{\varepsilon_p-1}\frac{E_t\sum_{k=0}^{\infty}(\beta\theta_H)^k\Lambda_{t,t+k}MC_{t+k}\frac{P_{t+k}}{P_{H,t+k}}GDP_{t+k}\left[\frac{P_{H,t}}{P_{H,t+k}}\left(\frac{P_{H,t+k-1}}{P_{H,t-1}}\right)^{\lambda_H}\right]^{-\varepsilon_p}}{E_t\sum_{k=0}^{\infty}(\beta\theta_H)^k\Lambda_{t,t+k}GDP_{t+k}\left(\frac{P_{H,t}}{P_{H,t+k}}\right)^{1-\varepsilon_p}\frac{P_{H,t+k}}{P_{t+k}}\left(\frac{P_{H,t+k-1}}{P_{H,t-1}}\right)^{\lambda_H(1-\varepsilon_p)}} \tag{26}$$

[8] This shock will allow us to estimate a version of the model where the law of one price holds as it breaks the multicollinearity between the terms of trade and the real exchange rate. See Section 6 below.

$$\frac{\hat{P}^*_{H,t}(h)}{P^*_{H,t}} = \frac{\varepsilon_p}{\varepsilon_p - 1} \frac{E_t \sum_{k=0}^{\infty} (\beta\theta_H)^k \Lambda_{t,t+k} \frac{MC_{t+k}}{RER_{t+k}} \frac{P^*_{t+k}}{P^*_{H,t+k}} GDP_{t+k} \left[\frac{P^*_{H,t}}{P^*_{H,t+k}} \left(\frac{P^*_{H,t+k-1}}{P^*_{H,t-1}} \right)^{\lambda^*_H} \right]^{-\varepsilon_p}}{E_t \sum_{k=0}^{\infty} (\beta\theta_H)^k \Lambda_{t,t+k} GDP_{t+k} \left(\frac{P^*_{H,t}}{P^*_{H,t+k}} \right)^{1-\varepsilon_p} \frac{P^*_{H,t+k}}{P^*_{t+k}} \left(\frac{P^*_{H,t+k-1}}{P^*_{H,t-1}} \right)^{\lambda^*_H(1-\varepsilon_p)}} \tag{27}$$

where $GDP_t = Y_{H,t} + Y^*_{H,t}$. Eq. (26) is the usual optimal price condition under a Calvo-type restriction with indexation, and includes the demand coming from both domestic and foreign firms. Eq. (27) is the expression for the price of exports and transforms the relevant real marginal cost of production to foreign currency by using the real exchange rate.

The evolution of the home-produced intermediate goods price indices in the home and foreign countries are, given indexation:

$$P^{1-\varepsilon_p}_{H,t} = (1-\theta_H)(\hat{P}_{H,t})^{1-\varepsilon_p} + \theta_H \left[P_{H,t-1} \left(\frac{P_{H,t-1}}{P_{H,t-2}} \right)^{\lambda_H} \right]^{1-\varepsilon_p} \tag{28}$$

$$P^{*1-\varepsilon_p}_{H,t} = (1-\theta_H)(\hat{P}^*_{H,t})^{1-\varepsilon_p} + \theta_H \left[P^*_{H,t-1} \left(\frac{P^*_{H,t-1}}{P^*_{H,t-2}} \right)^{\lambda_H} \right]^{1-\varepsilon_p} \tag{29}$$

2.3. *Closing the model*

In order to close the model, we impose market-clearing conditions for all types of home and foreign intermediate goods. For the final good, the market clearing condition is

$$Y_t = C_t + I_t + G_t \tag{30}$$

We introduce an exogenous demand shock for each country (G_t, G^*_t) which can be interpreted as government expenditure shocks that evolve as $AR(1)$ processes in logs. We assume that both governments run a balanced budget every period (i.e. $G_t = T_t$ and $G^*_t = T^*_t$).

The law of motion of the internationally traded bonds is given by

$$\frac{S_t D_t}{P_t R^*_t \Psi\left(\frac{S_t D_t}{P_t Y_t}\right)} = \frac{S_t D_{t-1} + S_t P^*_{H,t} Y^*_{H,t} - P_{F,t} Y_{F,t}}{P_t} \tag{31}$$

Finally, we assume that both countries follow a monetary policy rule that targets deviations of domestic CPI inflation and real GDP growth from their steady-state values, that we normalize to zero:

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R} \right)^{\varphi_R} [(P_t/P_{t-1})^{\varphi_\pi} (GDP_t/GDP_{t-1})^{\varphi_y}]^{1-\varphi_R} \exp(\varepsilon^m_t) \tag{32}$$

3. Dynamics

Since we have assumed a world technology shock that has a unit root, then real output, consumption, capital, investment, real wages, and the level of government spending inherit the same property and are nonstationary in levels. In order to render these variables stationary, we divide them by the level of world technology. Real marginal costs, hours, inflation, interest rates, the real exchange rate and other international relative prices are stationary. We obtain the model's dynamics by taking a linear approximation to the steady state values with zero inflation and balanced trade. We denote by lower case variables percent deviations from steady state values. Moreover, variables with a tilde have been normalized by the level of world technology to render them stationary. For instance, $\tilde{c}_t = (\tilde{C}_t - \tilde{C})/\tilde{C}$, where $\tilde{C}_t = C_t/X_t$.

In this subsection, we focus the discussion on the linearized equations that influence the behavior of the real exchange rate, to save space.[9] We need to take into account that shocks stemming from other regions beyond the United States and the euro area should not affect the bilateral euro-dollar real exchange rate, because they affect both countries symmetrically. Hence, we impose the constraint that the deep and policy rule parameters in both countries are the same.[10] Under incomplete markets, the net foreign asset (NFA) position for the home country consists of the holding of foreign bonds (since domestic bonds are in zero net supply in the symmetric equilibrium). By definition, the NFA position of the foreign country equals the stock of bonds outstanding with the home country. The risk sharing condition is obtained by combining the first order conditions of both domestic and foreign households with respect to their bond holdings, it holds

[9] The full set of linearized equations of the model for the home and foreign countries are fairly standard given our assumptions. See Lubik and Schorfheide (2006), Chari et al. (2002), Christiano et al. (2005) and Smets and Wouters (2003, 2007). An Appendix available upon request details the full set of normalized, linearized equiilibrium conditions.

