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ARTICLES

INVESTMENT AND REAL EXCHANGE RATES IN STICKY PRICE MODELS

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This paper investigates how the inclusion of capital in the workhorse new open economy macro model affects its ability to generate volatile and persistent real exchange rates. We show that capital accumulation facilitates intertemporal consumption smoothing and significantly reduces the volatility of the real exchange rate. Nonetheless, monetary and investment-specific technology (IST) shocks still induce more real exchange rate volatility and less consumption comovement than productivity shocks (with or without capital). We find that endogenous persistence is particularly sensitive to the inertia of the monetary policy rule even with persistent exogenous shocks. However, irrespective of whether capital is present, productivity and IST shocks trigger highly persistent real exchange rates, whereas monetary shocks do not. Moreover, we point out that IST shocks tend to generate countercyclical real exchange rates—unlike productivity or monetary shocks—but have the counterfactual effect of also producing excessive investment volatility and countercyclical consumption.

Keywords: Real Exchange Rates, Capital Accumulation, Sticky Prices, Local-Currency Pricing

1. INTRODUCTION

Finding a macroeconomic model that can replicate the volatility and persistence of the CPI-based real exchange rate (RER) has not been an easy task.[1] CPI-based RERs can fluctuate for multiple reasons, but Engel (1999) documented that

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deviations from the law of one price on traded goods seem to account for most of the movement of the RER in the U.S. data. That empirical finding and other related evidence generated a renewed interest in exchange rates in the literature. In particular, many new open economy macro (NOEM) models—including Betts and Devereux (2000), Bergin and Feenstra (2001), Chari et al. (2002), Benigno (2004), Bouakez (2005), Corsetti et al. (2008), Steinsson (2008), and Martínez-García (2010)—have investigated the dynamics of the CPI-based RER by looking more closely at the pricing decisions of firms.[2]

Departures from the law of one price in the workhorse NOEM model are motivated by nominal rigidities—sticky prices and local-currency pricing behavior in tradable goods—and goods market segmentation by country. However, the NOEM literature remains silent for the most part on the role of investment fluctuations, as it either abstracts from capital or more generally views capital accumulation as a secondary concern when the aim is to explain the stylized facts of the RER. We argue, that introducing capital has a first-order effect on the ability of the workhorse NOEM model to generate RERs as volatile as in the data while replicating other key international business cycle moments (specifically in output, consumption, and investment). Capital also plays an important role in the endogenous propagation of shocks, which cannot be disregarded.

Our intuition is rather straightforward. Adding capital gives households in both countries a margin of intertemporal adjustment, thereby making the consumption profiles smoother. Households attain their desired consumption path in part by distributing the effects of country-specific shocks over time, and generally depend less on RER movements facilitating consumption reallocation across countries to share the risks with other households not subject to the same shocks. Hence, the RER volatility tends to fall. Our work is related to that of Jermann (1998), who has shown in a closed-economy setting how asset price volatility is intricately linked to the smoothness of consumption allowed by the costs of adjusting capital [see also Boldrin et al. (2001), Lettau (2003), and De Paoli et al. (2010)]. Adding capital also changes the propagation of shocks, but the investment persistence more than the consumption or RER persistence.

To quantitatively investigate these aspects of the RER debate, we build a symmetric two-country model—similar to that of Chari et al. (2002)—with capital and the most salient features of the workhorse NOEM model including optimizing households and firms, complete and frictionless asset markets, and deviations from the law of one price to account for RER movements. We also incorporate the possibility of different consumption baskets across countries [à la Warnock (2003)] as a second channel of RER fluctuations. Our main results are as follows:

First, capital accumulation contributes to significantly lower the consumption and RER volatility in the NOEM model—irrespective of the shocks driving the cycle. Adjustment costs slow the response of investment to shocks, making it costlier for households to adjust intertemporally and pushing the volatility of consumption and the RER up. In response to productivity shocks, we find that a polar variant that abstracts from capital entirely is needed to pin down the RER persistence and to approximate the RER volatility [see Steinsson (2008)],

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but it cannot account for investment. In response to monetary shocks, a variant with capital and adjustment costs that penalize the growth rate of investment—as in Christiano et al. (2005)—produces sufficiently volatile RERs as well as fluctuations in output, consumption, and investment consistent with the data, but it falls short in RER persistence [see also Chari et al. (2002)]. Moreover, the fit of the model driven by monetary shocks worsens markedly—consumption and RER volatility drop—when we include variable capital utilization rates, because changes in the rate of utilization offer an alternative to costly investment and, hence, facilitate consumption smoothing when it is most needed.

Second, adding capital accumulation has a discernible impact on the endogenous persistence of the NOEM model. We find that a key difference in the propagation of shocks comes about because the investment response tends to be hump-shaped only after productivity shocks when the adjustment costs are determined by the scale of change in the stock of capital—as in Chari et al. (2002)—whereas investment shows a hump-shaped response irrespective of the type of shock when the adjustment costs are a function of the growth rate of investment—as in Christiano et al. (2005). We note that high persistence tends to occur in response to persistent productivity shocks if the Taylor (1993) monetary policy rule also has a very inertial component. With non-persistent monetary shocks—as in Benigno (2004)—the effect of interest rate smoothing depends on the specification of the adjustment cost function.

Third, our findings appear broadly robust to departures from two core assumptions of the workhorse NOEM model. We reestablish the law of one price by replacing the assumption of local-currency pricing in international goods markets with producer-currency pricing. Then, the RER moves in tandem with terms of trade and solely because of differences in the consumption baskets across countries. That illustrates how deviations from the law of one price are larger and more important in accounting for RER fluctuations when the model is primarily driven by monetary shocks [see, e.g., Betts and Devereux (2000)]. However, RERs are still less volatile the easier it gets for households to utilize capital to intertemporally smooth consumption. We also depart from the assumption of complete international asset markets, which imposes perfect international risk-sharing and a tight link between the RER and relative consumption. That shows how a bond economy with international borrowing costs and the workhorse NOEM model generate very similar international business cycle patterns in response to productivity and monetary shocks [see also Baxter and Crucini (1995), Chari et al. (2002), and Heathcote and Perri (2002)]. A more in-depth exploration of the complex role of asset markets goes beyond the scope of this paper and is left for future research.

Finally, the potential of investment-specific technology (IST) shocks—as in Greenwood et al. (1988) and Raffo (2010)—to generate RER dynamics appears limited. Although it is possible to roughly replicate the observed persistence and volatility of the RER when IST shocks are the primary drivers of the cycle, they also induce excessive investment volatility and countercyclical consumption that are inconsistent with the data. Unlike the case with productivity and monetary shocks, the volatility of the RER with IST shocks tends to fall significantly if we abandon the assumption of complete international asset markets. Interestingly, the optimal decision to postpone consumption to invest more in response to a positive IST shock induces the RER to appreciate on impact when domestic output increases, but the opposite occurs with either productivity or monetary shocks.

The remainder of the paper is structured as follows: Section 2 describes our two-country benchmark model with capital accumulation, whereas Section 3 outlines our parameterization strategy for the simulations. Section 4 summarizes the quantitative findings, and Section 5 the sensitivity analysis. Section 6 concludes.

2. THE OPEN ECONOMY MODEL

As a notational convention, the superscript "$*$" identifies variables that depend on the choices of agents located in the foreign country. Because the model is built around two symmetric countries, we discuss only the home country unless otherwise noted.

2.1. The Household's Problem

Each country is populated by an infinitely lived, representative household. The domestic household maximizes a per-period utility function that is additively separable in consumption, C_t, and labor, L_t; i.e.,

$$\sum_{\tau=0}^{+\infty} \beta^{\tau} \mathbf{E}_t \left[\frac{1}{1-\sigma^{-1}} \left(C_{t+\tau}\right)^{1-\sigma^{-1}} - \frac{1}{1+\varphi} \left(L_{t+\tau}\right)^{1+\varphi} \right], \tag{1}$$

where $0 < \beta < 1$ is the intertemporal discount factor. The elasticity of intertemporal substitution satisfies that $\sigma > 0$ ($\sigma \neq 1$), whereas the inverse of the Frisch elasticity of labor supply satisfies that $\varphi > 0$. The domestic household's maximization problem is subject to the sequential budget constraints

$$P_t[C_t + X_t + A(U_t)\widetilde{K}_t] + \int P^b(s^{t+1} \mid s^t) B(s^{t+1}) ds_{t+1} \leq B(s^t) + D_t + W_t L_t + Z_t K_t, \tag{2}$$

where X_t is domestic real investment, K_t are domestic capital services, W_t is the domestic nominal wage, Z_t denotes the nominal rental rate on capital services, D_t are the nominal aggregate profits of all domestic firms, and P_t is the domestic consumption price index (CPI).

We denote by s_{t+1} the event that occurs at time $t+1$ and $s^{t+1} = (s^t, s_{t+1})$ the history of events up to that point. The household's portfolio includes a complete set of one-period contingent claims (Arrow–Debreu securities), traded internationally and quoted in units of the domestic currency. Households have unrestricted access to all contingent claims, $P^b(s^t \mid s^{t-1})$ is the domestic price of a given claim, and $P^b(s^t \mid s^{t-1})/S_t$ is its price in foreign currency units. S_t denotes the nominal exchange rate. $B(s^t)$ is the nominal payoff perceived by the domestic household

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after the event s_t occurs at time t on a claim purchased at time $t-1$ that would have paid nothing if event s_t had not happened. The foreign household maximizes its lifetime utility subject to an analogous sequence of budget constraints and the same set of contingent claims.

Capital utilization and the law of motion for capital. Domestic capital services, K_t, are linearly related to domestic physical capital, $\widetilde{K}_t$, as follows:

$$K_t = U_t \widetilde{K}_t, \quad (3)$$

where U_t is the domestic capital utilization rate.[3] As in Smets and Wouters (2003) and Christiano et al. (2005), the increasing and convex function $A(U_t)$ represents the cost (per unit of physical capital) of setting the utilization rate to U_t in terms of foregone consumption.[4] When the utilization rate is one, as in steady state, we assume that the cost of capital utilization is zero ($A(1) = 0$). We define the elasticity of the capital utilization cost in steady state as $\lambda \equiv A''(1)/A'(1)$.

Although we keep the convention of denoting $A(U_t)$ as a cost and U_t as a utilization rate, the concept is more closely aligned with that of an *operating ratio*. In that sense, U_t measures whether physical capital is utilized more or less intensely than in the steady state. The function $A(U_t)$ only subtracts net resources from the household's budget ($A(U_t) > 0$) whenever physical capital is overutilized ($U_t > 1$). In turn, if the household keeps the physical capital underutilized ($U_t < 1$), it transfers net resources ($A(U_t) < 0$) that can be used for consumption, investment, paying taxes, or acquiring new bonds.