[10] We are grateful to an anonymous referee for suggesting this restriction.

in expected first difference terms and depends on the NFA position and preference shocks:

$$E_t rer_{t+1} - rer_t = \frac{E_t \Delta\tilde{c}_{t+1} - b\Delta\tilde{c}_t - (E_t \Delta\tilde{c}^*_{t+1} - b\Delta\tilde{c}^*_t)}{1-b} + (1-\rho_{c,d})d_{c,t} - (1-\rho^*_{c,d})d^*_{c,t} + \chi d_t + uip_t \tag{33}$$

where $\chi = -\Psi'(0)Y$, and $d_t = (S_t D_t / Y_t P_t)$. uip_t is the Uncovered Interest Rate Parity (UIP) shock, that tries to explain the remaining real exchange rate fluctuations not directly explained by the model, and that evolves as[11]

$$uip_t = \rho_{uip} uip_{t-1} + \varepsilon^{uip}_t$$

The net foreign asset position as percent of final output depends on the stock of previous debt and on the trade deficit (or surplus) as percent of final output:

$$\beta d_t = d_{t-1} + (rer_t + \hat{p}^*_{H,t} + \tilde{y}^*_{H,t} - (\hat{p}_{F,t} + \tilde{y}_{F,t}) - \tilde{y}_t) \tag{34}$$

where hatted price levels denote the relative price of that good with respect to the aggregate price level in each country, i.e. $\hat{p}^*_{H,t} = \log(P^*_{H,t}/P^*_t) - \log(\overline{P}^*_H/\overline{P}^*)$, and $\hat{p}_{F,t} = \log(P_{F,t}/P_t) - \log(\overline{P}_F/\overline{P})$.

The inflation equations for intermediate goods sold in the home and foreign country are

$$\Delta p_{H,t} - \lambda_H \Delta p_{H,t-1} = \beta(E_t \Delta p_{H,t+1} - \lambda_H \Delta p_{H,t}) + \kappa_H (mc_t - \hat{p}_{H,t}) \tag{35}$$

$$\Delta p^*_{H,t} - \lambda_H \Delta p^*_{H,t-1} = \beta(E_t \Delta p^*_{H,t+1} - \lambda^*_H \Delta p^*_{H,t}) + \kappa_H (mc_t - \hat{p}^*_{H,t} - rer_t) \tag{36}$$

where $\kappa_H = (1-\theta_H)(1-\beta\theta_H)/\theta_H$. Note that the slopes of the Phillips Curve are the same for the same type of product regardless of the market of destination. We assume that when a firm receives the Calvo signal to reoptimize, it does so in both markets, and that the probability of reoptimizing is the same in both markets as well.

Domestic inflation is determined by domestic marginal costs and the relative price $\hat{p}_{H,t}$. This last variable appears because real wages are deflated by the CPI: an increase in imports goods prices will cause real wages to drop, and households will demand higher wages. As a result, domestic inflation will also increase.

CPI inflation is as follows:

$$\Delta p_t = \omega \Delta p_{H,t} + (1-\omega)\Delta p_{F,t} + \mu_{f,t} - \mu_{f,t-1} \tag{37}$$

where the deviation of the markup with respect to its steady-state value ($\mu_{f,t}$) enters due to the monopolistic competition assumption in the final goods sector. $\Delta p_{F,t}$ denotes imported inflation from the foreign country and it is the analogous expression to (36). Since we have assumed local currency pricing, the nominal exchange (s_t) does not have a direct impact on the price of imported goods, but rather its effect builds over time.

4. Bayesian estimation of the benchmark model

Using Bayes' rule, the posterior distribution of the parameters is proportional to the product of the prior distribution of the parameters and the likelihood function of the data.[12] An appealing feature of the Bayesian approach is that additional information about the model's parameters (i.e. micro-data evidence, features of the first moments of the data) can be introduced via the prior distribution. To implement the Bayesian estimation method, we need to be able to numerically evaluate the prior and the likelihood function. The likelihood function is evaluated using the state-space representation of the law of motion of the model and the Kalman filter. Then, we use the Metropolis–Hastings algorithm to obtain 250,000 draws from the posterior distribution, from which we obtain the relevant moments of the posterior distribution of the parameters.[13]

4.1. Data

We use seven domestic variables per region (real GDP, real consumption, real investment, real wages, CPI, GDP deflator and nominal interest rates) and the bilateral real exchange rate. We perform the estimation with CPI inflation as a measure of the price level relevant to consumers, and with GDP deflator inflation as a measure of the relevant price level for domestic producers. Data sources for the United States are as follows: we use quarterly real GDP, the GDP deflator, real consumption, and real investment from the Bureau of Economic Analysis. We use real hourly compensation and the CPI for all Urban Consumers from the Bureau of Labor Statistics. We obtain the 3-month T-bill interest rate (FTB3) from the FRED database. To express real variables in per capita terms, we divide real GDP, consumption and investment by total population of 16 years and over. Data for the euro area come from the Fagan et al. (2005) dataset. We extract from that database real GDP (pnemonic: YER), real consumption (PCR), real investment (ITR), wage rate (WRN), the CPI (HICP), the GDP deflator (obtained by diving the nominal GDP, YEN, by the real GDP, YER) and short-term interest rates (STN). We

[11] Bergin (2006) shows that this shock explains more than 60 percent of the current account dynamics in a similar two-country framework.
[12] For a description on how to implement the Bayesian approach, see An and Schorfheide (2007).
[13] The Kalman filter is initialized at the steady state, such that the initial vector of state variables is zero.