The law of motion for domestic physical capital is given by

$$\widetilde{K}_{t+1} \leq (1-\delta)\,\widetilde{K}_t + e^{v_t}\Phi\left(\frac{X_t}{K_t}, \frac{X_t}{X_{t-1}}\right), \quad (4)$$

where $0 < \delta < 1$ is the depreciation rate. Investment is fully reversible. The law of motion for foreign physical capital is analogous to (4). The domestic IST shock, v_t, is modeled as in Greenwood et al. (1988), and it follows an $AR(1)$ process of the form

$$v_t = \rho_v v_{t-1} + \varepsilon_t^v, \quad (5)$$

where the first-order autocorrelation is denoted by $-1 < \rho_v < 1$. The innovation ε_t^v has zero mean and is normally distributed. The foreign IST shock, v_t^*, follows a symmetric $AR(1)$ process, and we allow domestic and foreign innovations, ε_t^v and ε_t^{v*}, to be contemporaneously correlated (i.e., $\text{corr}(\varepsilon_t^v, \varepsilon_t^{v*}) \neq 0$).

As in Uzawa (1969), our model introduces adjustment costs through the law of motion for capital in (4).[5] The adjustment cost function takes the generic form

$$\Phi\left(\frac{X_t}{K_t}, \frac{X_t}{X_{t-1}}\right) = 1 - \frac{1}{2}\left[\chi\left(\frac{\left(\frac{X_t}{K_t} - \delta\right)^2}{\frac{X_t}{K_t}}\right) + \kappa\left(\frac{\left(\frac{X_t}{X_{t-1}} - 1\right)^2}{\frac{X_t}{X_{t-1}}}\right)\right], \quad (6)$$

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where X_t/K_t is the investment-to-capital ratio, and X_t/X_{t-1} is the gross investment growth rate. In the steady state, investment continuously replaces the depreciated physical capital and these adjustment costs must dissipate ($\Phi(\delta, 1) = 1$).[6] The parameters $\chi \geq 0$ and $\kappa \geq 0$ regulate the degree of concavity of the adjustment cost function around the steady state. Foreign households face an analogous adjustment cost function.

The exogenous IST shocks in (5) and endogenous adjustment costs in (6) capture changes in the efficiency with which today's investment gets transformed into tomorrow's stock of physical capital. Alternatively, one could interpret the adjustment cost function as a reduced-form dual representation of—and the IST shock as similar to a productivity shock to—the production function for capital goods in a two-sector version of our model.

We explore three polar cases of the cost specification in (6). The capital adjustment cost (CAC) case used by, among others, Baxter and Crucini (1995) and Chari et al. (2002) (which requires $\chi > 0$ and $\kappa = 0$) assumes that adjustment costs are determined by the size of investment relative to the level of capital services. The investment adjustment cost (IAC) case favored by Christiano et al. (2005) (which requires $\chi = 0$ and $\kappa > 0$) presumes that these costs depend on changes in investment instead. Moreover, we also consider the no adjustment cost (NAC) case (where $\chi = \kappa = 0$).

The CAC function is motivated by the idea that installation costs on new investment depend on the scale of production, as given by the level of capital services utilized. This specification has a longstanding tradition within the neoclassical theory of investment [see Hayashi (1982) for further details]. Christiano et al. (2005) motivate the IAC function on the grounds that it fits better with the empirical macro evidence, because the U.S. data suggest that aggregate investment exhibits a persistent, hump-shaped response to monetary shocks that cannot be matched with the CAC function [an argument echoed by Smets and Wouters (2003)]. Lucca (2007) provides some microeconomic foundations by showing that a model with time-to-build—in which firms invest in many complementary projects of uncertain duration—is equivalent, up to a first-order approximation, to a model with IAC costs. Edge (2007) points out that IAC costs can approximate investment gestation lags and further discusses the role of time-to-build and time-to-plan assumptions in investment.

Aggregation rules and price indexes. The home and foreign consumption bundles of the domestic household, C_t^H and C_t^F, and the investment bundles, X_t^H and X_t^F, are aggregated with a CES index as,

$$C_t^H = \left[\int_0^1 C_t(h)^{\frac{\theta-1}{\theta}} dh\right]^{\frac{\theta}{\theta-1}}, \quad C_t^F = \left[\int_0^1 C_t(f)^{\frac{\theta-1}{\theta}} df\right]^{\frac{\theta}{\theta-1}}, \tag{7}$$

$$X_t^H = \left[\int_0^1 X_t(h)^{\frac{\theta-1}{\theta}} dh\right]^{\frac{\theta}{\theta-1}}, \quad X_t^F = \left[\int_0^1 X_t(f)^{\frac{\theta-1}{\theta}} df\right]^{\frac{\theta}{\theta-1}}, \tag{8}$$

where $C_t(h)$ and $X_t(h)$ are the domestic consumption and investment of variety h (produced at home) and $C_t(f)$ and $X_t(f)$ are the domestic consumption and investment of variety f (produced abroad). Domestic aggregate consumption and investment, C_t and X_t, are aggregated with another CES index as

$$C_t = \left[\phi_H^{\frac{1}{\eta}} \left(C_t^H\right)^{\frac{\eta-1}{\eta}} + \phi_F^{\frac{1}{\eta}} \left(C_t^F\right)^{\frac{\eta-1}{\eta}}\right]^{\frac{\eta}{\eta-1}}, \quad (9)$$

$$X_t = \left[\phi_H^{\frac{1}{\eta}} \left(X_t^H\right)^{\frac{\eta-1}{\eta}} + \phi_F^{\frac{1}{\eta}} \left(X_t^F\right)^{\frac{\eta-1}{\eta}}\right]^{\frac{\eta}{\eta-1}}. \quad (10)$$

The elasticity of substitution across varieties produced within a country is $\theta > 1$, and the elasticity of intratemporal substitution between the home and foreign bundles of varieties is $\eta > 0$. The share of the home goods in the domestic aggregator is ϕ_H, whereas the share of foreign goods is $\phi_F = 1 - \phi_H$. We define the aggregators for foreign consumption and investment similarly but denote the shares of domestic and foreign goods in them as ϕ_H^* and ϕ_F^*, respectively. We further assume—as in Warnock (2003)—that the share of imported goods is the same at home and abroad; i.e., $\phi_H^* = \phi_F$ and, $\phi_F^* = \phi_H = 1 - \phi_F$.

The domestic CPI, P_t, corresponding to our specification of the consumption aggregator in (9) is

$$P_t = \left[\phi_H \left(P_t^H\right)^{1-\eta} + \phi_F \left(P_t^F\right)^{1-\eta}\right]^{\frac{1}{1-\eta}}. \quad (11)$$

The price subindices, P_t^H and P_t^F, implied by the bundles of home and foreign goods in (7) are

$$P_t^H = \left[\int_0^1 P_t(h)^{1-\theta} dh\right]^{\frac{1}{1-\theta}}, \quad P_t^F = \left[\int_0^1 P_t(f)^{1-\theta} df\right]^{\frac{1}{1-\theta}}, \quad (12)$$

where $P_t(h)$ and $P_t(f)$ denote the domestic prices of the home variety h and the foreign variety f, respectively. We define the foreign price indices similarly and characterize the CPI-based RER, RS_t, as

$$RS_t \equiv \frac{S_t P_t^*}{P_t}, \quad (13)$$

where S_t denotes the nominal exchange rate.

If the law of one price holds at the variety level, then it follows from the definition of the domestic price subindices in (12) and the symmetry of their foreign counterparts that $P_t^H = S_t P_t^{H*}$ and $P_t^F = S_t P_t^{F*}$. In that case, the

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CPI-based RER in (13) can be expressed as[7]

$$RS_t = \left[\left(\frac{\phi_H^*}{1-\phi_F} \right) \left(\frac{1 + \left(\frac{1-\phi_H^*}{\phi_H^*} \right) \left(\frac{P_t^F}{P_t^H} \right)^{1-\eta}}{1 + \left(\frac{\phi_F}{1-\phi_F} \right) \left(\frac{P_t^F}{P_t^H} \right)^{1-\eta}} \right) \right]^{\frac{1}{1-\eta}}$$

$$= \left[\left(\frac{\phi_F}{1-\phi_F} \right) \left(\frac{1 + \left(\frac{1-\phi_F}{\phi_F} \right) \left(\frac{P_t^F}{P_t^H} \right)^{1-\eta}}{1 + \left(\frac{\phi_F}{1-\phi_F} \right) \left(\frac{P_t^F}{P_t^H} \right)^{1-\eta}} \right) \right]^{\frac{1}{1-\eta}}, \quad \textbf{(14)}$$

where the second equality follows from the assumption of identical import shares à la Warnock (2003), i.e., $\phi_H^* = \phi_F$. Hence, $RS_t = 1$ only if the domestic CPI in (11) and its foreign counterpart are identical, i.e., $\phi_H^* = \phi_H$. RER fluctuations in our model occur not only because pricing decisions in segmented markets under sticky prices and local-currency pricing introduce systematic deviations from the law of one price (which we describe in the next section), but also because of the differences in the consumption baskets across countries highlighted here. Other papers that model these two channels include Chari et al. (2002), which is closer to our model, and more recently Steinsson (2008), among others.

The optimality conditions. Given the structure in (7) and (8), the domestic demands for each local and foreign variety—$C_t(h)$ and $C_t(f)$ for consumption and $X_t(h)$ and $X_t(f)$ for investment—are given by

$$C_t(h) = \left(\frac{P_t(h)}{P_t^H} \right)^{-\theta} C_t^H, \quad X_t(h) = \left(\frac{P_t(h)}{P_t^H} \right)^{-\theta} X_t^H, \forall h \in [0,1], \quad \textbf{(15)}$$

$$C_t(f) = \left(\frac{P_t(f)}{P_t^F} \right)^{-\theta} C_t^F, \quad X_t(f) = \left(\frac{P_t(f)}{P_t^F} \right)^{-\theta} X_t^F, \forall f \in [0,1]. \quad \textbf{(16)}$$

In turn, the domestic demands for the bundles of local and foreign goods are equal to

$$C_t^H = \phi_H \left(\frac{P_t^H}{P_t} \right)^{-\eta} C_t, \quad X_t^H = \phi_H \left(\frac{P_t^H}{P_t} \right)^{-\eta} X_t, \quad \textbf{(17)}$$

$$C_t^F = \phi_F \left(\frac{P_t^F}{P_t} \right)^{-\eta} C_t, \quad X_t^F = \phi_F \left(\frac{P_t^F}{P_t} \right)^{-\eta} X_t. \quad \textbf{(18)}$$

Equations (17) and (18), combined with the analogous foreign counterparts, characterize the demand functions of our model. Therefore, we can express the domestic aggregate output, Y_t, from the demand side as

$$Y_t = \left[\int_0^1 \left(\frac{P_t(h)}{P_t^H} \right)^{-\theta} dh \right] \phi_H \left(\frac{P_t^H}{P_t} \right)^{-\eta} (C_t + X_t)$$
$$+ \left[\int_0^1 \left(\frac{P_t^*(h)}{P_t^{H*}} \right)^{-\theta} dh \right] \phi_F \left(\frac{P_t^{H*}}{P_t^*} \right)^{-\eta} (C_t^* + X_t^*) + A(U_t) \widetilde{K}_t. \quad \textbf{(19)}$$

An analogous expression can be derived for the foreign aggregate output, Y_t^*.