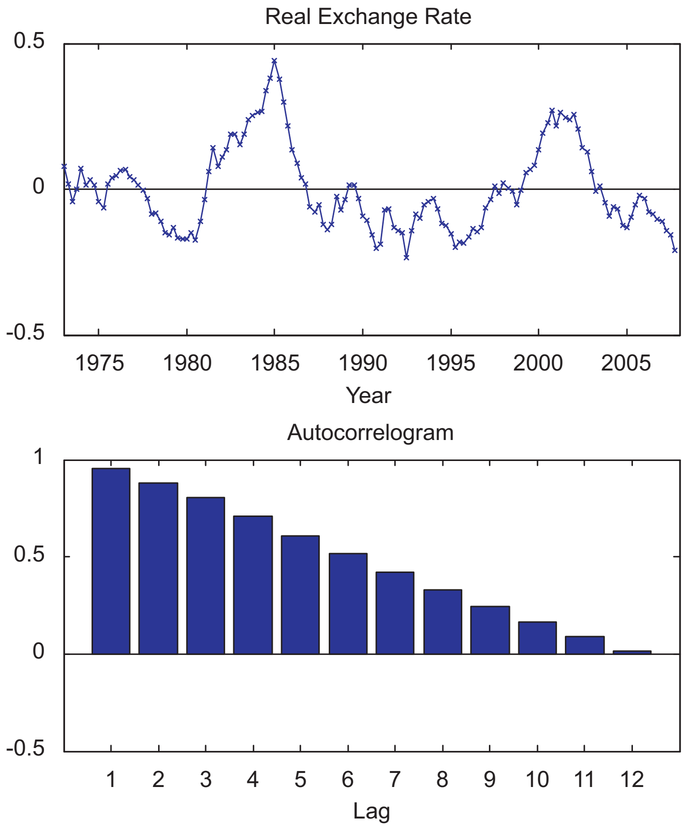

Fig. 1. The euro-dollar real exchange rate.

compute the real wage by dividing the wage rate by the CPI. The euro area population series is taken from Eurostat. Since it consists of annual data, we transform it to quarterly frequency by using linear interpolation.

The convention we adopt is that the home country is the euro area, and the foreign country is the United States, such that the real exchange rate consists of the nominal exchange rate in euros per U.S. dollar, converted to the real exchange rate index by multiplying it by the U.S. CPI and dividing it by the Euro area CPI. Therefore, an increase of the real exchange rate means a depreciation. The "synthetic" euro/U.S. dollar exchange rate prior to the launch of the euro in 1999 also comes from Eurostat. Our sample period goes from 1973:1 to 2008:4, at quarterly frequency. To compute real growth and inflation rates, we take natural logs and first differences of: real GDP per capita, consumption per capita, investment per capita, real wages, the GDP deflator and the CPI, respectively. We divide the short term interest rate by four to obtain its quarterly equivalent. We also take natural logs to the euro/dollar real exchange rate.

Let Ω denote the vector of parameters that describe preferences, technology, the monetary policy rules, and the shocks in the two countries of the model. The vector of observable variables consists of $\varkappa_t = \{\Delta gdp_t, \Delta gdp_t^*, \Delta c_t, \Delta c_t^*, \Delta i_t, \Delta i_t^*, \Delta p_t, \Delta p_t^*, \Delta p_{H,t}, \Delta p_{F,t}^*, \Delta(w_t - p_t), \Delta(w_t^* - p_t^*), r_t, r_t^*, rer_t\}$, where all observable variables are demeaned. The assumption of a world technology shock with a unit root makes real variables stationary in the model in first differences, and provides a model consistent way of detrending real variables. To be consistent with the model, the nominal interest rate and the real exchange rate are already stationary in levels, so no further transformation beyond demeaning is performed. In Fig. 1 we show the real exchange rate series, together with its autocorrelogram.[14] It is a highly persistent series, but still displays mean reversion. The autocorrelogram function decays quite fast, suggesting that it is a stationary series. Hence, the assumption that is stationary in the model and in the data is appropriate.[15] We express all variables as deviations from their sample mean. We denote by $L(\{\varkappa_t\}_{t=1}^T | \Omega)$ the likelihood function of $\{\varkappa_t\}_{t=1}^T$.

4.2. Priors

To reduce the number of parameters to be estimated, we decide to fix a few parameters that we calibrate using first moments of the data, because most of these parameters are weakly identified by the variables we use as observables. Table 1 presents the parameter values we calibrate. We set the discount factor to $\beta = 0.995$. The depreciation rate, δ, is set equal to 0.025 per quarter, which implies an annual depreciation on capital equal to 10 percent. We set α equal to 0.36. We

[14] In Fig. 1 we plot the demeaned natural logarithm of the real exchange rate.

[15] We also estimated the model with the real exchange rate in logs and first differences and obtained very similar results.

Table 1
Calibrated parameters.

	Value	Parameter
β	0.99	Discount factor
δ	0.025	Depreciation rate
α	0.36	Capital share on the production of intermediate goods
ψ	1	Investment adjustment cost
ε_w	6	Elasticity of substitution across types of labor
ε_p	11	Elasticity of substitution across types of goods
$\overline{G}/\overline{Y}$	0.2	Fraction of government spending in GDP
ω	0.95	Degree of home bias

Table 2
Prior distributions.

Parameters	Description		Mean	Standard Deviation
$b=b^*$	Habit persistence	*Normal*	0.7	0.05
$\eta=\eta^*$	Labor disutility	*Gamma*	1.0	0.25
θ	Elasticity of substitution between goods	*Normal*	1.5	0.25
χ	Cost of foreign position	*Gamma*	0.02	0.014
$\theta_H=\theta_{F^*}$	Calvo lotteries in prices	*Beta*	0.66	0.1
$\lambda_H=\lambda_{F^*}$	Indexation	*Beta*	0.50	0.2
$\theta_w=\theta_{w^*}$	Calvo lotteries in wages	*Beta*	0.75	0.1
$\varphi_\pi=\varphi_{\pi^*}$	Taylor rule Inflation	*Normal*	1.5	0.25
$\varphi_y=\varphi_{y^*}$	Taylor rule output growth	*Normal*	1.0	0.2
$\varphi_R=\varphi_{R^*}$	Interest rate smoothing	*Beta*	0.5	0.28
$\rho_c, \rho_{c^*}, \rho_n, \rho_{n^*}, \rho_v, \rho_{v^*}, \rho_a, \rho_{a^*}, \rho_g, \rho_{g^*}, \rho_{uip}$	AR(1) coefficients of shocks	*Beta*	0.75	0.1
Standard deviation of shocks				
$\sigma(\varepsilon_t^i), i=c,c^*,n,n^*$	Preference	*Gamma*	1.0	0.5
$\sigma(\varepsilon_t^i), i=v,v^*,a,a^*$	Investment and TFP	*Gamma*	0.7	0.3
$\sigma(\varepsilon_t^i), i=g,g^*$	Government spending	*Gamma*	1.0	0.5
$\sigma(\varepsilon_t^x)$	TFP unit root shock	*Gamma*	0.7	0.3
$\sigma(\varepsilon_t^{uip})$	Uncovered interest parity	*Gamma*	1.0	0.5
$\sigma(\varepsilon_t^i), i=m,m^*$	Monetary	*Gamma*	0.4	0.2
$\sigma(\varepsilon_t^i), i=\mu_f,\mu_{f^*}$	CPI mark-up	*Gamma*	0.2	0.1

set the adjustment cost of investment, ψ, equal to 1, a standard value in the literature.[16] We set the elasticity of substitution across types of labor, ε_w, and across types of goods, ε_p, equal to 6 and 11, respectively, as it is standard in the DSGE literature. We use U.S. national accounts to set the steady-state ratio of government expenditures over GDP, equal to 0.2. We set the fraction of imported goods, $1-\omega$, equal to 0.05, which is in between the ratio of bilateral imports/GDP between the USA and the euro area. This value is also in between the calibrations in CKM (2002) and Heathcote and Perri (2002).

The remaining parameters are estimated. Table 2 gives an overview of the assumptions regarding the prior distribution of the estimated parameters that we denote by $\Pi(\Omega)$. We use beta distributions for parameters bounded between 0 and 1. For parameters assumed to be positive we use a gamma distribution, and for unbounded parameters we use normal distribution.

The parameters that incorporate the open economy features of the model take the following distributions. The elasticity of substitution between home and foreign goods, θ, has the following distribution: we assign a prior mean value of 1.5 as suggested by CKM, but with a large enough standard deviation to accommodate other feasible parameters, even those below one.[17] The parameter χ, that measures the elasticity of the risk premium with respect to the net foreign asset position, is assumed to have a gamma distribution with mean 0.02 and standard deviation 0.014, following the evidence in Selaive and Tuesta (2003a, b).

[16] We estimated a version of the model where ψ was estimated with a prior mean of 1. The prior and posterior looked very much alike, suggesting that this parameter was not identified.

[17] Trade studies typically find values for the elasticity of import demand to respect to price (relative to the overall domestic consumption basket) in the neighborhood of 5–6, see Trefler and Lai (1999). Most of the NOEM models assign a unity value to this elasticity which implies Cobb–Douglas preferences in aggregate production.

Table 3
Posterior Distributions

Model Parameters			
b	0.55 (0.51–0.58)	λ_H	0.04 (0.01–0.07)
η	0.29 (0.17–0.38)	θ_w	0.56 (0.49–0.61)
θ	0.94 (0.83–1.01)	φ_π	1.30 (1.19–1.43)
χ	0.015 (0.006–0.03)	φ_y	0.75 (0.64–0.87)
θ_H	0.78 (0.74–0.81)	φ_R	0.79 (0.75–0.81)
AR(1) coefficients of shocks			
ρ_c	0.95 (0.93–0.97)	ρ_{c^*}	0.81 (0.75–0.87)
ρ_n	0.92 (0.89–0.95)	ρ_{n^*}	0.82 (0.78–0.89)
ρ_v	0.92 (0.87–0.97)	ρ_{v^*}	0.71 (0.63–0.79)
ρ_a	0.92 (0.88–0.96)	ρ_{a^*}	0.91 (0.86–0.97)
ρ_g	0.94 (0.90–0.98)	ρ_{g^*}	0.90 (0.83–0.98)
ρ_{uip}	0.90 (0.86–0.94)		
Standard deviations of shocks			
$\sigma\ (\varepsilon_t^c)$	2.14 (1.66–2.56)	$\sigma\ (\varepsilon_t^{c^*})$	1.69 (1.42–1.97)
$\sigma\ (\varepsilon_t^n)$	2.57 (2.20–3.11)	$\sigma\ (\varepsilon_t^{n^*})$	3.42 (2.63–4.43)
$\sigma\ (\varepsilon_t^v)$	1.40 (1.11–1.63)	$\sigma\ (\varepsilon_t^{v^*})$	2.83 (2.41–3.17)
$\sigma\ (\varepsilon_t^a)$	1.63 (1.35–1.91)	$\sigma\ (\varepsilon_t^{a^*})$	1.85 (1.51–2.13)
$\sigma\ (\varepsilon_t^g)$	2.03 (1.89–2.19)	$\sigma\ (\varepsilon_t^{g^*})$	2.99 (2.75–3.28)
$\sigma\ (\varepsilon_t^m)$	0.20 (0.19–0.24)	$\sigma\ (\varepsilon_t^{m^*})$	0.22 (0.21–0.24)
$\sigma\ (\varepsilon_t^{\mu^f})$	0.41 (0.37–0.42)	$\sigma\ (\varepsilon_t^{\mu^{f^*}})$	0.39 (0.37–0.40)
$\sigma\ (\varepsilon_t^{uip})$	0.58 (0.42–0.73)	$\sigma\ (\varepsilon_t^x)$	0.48 (0.33–0.61)

Note: deep parameters of the model are the same between the Euro Area and the United States. Shock processes are different. We denote with an asterisk the estimated parameters for the United States. Figures in parenthesis denote 90 percent posterior confidence intervals.