Under complete international asset markets, the intertemporal first-order conditions in both countries pin down the price of the contingent claims in every state, $P^b(s^t \mid s^{t-1})$, and give us the following *perfect international risk-sharing* condition for the real exchange rate:

$$RS_t = \nu \left(\frac{C_t}{C_t^*} \right)^{\sigma^{-1}}, \quad \textbf{(20)}$$

where $\nu \equiv (S_0 P_0^* / P_0)(C_0^* / C_0)^{\sigma^{-1}}$ is a constant (derived by backward induction) that depends on the initial conditions. Domestic consumption becomes high relative to foreign consumption whenever it is also relatively cheap, that is, whenever there is real depreciation (an increase in RS_t).

Moreover, we can also use the intertemporal first-order conditions to price a one-period nominal domestic (uncontingent) bond as

$$\frac{1}{I_t} = \mathbf{E}_t \left[\beta \left(\frac{C_{t+1}}{C_t} \right)^{-\sigma^{-1}} \frac{P_t}{P_{t+1}} \right], \quad \textbf{(21)}$$

where I_t would be the corresponding nominal (gross) interest rate. Equation (21) is a standard domestic consumption Euler equation. The domestic household's equilibrium conditions also include a labor supply equation (the intratemporal first-order condition) expressed as

$$\frac{W_t}{P_t} = (C_t)^{\sigma^{-1}} (L_t)^{\varphi}, \quad \textbf{(22)}$$

plus the appropriate transversality condition. Similarly, we can price a one-period nominal foreign (uncontingent) bond with interest rate I_t^* (the foreign consumption Euler equation) and define the foreign labor supply equation from the intratemporal first-order condition of the foreign household's problem.

The remaining equilibrium conditions from the household's optimization problem account for the domestic capital–investment decisions. Without adjustment costs and IST shocks, consumption goods and (fully reversible) investment goods would be perfect substitutes on the supply side and their relative price equal to one. In our model, in turn, the real shadow value of an additional unit of investment in terms of consumption (or marginal Q), Q_t, is tied to the IST shock in (5) and the adjustment cost function $\Phi(X_t/K_t, X_t/X_{t-1})$ in (6) as

$$Q_t = e^{-v_t}\left[\frac{1+\beta \mathbf{E}_t\left\{\left(\frac{C_{t+1}}{C_t}\right)^{-\sigma^{-1}} Q_{t+1}e^{v_{t+1}}\Phi_2\left(\frac{X_{t+1}}{K_{t+1}}, \frac{X_{t+1}}{X_t}\right)\left(\frac{X_{t+1}}{X_t}\right)^2\right\}}{\Phi\left(\frac{X_t}{K_t}, \frac{X_t}{X_{t-1}}\right)+\Phi_1\left(\frac{X_t}{K_t}, \frac{X_t}{X_{t-1}}\right)\left(\frac{X_t}{K_t}\right)+\Phi_2\left(\frac{X_t}{K_t}, \frac{X_t}{X_{t-1}}\right)\left(\frac{X_t}{X_{t-1}}\right)}\right]. \tag{23}$$

Equation (23) shows that marginal Q is time-varying except in the NAC case without IST shocks. The CAC function—i.e., the cost of changing the capital stock, adjusting for the rate of utilization—links the marginal Q to the investment-to-capital services ratio, whereas the IAC function—i.e., the cost of changing the flow of investment—involves the growth rate of investment instead. In all, IST shocks directly influence the marginal Q.

The returns to physical capital in units of domestic consumption, $R_t^{\widetilde{k}}$, can be defined as[8]

$$R_t^{\widetilde{k}} \equiv \frac{\frac{Z_t}{P_t}U_t - A\left(U_t\right) + Q_t\left[(1-\delta) - e^{v_t}\Phi_1\left(\frac{X_t}{K_t}, \frac{X_t}{X_{t-1}}\right)\left(\frac{X_t}{K_t}\right)^2 U_t\right]}{Q_{t-1}}. \tag{24}$$

Thus, the capital–investment decision of the domestic household in its extensive margin (the domestic investment Euler equation) must satisfy that

$$1 = \mathbf{E}_t\left[\beta\left(\frac{C_{t+1}}{C_t}\right)^{-\sigma^{-1}} R_{t+1}^{\widetilde{k}}\right]. \tag{25}$$

In the NAC case with a fixed capital utilization rate, the investment Euler equation in (25) links the real interest rate, $R_t^{-1} \equiv \mathbf{E}_t[\beta(C_{t+1}/C_t)^{-\sigma^{-1}}]$, with the domestic real rental rate of capital, Z_{t+1}/P_{t+1}. A shock that raises the marginal product of capital and the real rental rate tends to also increase the real interest rate. Adding adjustment costs, variable utilization, and/or IST shocks introduces a wedge between the real interest rate and the real rental rate influenced by the marginal Q in equation (23) and the capacity utilization rate.