5. Results

5.1. Posterior distributions

In Table 3, we present the estimates of the benchmark economy. We present the posterior mean, together with a 90 percent posterior confidence band. First of all, we would like to mention that we also estimated the model as two separate closed economies, by setting $\omega = 1$ and dropping θ from the set of estimated parameters (as this parameter plays no role in a closed-economy version of the model), and modeling the real exchange rate as an exogenous AR(1) process. The parameter estimates of such model are not very different to what we present in Table 3, so to save space we do not present them.

The posterior mean estimates for the external habit formation parameters which are roughly in line with previous studies ($b = 0.55$), while the estimated inverse elasticities of labor supply are relatively small ($\eta = 0.29$). Our point estimates imply stronger nominal rigidities in price-setting than in wage-setting: the posterior mean for the Calvo lottery from price setting is 0.78, but the one on wage setting is 0.56. These estimates are in line with Rabanal and Rubio-Ramírez (2005), Justiniano and Preston (2008), and Fernández-Villaverde and Rubio-Ramírez (2008), but diverging from Smets and Wouters (2003), who have much more informative priors. The posterior mean of the price indexation parameter is much smaller than the mean value of the prior distribution: $\lambda_H = 0.04$, implying that a forward-looking Phillips curve fits both countries well.[18] Estimates of the Taylor rule for are also similar to what has been obtained in previous studies.

The crucial parameter in the model for international relative price dynamics (i.e. the terms of trade and the real exchange rate) is the elasticity of substitution between goods across countries, θ. In our benchmark model, we find that the estimate for the elasticity θ is below but close to one, with a posterior mean of 0.94. Our prior distribution was centered at a value of 1.5, so the data clearly provide evidence that the estimated elasticity is smaller but close to one. Note, however, that this value is higher than the value in Lubik and Schorfheide (2006), who found a posterior mean of 0.43, and closer to Justiniano and Preston (2009), who used data for the United States and Canada.

In Table 3 we also provide estimates for χ. We find a mean value of 0.015, which is similar to other values in the literature, using different econometric approaches and methodologies. For instance, Bergin (2006) obtained, using data from the G7 countries and estimated value of 0.0038, while Lane and Milesi-Ferretti (2001) obtained a value of 0.0254 from a panel of OECD countries. Selaive and Tuesta (2003b), by using GMM, estimate a risk-sharing condition similar to ours, and obtain estimates in the range between 0.004 and 0.071 for a sample of OECD countries.

[18] At this point it is work mentioning that wage indexation was also estimated to be close to zero, and hence we decided to exclude this mechanism from the analysis.

It is difficult to draw comparisons with other studies regarding the estimated process of the shocks. Hence, in the next section, we perform a variance decomposition exercise for the group of observable variables, and focus on the contribution of each shock in explaining real exchange rate dynamics.

5.2. Second moments

In this subsection we present some selected second moments with a focus on real exchange rate dynamics. Table 4 reports the posterior second moments implied by our estimation and are compared with those in the actual data. Overall, we find that the benchmark model does a reasonable good job in matching the real exchange rate volatility but it implies a volatility of output, and specially of consumption and investment in both countries that is higher than in the data. The benchmark model predicts a standard deviation for the level of the real exchange rate of 13 where as in the data it takes a value of 14.38. The model performs well in matching CPI inflation, GDP deflator inflation, nominal interest rates and real wage growth volatility for both countries, getting very close to the values observed in the data. An interesting result to highlight is that the fit of the open economy model goes in accordance with that of the closed economy estimation.[19]

In Table 4 we also report some cross-correlations that are the focus of International Real Business Cycle models.[20] In the closed economy version of the model, there is some cross-correlation due to the presence of the common TFP shock with unit roots. We present this result as a benchmark to understand what happens when countries are open to trade in goods and financial assets. Both models underpredict the cross-country correlations of the growth rates of output, consumption and investment.[21] Yet, the open economy model performs slightly better than the closed economy one, getting closer to the data. However, the model seems to be able to replicate that growth rate of consumption is less correlated across countries than the growth rate of output, but by a small margin. This is an improvement over many international macroeconomic models, where the correlation of consumption is higher than the correlation of output in the model, regardless of the international asset market structure.

How does the benchmark model perform in terms of the correlation between the change in the real exchange rate and the change in relative consumptions across countries? As the last column of Table 4 indicates, in the data this correlation is negative (−0.18), where as in the model this correlation is positive but very close to zero (0.09). These magnitudes are similar when we compare the level of the real exchange rate with the growth rate of relative consumption across countries. Traditional international real business cycle models predict that this correlation is positive and very close to one. This discrepancy between the model and the data is known as "the consumption-real exchange rate anomaly." Overall our estimated model does a fairly good job in matching this correlation compared to calibrated IRBC models.[22]

5.3. Variance decomposition

In this subsection we investigate what is the importance of the shocks in the model for explaining the set of observable macro variables. Table 5 reports the stationary variance decomposition of the model for the 15 observable variables. Rather than describing the effect of each shock in isolation, we have regrouped them as follows: (a) supply shocks include both AR(1) technology shocks of each country, the unit root world technology shock, and the mark-up shocks in the final goods sector, (b) preference shocks include both intertemporal and intratemporal preferences shocks of each country, (c) demand shocks consider both the fiscal policy and the investment-specific technology shock,[23] and (d) includes the two monetary policy shocks.

The main result to note of Table 5 is that about half of the volatility of the real exchange rate is explained by the UIP shock, despite the rich transmission mechanisms that we have introduced in the model. It explains 49.3 percent of its variance. The second largest component are the supply shocks that explains 21.1 percent of the variance of the real exchange rate. The estimated model reveals that real exchange rate fluctuations are not largely driven by either monetary (1.6 percent of the RER variance), preference (16.5 percent) or demand shocks (11.3 percent). Hence, the exercise suggested by Chari et al. (2002) of attempting to explain real exchange rate fluctuations with only monetary policy shocks is misguided, as it will require very large and unreasonable monetary policy shocks to explain the data.

Some other interesting results arise from the variance decomposition. First, it is important to note that the UIP shock has a very small impact on the rest of macrovariables. This suggests that the determination of the exchange rates is disconnected from fundamentals. Monetary policy shocks explain an important fraction (between 12 and

[19] In a previous version of the paper (Rabanal and Rubio-Ramírez, 2006), we found that the fit of the open economy model was worse to most variables compared to the closed economy version in a model without investment and sticky wages. Clearly, adding these features as in the present version removes the tension between fitting the closed economy and the open economy dimension of the data. We are grateful to one anonymous referee for suggesting that we extend the model to allow for these important frictions.

[20] See Heathcote and Perri (2002) and Chari et al. (2002).

[21] This result is present also in Justiniano and Preston (2009) and De Walque et al. (2005): with UIP-shocks, two country models lose the ability to explain comovement of key macro variables across countries.

[22] See Corsetti et al. (2008b) and Benigno and Thoenissen (2008) for some interesting avenues to explain the consumption real exchange rate anomaly.

[23] We label this shock as a demand shock because it leads to an "exogenous" increase in investment.

Table 4
Moments in the models and in the data.

	Data	Closed Economy	Open Economy
Standard deviations			
Δgdp	0.55	0.81 (0.76–0.84)	0.75 (0.71–0.79)
Δgdp^*	0.81	0.91 (0.85–0.95)	0.88 (0.84–0.93)
Δc	0.54	0.88 (0.85–0.95)	0.83 (0.78–0.86)
Δc^*	0.64	0.92 (0.85–0.98)	0.93 (0.88–0.98)
Δi	1.35	3.36 (3.06–3.66)	3.47 (3.63–4.23)
Δi^*	4.36	6.53 (5.99–7.29)	6.01 (5.38–6.51)
Δp	0.88	1.00 (0.86–1.09)	0.87 (0.71–1.03)
Δp^*	0.80	0.73 (0.64–0.80)	0.74 (0.67–0.81)
Δp_H	0.93	0.96 (0.82–1.09)	0.84 (0.66–1.00)
Δp_{F^*}	0.64	0.67 (0.56–0.74)	0.71 (0.61–0.78)
$\Delta(w-p)$	0.68	0.74 (0.71–0.77)	0.77 (0.72–0.80)
$\Delta(w^*-p^*)$	0.72	0.90 (0.85–0.97)	0.85 (0.79–0.91)
r	0.90	0.84 (0.70–0.98)	0.78 (0.57–0.95)
r^*	0.73	0.56 (0.49–0.63)	0.55 (0.47–0.62)
rer	14.38	–	13.00 (10.44–14.76)
Cross-Correlations			
$\Delta gdp, \Delta gdp^*$	0.29	0.05 (0.02–0.08)	0.12 (0.09–0.14)
$\Delta c, \Delta c^*$	0.24	0.02 (−0.01–0.04)	0.05 (0.03–0.07)
$\Delta i, \Delta i^*$	0.09	0.003 (0.001–0.005)	0.00 (−0.01–0.01)
$\Delta rer, (\Delta c-\Delta c^*)$	−0.18	–	0.09 (0.04,0.13)
$rer, (\Delta c-\Delta c^*)$	−0.22	–	0.04 (0.01,0.07)

Note: Figures in parenthesis denote 90 percent posterior confidence intervals.

19 percent) of the volatility of real GDP growth and consumption growth in both countries, and investment in the euro area. A large fraction of the volatility of consumption growth in each country is mainly explained by preference shocks (40.7 and 47.3 percent for euro area and USA, respectively), while the investment shock explains the largest part of investment in the United States, and to a lesser extent, in the euro area (not shown as it is aggregated under the ''Demand'' column). Output growth volatility in both countries is mostly evenly split between demand, preference and supply factors. Regarding inflation rates, both supply and preference shocks (through their effect on real wages) are important.

6. Robustness: the role of asset markets and currency denomination of exports

So far, we have presented the estimates of a medium scale two-country model that tries to explain the real exchange rate and the linkages between the euro area and the United States. Besides all the features that are necessary to explain the closed-economy dimension of the data, we have introduced two main ingredients: incomplete asset markets and local currency pricing for imports and exports. In this section, we study how important are these two features in explaining the data. To that end, we first explain how the models change if we allow for complete asset markets and if we allow for the law of one price to hold across countries. Then, we explain what are the implications for model fit.[24]

[24] The posterior distributions of the model parameters in all cases are available upon request.

Table 5
Variance decomposition (in percent).

	Supply	Preference	Demand	Monetary	UIP
Δgdp	33.2	30.1	21.5	15.1	0.2
Δgdp^*	25.1	29.5	33.0	12.1	0.1
Δc	32.4	40.7	6.7	19.2	1.1
Δc^*	26.4	47.3	8.5	16.9	0.9
Δi	15.4	24.9	42.4	15.9	1.4
Δi^*	7.3	8.0	78.3	5.9	0.5
Δp	30.4	58.3	3.7	5.6	1.8
Δp^*	45.8	34.7	9.0	8.2	2.5
Δp_H	21.9	66.0	4.3	6.0	1.7
Δp_{F^*}	36.7	41.2	10.4	9.1	2.4
$\Delta(w-p)$	47.4	43.0	5.0	3.6	1.0
$\Delta(w^*-p^*)$	39.1	50.9	6.0	3.3	0.8
r	8.3	76.1	9.1	4.3	2.2
r^*	17.3	46.2	22.9	9.2	4.4
rer	21.1	16.5	11.3	1.6	49.3

6.1. Complete markets

The assumption of complete markets implies that the level of the real exchange rate equals the marginal rate of substitution of consumption across countries. Taking a loglinear approximation and adding the UIP shock, delivers

$$rer_t = \frac{\tilde{c}_t - b\tilde{c}_{t-1} - (\tilde{c}_t^* - b\tilde{c}_{t-1}^*)}{1-b} - (d_{c,t} - d_{c,t}^*) + uip_t \tag{38}$$

This risk-sharing condition differs with respect to the one in CKM, under complete markets, because of the presence of intertemporal preference shocks, UIP shocks and habit formation.