The returns from adjusting the capital utilization rate in units of domestic consumption, R_t^u, can be defined as

$$R_t^u \equiv \left[\frac{Z_t}{P_t} - A'\left(U_t\right) - Q_t e^{v_t}\Phi_1\left(\frac{X_t}{K_t}, \frac{X_t}{X_{t-1}}\right)\left(\frac{X_t}{K_t}\right)^2\right]\widetilde{K}_t, \tag{26}$$

and the capital–investment decision in its intensive margin (setting the utilization rate) can be expressed as

$$0 = \mathbf{E}_t\left[\beta\left(\frac{C_{t+1}}{C_t}\right)^{-\sigma^{-1}} R_{t+1}^u\right]. \tag{27}$$

Variable capital utilization introduces an additional margin of flexibility subject to the condition that the expected (discounted) marginal benefit of raising utilization must equal its expected (discounted) marginal cost [equation (27)]. Equations (23)–(27) have similar counterparts in the foreign household's problem.

2.2. The Firms' Problem

There is a continuum of firms in each country located in the interval [0, 1]. Each firm supplies the home and foreign markets and sets prices in the local currency. Firms specialize in a given variety, engage in third-degree price discrimination across markets (reselling is infeasible), and enjoy monopolistic power. Nominal rigidities in the goods market are modeled with price stickiness à la Calvo (1983). With probability $0 < \alpha < 1$ in each period, the firm is forced to maintain its previous period prices. With probability $(1 - \alpha)$, the firm optimally resets all its prices.

We assume that domestic production is based on a Cobb–Douglas technology; i.e.,

$$Y_t(h) = e^{a_t} (K_t(h))^{1-\psi} (L_t(h))^{\psi}, \tag{28}$$

which is identical for all domestic firms $h \in [0, 1]$. The labor share in the production function is given by the parameter $0 < \psi \leq 1$. The domestic aggregate productivity shock, a_t, follows an $AR(1)$ process of the form

$$a_t = \rho_a a_{t-1} + \varepsilon_t^a, \tag{29}$$

where the first-order autocorrelation is denoted as $-1 < \rho_a < 1$. The innovation ε_t^a has zero mean and is normally distributed. We assume a technology analogous to (28) for all foreign firms $f \in [0, 1]$, and a foreign-specific aggregate productivity shock, a_t^*, that follows a symmetric $AR(1)$ process. We allow the domestic and foreign innovations, ε_t^a and ε_t^{a*}, to be contemporaneously correlated (i.e., $\text{corr}(\varepsilon_t^a, \varepsilon_t^{a*}) \neq 0$).

Labor and capital services are homogeneous factors of production within each country but are immobile across borders. All trade between countries occurs at the variety level. By factor market clearing, it follows that the aggregate domestic capital services rented out by the domestic household, K_t, and the aggregate labor supplied, L_t, correspond to the aggregate demand across all domestic firms; i.e.,

$$K_t = \int_0^1 K_t(h)\, dh, \; L_t = \int_0^1 L_t(h)\, dh. \tag{30}$$

Analogous factor market clearing conditions hold for the foreign country.

Because factor markets are perfectly competitive, wages and the rental rate on capital services equalize within each country. Solving the cost-minimization problem of each individual domestic firm yields an efficiency condition linking the capital-to-labor ratio for all $h \in [0, 1]$ to the factor price ratio as

$$\frac{K_t}{L_t} = \frac{K_t(h)}{L_t(h)} = \frac{1-\psi}{\psi}\frac{W_t}{Z_t}, \tag{31}$$

as well as a characterization of the domestic nominal marginal costs as

$$\mathrm{MC}_t(h) = \frac{1}{e^{a_t}} \frac{1}{\psi^{\psi}(1-\psi)^{1-\psi}} (W_t)^{\psi} (Z_t)^{1-\psi}. \tag{32}$$

All local firms choose the same capital-to-labor ratio under the constant returns to scale production function in (28). The marginal cost function is identical across domestic firms due to factor price equalization. An analogous efficiency condition and nominal marginal cost function can be derived for the foreign firms.

A reoptimizing domestic firm $h \in [0, 1]$ chooses domestic and foreign prices, $\widetilde{P}_t(h)$ and $\widetilde{P}_t^*(h)$, expressed in the local currency of each market, to maximize the expected discounted value of its net profits; i.e.,

$$\sum\nolimits_{\tau=0}^{+\infty} \mathbf{E}_t\{\alpha^{\tau} M_{t,t+\tau}[\widetilde{Y}_{t,t+\tau}(h)(\widetilde{P}_t(h) - MC_{t+\tau}) + \widetilde{Y}_{t,t+\tau}^*(h)(S_{t+\tau}\widetilde{P}_t^*(h) - MC_{t+\tau})]\}, \tag{33}$$

where $M_{t,t+\tau} \equiv \beta^{\tau}(C_{t+\tau}/C_t)^{-\sigma^{-1}} P_t/P_{t+\tau}$ is the domestic stochastic discount factor for nominal payoffs τ-periods ahead, subject to a pair of demand constraints,

$$\widetilde{Y}_{t,t+\tau}(h) = \widetilde{C}_{t,t+\tau}(h) + \widetilde{X}_{t,t+\tau}(h) = \left(\frac{\widetilde{P}_t(h)}{P_{t+\tau}^H}\right)^{-\theta} \left(C_{t+\tau}^H + X_{t+\tau}^H\right), \tag{34}$$

$$\widetilde{Y}_{t,t+\tau}^*(h) = \widetilde{C}_{t,t+\tau}^*(h) + \widetilde{X}_{t,t+\tau}^*(h) = \left(\frac{\widetilde{P}_t^*(h)}{P_{t+\tau}^{H*}}\right)^{-\theta} \left(C_{t+\tau}^{H*} + X_{t+\tau}^{H*}\right), \tag{35}$$

where $\widetilde{Y}_{t,t+\tau}(h)$ and $\widetilde{Y}_{t,t+\tau}^*(h)$ indicate the demands for consumption and investment of any variety h, at home and abroad respectively, given that prices $\widetilde{P}_t(h)$ and $\widetilde{P}_t^*(h)$ remain unchanged between times t and $t+\tau$. Equations (34) and (35) follow from (15) and (16) and their foreign counterparts. Firms must meet any domestic and foreign demand at the prevailing prices because rationing is not an option. The aggregate profits of all domestic firms (whether they reoptimize or not) in each period can be characterized as

$$D_t \equiv \int_0^1 [P_t(h)(C_t(h) + X_t(h)) + S_t P_t^*(h)(C_t^*(h) + X_t^*(h)) - MC_t]dh. \tag{36}$$