6.2. Producer currency pricing

We assume that the law of one price holds for each intermediate good that is traded internationally. Therefore, firms maximize a profit condition similar to (25), but firms choose the price for the home market, $P_{H,t}(h)$, and the price in the foreign market is simply given by $P_{H,t}(h) = S_t P_{H,t}^*(h)$ for all t. In the aggregate, the price of goods shipped internationally is $P_{H,t} = S_t P_{H,t}^*$ for all t. Taking a loglinear approximation to the pricing equations implies that domestically produced intermediate goods inflation dynamics in each country are given by

$$\Delta p_{H,t} - \lambda_H \Delta p_{H,t-1} = \beta(E_t \Delta p_{H,t+1} - \lambda_H \Delta p_{H,t}) + \kappa_H(mc_t - \hat{p}_{H,t}) \tag{39}$$

Then, the prices of imports are given by

$$\Delta p_{F,t} = \Delta s_t + \Delta p_{F,t}^* \tag{40}$$

where $\Delta p_{F,t}^*$ is domestic inflation in the foreign country. The CPI inflation rates are now a combination of domestically produced intermediate goods inflation and imported intermediate goods inflation. Since prices are set in the producer currency, and the law of one price holds, the nominal exchange rate has a direct inflationary impact on CPI inflation:

$$\Delta p_t = \omega \Delta p_{H,t} + (1-\omega)(\Delta p_{F,t}^* + \Delta s_t) + \mu_{f,t} - \mu_{f,t-1} \tag{41}$$

When the law of one price holds, it can be shown that the real exchange rate and the terms of trade under producer currency pricing are linked as follows:

$$rer = (2\omega - 1)(p_{F,t} - p_{H,t}) + \mu_{f,t} - \mu_{f,t}^* \tag{42}$$

If there were no markup shocks in the final goods sector, the previous expression would imply a correlation of 1 between the two variables in the model. Given that we estimate the model with CPI inflation and GDP deflator inflation, the mark-up shocks in the final goods sector become crucial to be able to estimate the model under PCP and avoid singularity problems in the likelihood function. The degree of home bias is crucial to account for the volatility of the real exchange rate: the larger the degree of home bias (larger ω), the larger the volatility of the real exchange rate.

6.3. Model comparison

In order to compare how these two modelling frictions affect overall model fit, in Table 6 we present the marginal likelihood of the four open economy models. The marginal likelihood is key to performing a model comparison exercise in

Table 6
Model comparison.

	Data	LCP-Incomplete	LCP-Complete	PCP-Incomplete	PCP-Complete
Marginal likelihood	–	7048.89	7032.77	7006.42	7003.32
Std(*rer*)	14.38	13.00	13.96	17.36	15.43
		(10.44–14.76)	(12.20–15.52)	(14.68–21.28)	(13.60–17.32)
Corr ($\Delta rer, \Delta c - \Delta c^*$)	−0.18	0.09	0.06	−0.11	−0.04
		(0.04,0.13)	(0.01,0.11)	(−0.17, −0.05)	(−0.10,0.03)
Estimated θ		0.94	0.68	0.57	0.16
		(0.83–1.1)	(0.52–0.83)	(0.54–0.60)	(0.07–0.25)
Variance decomposition of RER (in %)					
Supply	–	21.1	22.6	24.8	21.8
Preference	–	16.5	20.6	20.0	21.6
Demand	–	11.3	9.9	5.4	10.8
Monetary	–	1.6	1.6	1.2	0.1
UIP	–	49.3	45.4	48.6	44.7
No UIP Shocks, Marginal likelihood	–	6853.08	6765.75	6830.82	6750.52

Note: LCP, local currency pricing; PCP, producer currency pricing. Figures in parenthesis denote 90 percent posterior confidence intervals.

the Bayesian framework, since it tells the researcher how she would update her priors on which model is the true one after observing the data.[25] Three clear results emerge. First, introducing local currency pricing (LCP) is always better than PCP. This result is consistent with the results of Bergin (2006). Second, in a PCP model, it is difficult to distinguish which asset market structure is better: the log Bayes factor between the PCP-complete and the PCP-incomplete model is smaller than three, which makes both models barely different. Third, as shown in Table 6, between LCP models there is an improvement in model fit when introducing incomplete markets (the log-likelihood increases from 7022.77 in a LCP-complete model to 7048.89 in a LCP-incomplete model).

The combination of incomplete markets and LCP results in an improvement in model fit, with respect to a model without any of the two features. Indeed, the differences in the marginal likelihoods are important. For this case the differences imply "decisive" evidence for the model with highest (log) marginal likelihood, using the Bayesian model comparison language (Kass and Raftery, 1995). Note that the (log) Bayes factor between the LCP-incomplete market model and the PCP-complete market models is about 45.6. This means that we would need a prior that favors the latter over the former by a factor of exp(45.6) in order to accept it after observing the data. Since this is a large number, we conclude that the incomplete market model with LCP outperforms the models with PCP (either with complete or incomplete markets).

The marginal likelihood is a summary measure of model fit, but we also would like to examine how these four versions of the model perform in explaining some facts about international business cycles.[26] Hence, in Table 6 we also present some posterior moments for key parameters and statistics for each of the four models. Note that the models with PCP slightly overpredict real exchange rate volatility. All models do a fairly good job in matching the lack of risk sharing (the near-zero correlation between changes in the real exchange rate and the ratio of consumptions across countries), with the PCP-incomplete market model being the one that gets the correct. However, in all cases the numerical differences are small. The baseline model delivers the largest estimated value of the elasticity of substitution between tradable goods, which is in the range of acceptable calibrations for open economy DSGE models (Corsetti et al., 2008a). The posterior mean for θ obtained under the PCP-complete market case estimate is low by any standards (0.16). Finally, for all models the UIP shock is the one that explains most of the real exchange rate volatility, with its contribution ranging between 45.4 percent for the LCP-complete model to 49.3 percent in the baseline (LCP-incomplete) model.