The problem of the reoptimizing foreign firm f is to maximize the expected discounted value of its net profits subject to a similar pair of demand constraints.

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The optimal pricing rules. The first-order conditions for the domestic reoptimizing firm h give us the following pair of price-setting formulas for the domestic and foreign markets:

$$\widetilde{P}_t(h) = \frac{\theta}{\theta-1}\frac{\sum_{\tau=0}^{+\infty}\alpha^{\tau}\mathbf{E}_t[M_{t,t+\tau}\widetilde{Y}_{t,t+\tau}(h)\,MC_{t+\tau}]}{\sum_{\tau=0}^{+\infty}\alpha^{\tau}\mathbf{E}_t[M_{t,t+\tau}\widetilde{Y}_{t,t+\tau}(h)]}, \tag{37}$$

$$\widetilde{P}_t^*(h) = \frac{\theta}{\theta-1}\frac{\sum_{\tau=0}^{+\infty}\alpha^{\tau}\mathbf{E}_t[M_{t,t+\tau}\widetilde{Y}^*_{t,t+\tau}(h)\,MC_{t+\tau}]}{\sum_{\tau=0}^{+\infty}\alpha^{\tau}\mathbf{E}_t[M_{t,t+\tau}\widetilde{Y}^*_{t,t+\tau}(h)\,S_{t+\tau}]}. \tag{38}$$

The pricing rules imply that in the limit when α converges toward zero the price is set as a constant markup $\theta/(\theta-1)$ over current marginal cost. Otherwise, the pricing rules are forward-looking and take into account current as well as expectations of future discounted marginal costs. Using the Calvo randomization assumption and the inherent symmetry of all the domestic firms, the price subindices on domestic varieties defined in (12) and its foreign counterpart, P_t^H and P_t^{H*}, become

$$P_t^H = \left[\alpha\left(P_{t-1}^H\right)^{1-\theta} + (1-\alpha)\left(\widetilde{P}_t(h)\right)^{1-\theta}\right]^{\frac{1}{1-\theta}}, \tag{39}$$

$$P_t^{H*} = \left[\alpha\left(P_{t-1}^{H*}\right)^{1-\theta} + (1-\alpha)\left(\widetilde{P}_t^*(h)\right)^{1-\theta}\right]^{\frac{1}{1-\theta}}. \tag{40}$$

Similarly, we derive the optimal pricing rules for the foreign reoptimizing firm f and the corresponding aggregation formulas for the price subindices on the bundle of foreign varieties, P_t^F and P_t^{F*}.

2.3. Monetary Policy Rule

Because the Taylor (1993) rule has become the trademark of modern monetary policy, we assume that the domestic monetary authority sets short-term nominal interest rates accordingly; i.e.,

$$i_t = \rho_i i_{t-1} + (1-\rho_i)\left[\overline{i} + \psi_\pi(\pi_t - \overline{\pi}) + \psi_y(y_t - \overline{y})\right] + \varepsilon_t^m. \tag{41}$$

We define all variables in (41) in logs. Hence, $i_t \equiv \ln(I_t)$ is the domestic monetary policy instrument, $\pi_t \equiv \ln(P_t) - \ln(P_{t-1})$ is the (gross) domestic CPI inflation rate in logs, and $y_t \equiv \ln(Y_t)$ denotes the domestic aggregate output in logs. The variables with an upper bar on top and no time subscript are the corresponding steady state values. An analogous Taylor rule is followed by the foreign monetary authority.

The sensitivity of the policy instrument to deviations of output and inflation from their long-run steady state is given by the parameters $\psi_y \geq 0$ and $\psi_\pi \geq 0$, respectively. In keeping with much of the literature, we augment the Taylor rule with an interest rate–smoothing term regulated by the inertia parameter $0 < \rho_i < 1$

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TABLE 1. Parameters used in the benchmark model