6.4. The role of UIP shocks in model comparison

Table 6 shows that the models with complete and incomplete markets deliver very similar results in terms of model fit. Does this mean that the asset market structure does not matter to explain RER dynamics and to estimate open economy DSGE models? So far, we have compared the asset market structure but keeping the uncovered interest rate parity shock. Hence, if one of the two asset market structures results in severe mispecification of the model, this might not show up in the model comparison exercises since the UIP shock could be absorbing this misspecification, making it difficult to distinguish between both asset market structures.

In order to study the role of UIP shocks in explaining the differences between asset market structures, we also estimated the four models eliminating the autoregressive UIP shock from the risk-sharing expressions (depending on the asset market structure, the relevant equation is either (33) and (38)). Note that the intertemporal preference shocks still get in

[25] See An and Schorfheide (2007) and Fernández-Villaverde and Rubio-Ramírez (2004).
[26] Del Negro and Schorfheide (2008) discuss how to appropriately select prior distributions to compare between models.

Table 7
Estimating the fraction of LCP firms.

		Incomplete		Complete	
		LCP	LCP-share	LCP	LCP-share
Marginal likelihood		7048.89	7037.49	7032.77	7028.89
Parameter estimate	α^{lcp}	1	0.85	1	0.89
		(–)	(0.68–1.00)	(–)	(0.78–1.00)
	θ	0.94	0.93	0.68	0.72
		(0.83–1.1)	(0.75–1.11)	(0.52–0.83)	(0.47–0.98)

Note: LCP, local currency pricing. Figures in parenthesis denote 90 percent posterior confidence intervals.

the way of taking the risk-sharing conditions literally. But since these shocks also enter the consumption Euler equations, they cannot be considered as "cost free" shocks like the UIP shocks, that only entered the risk-sharing equation. The last row of Table 6 summarizes our findings. First, by comparing the results of the models with and without UIP shocks, we can conclude that the log marginal likelihoods are overwhelmingly rejecting the models without UIP shocks in favor of the models with UIP shocks. The second interesting result is that when estimating the model without UIP shocks, the asset market structure matters. Indeed, the log marginal likelihoods of Table 6 indicate that models with incomplete markets outperform models with complete markets. Third, in terms of model comparison the model that ranks the best is still the LCP-incomplete markets, with large log Bayes factors with respect to the other models (at least 23).[27]

Therefore, our conclusion of this subsection is as follows: as the degree of model misspecification decreases, the asset market structure becomes more relevant, and incomplete markets is more important than complete markets. However, if the model has a rich structure of shocks, and in particular of those shocks that affect the risk sharing condition, then the difference between complete and incomplete markets becomes smaller. On the other hand, the richer is the structure of the shocks in the economy, the more relevant the LCP assumption with respect to the PCP assumption becomes.

6.5. Assuming that a fraction of firms engages in LCP

Our findings so far indicate that introducing LCP is always better than PCP. Note that introducing either the LCP or PCP assumption implies a discontinuity in the set of models to be compared, as one model is not nested into the other. In order to restore such continuity, in this subsection we assume that a fraction of firms in each country (α^{lcp}) engage in LCP when shipping their goods, while the remaining fraction set the price of exports according to PCP.

This assumption implies the following consumer price indexes for each country:

$$\Delta p_t = \omega \Delta p_{H,t} + (1-\omega)[\alpha^{lcp}\Delta p_{F,t} + (1-\alpha^{lcp})(\Delta p^*_{F,t} + \Delta s_t)] \tag{43}$$

where the above equation is obtained by combining the CPI indexes under both LCP (Eq. (37)) and PCP (Eq. (41)). We estimate the models under the assumptions of complete and incomplete markets, and use a uniform prior for (α^{lcp}) in the [0,1] interval.

Table 7 summarizes our results. First, based on the marginal likelihood the model that performs the best is still the benchmark LCP-incomplete model of Section 2. Under complete markets the log Bayes factor is less than 4, while under incomplete markets the log Bayes factor is 11. The estimated shares of firms following LCP is large and close to one, regardless of the asset market assumption. Also, the elasticity of substitution θ barely changes with this particular extension of the model.

7. Concluding remarks

In this paper we have estimated a two-country model for the euro area and the U.S. with a particular focus on the implications for real exchange rate dynamics. We have used a Bayesian approach to estimate the models' parameters and to compare a baseline two-country model with incomplete markets and local currency pricing with two main simplifications, namely complete markets and producer currency pricing.

Our main finding is that an incomplete markets model combined with sticky prices in export prices provides plausible parameter estimates and does a good job in matching the real exchange rate dynamics. In addition, the law of one price assumption is rejected by the data. In addition, the estimation results highlight that a shock to the risk sharing condition

[27] Finally, we have also estimated versions of the four models where we take the risk sharing condition literally. Therefore, we have taken out the intertemporal preference shock and the UIP shock. Since we are left with only 13 shocks in the model, we also took out real GDP growth in each country as observable variables. The results, that are available upon request, suggest that the best model is the LCP-incomplete model, and the Bayes factor between models of complete and incomplete markets is larger than 100. In this exercise we make the risk-sharing condition hold exactly, which is a very strong assumption for the complete markets case, and hence model fit is much worse.

(UIP shock) is essential to fit the data, at the cost of making difficult to distinguish which asset market structure is more important. Not surprisingly, this shock accounts for most of the variation of the real exchange rate whereas, in contrast with CKM, monetary shocks have played a minor role.

There are some interesting avenues for future research. Introducing cointegration of TFP processes across countries helps in explaining real exchange rate volatility in an IRBC model without any nominal or real friction, as shown by Rabanal et al. (2009). Analyzing the out-of-sample forecasting performance of competing NOEM models, along the lines of the exercise performed by Del Negro et al. (2007) in the closed economy would help clarify the role of these models for policy formulation and analysis. A first step in this direction using euro area data has been performed by Adolfson et al. (2008). Finally, estimation of NOEM models with higher order approximations, with the tools developed by An (2005) and Fernández-Villaverde and Rubio-Ramírez (2007) would allow to understand what is the role of uncertainty in explaining real exchange rate fluctuations.

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