Structural parameters		
Intertemporal discount factor	β	0.99
Elasticity of intratemporal substitution	η	1.5
Elasticity of substitution across varieties	θ	10
Elasticity of intertemporal substitution	σ	$1/5$
(Inverse) Frisch elasticity of labor supply	φ	3
Share of foreign goods	ϕ_F	0.06
Calvo price stickiness	α	0.75
Depreciation rate	δ	0.021
Capital/investment adjustment cost	χ, κ	varies
Elasticity of capital utilization cost	λ	5.80
Labor share	ψ	$2/3$
Taylor rule parameters		
Interest rate inertia	ρ_i	0.85
Sensitivity to inflation target	ψ_π	2
Sensitivity to output target	ψ_y	0.5
Exogenous shock parameters		
Productivity shock persistence	ρ_a	0.9
Productivity shock cross-correlation	$\text{corr}(\widehat{\varepsilon}_t^a, \widehat{\varepsilon}_t^{a*})$	[0.43, 0.57]
Productivity shock volatility	$\sigma(\widehat{\varepsilon}_t^a) = \sigma(\widehat{\varepsilon}_t^{a*})$	[1.27, 3.41]
IST shock persistence	ρ_v	0.9
IST shock cross-correlation	$\text{corr}(\widehat{\varepsilon}_t^v, \widehat{\varepsilon}_t^{v*})$	[0.42, 0.61]
IST shock volatility	$\sigma(\widehat{\varepsilon}_t^v) = \sigma(\widehat{\varepsilon}_t^{v*})$	[2.47, 10]
Monetary shock cross-correlation	$\text{corr}(\widehat{\varepsilon}_t^m, \widehat{\varepsilon}_t^{m*})$	[0.32, 0.64]
Monetary shock volatility	$\sigma(\widehat{\varepsilon}_t^m) = \sigma(\widehat{\varepsilon}_t^{m*})$	[0.29, 2.63]
Composite parameters		
Steady state investment share	$\gamma_x \equiv \frac{(1-\psi)\delta}{\left(\frac{\theta}{\theta-1}\right)\left(\beta^{-1}-(1-\delta)\right)}$	0.203

Note: This table summarizes our parameterization. The choice of the capital adjustment cost or the investment adjustment cost parameters is explicitly stated in Tables 2 and 3. The exact parameterization of the shock processes in each experiment can be obtained from the authors upon request; the setting of the international borrowing costs parameters is discussed in Section 5.3.

and a discretionary monetary policy shock ε_t^m that is normally distributed with zero mean. We assume that the foreign monetary shock, ε_t^{m*}, also has zero mean and is normally distributed. We permit the domestic and foreign monetary shocks, ε_t^m and ε_t^{m*}, to be contemporaneously correlated (i.e., $\text{corr}(\varepsilon_t^m, \varepsilon_t^{m*}) \neq 0$).

3. MODEL PARAMETERIZATION

Table 1 summarizes the model parameters adopted in our simulations. Because our parameterization is roughly similar to that in Chari et al. (2002), we keep our description brief.

The intertemporal discount factor, β, equals 0.99 and the intertemporal elasticity of substitution, σ, is $1/5$. The share of foreign goods, ϕ_F, is set to 0.06. The elasticity of substitution across varieties, θ, is chosen to equal 10. The choice of θ is consistent with a price mark-up of 11% for the United States, as documented by Basu (1996). Moreover, θ serves to pin down the steady state investment share (over GDP), γ_x, at 0.203.[9] We set the labor share, ψ, equal to 2/3 and the depreciation rate, δ, equal to 0.021.

We choose the intratemporal elasticity of substitution, η, to be equal to 1.5, which is similar to Backus et al. (1995) and Chari et al. (2002), but significantly lower than in Steinsson (2008). The inverse of the Frisch elasticity of labor supply, φ, is set at 3 [see the micro evidence in Blundell and MaCurdy (1999) and Browning et al. (1999) and the macro estimates in Justiniano and Primiceri (2008) and Justiniano et al. (2010)]. When appropriate, we set the elasticity of the capital utilization cost, λ, at 5.80 to be consistent with the range of estimates reported by Justiniano and Primiceri (2008) and Justiniano et al. (2010).

The Calvo price stickiness parameter, α, is assumed to be 0.75. This implies that the average price duration in our model is 4 quarters—the same average duration as in Chari et al. (2002) and Steinsson (2008). The interest rate inertia parameter, ρ_i, equals 0.85, whereas the sensitivity of the nominal policy rate to the inflation target, ψ_π, equals 2, and the sensitivity to the output target, ψ_y, is 0.5, as in Steinsson (2008).

We assume that the persistence of the productivity shock, ρ_a, is fixed at 0.9 as in Steinsson (2008). Likewise, we set the persistence of the IST shock, ρ_v, at 0.9. We adopt a simulation strategy similar to Chari et al. (2002) and set the other parameters of the stochastic processes to match certain features of the U.S. real GDP data. The aim is to investigate the properties of consumption, investment, and the RER under different assumptions on capital accumulation while replicating key empirical moments of U.S. real GDP.

We set the standard deviation of all shocks to match U.S. real GDP volatility (1.54%). In addition, we parameterize the cross-country correlation of the innovations to replicate the observed cross-correlation of U.S. and Euro area real GDP (0.44). In experiments where productivity shocks drive the business cycle in combination with either monetary or IST shocks, we set the standard deviation of the productivity shock innovation always to 0.7% and the cross-country correlation to 0.25 [e.g., Chari et al. (2002) and Heathcote and Perri (2002)]. In turn, we parameterize the volatility and the cross-correlation of the innovations of the other shock—the monetary or IST shock—to match the volatility and cross-country correlation of U.S. real GDP. When appropriate, we select the adjustment cost parameter, either χ (CAC) or κ (IAC), to ensure that the volatility of investment relative to output roughly matches the data (3.38 times the volatility of U.S. real GDP).

In the simulations with IST shocks, an exact match of the investment and output volatilities cannot be attained without pushing the adjustment cost and the shock volatility parameters beyond a reasonable range of values. In that case, we match the volatility of U.S. real GDP with the volatility of the IST shock bounded to be below 10%, and we pick the adjustment cost to keep the volatility of investment low.[10]

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4. QUANTITATIVE FINDINGS

Our benchmark model, described in Section 2, incorporates the basic features of the NOEM literature—price stickiness and local-currency pricing. It also nests a wide range of alternative capital specifications from linear-in-labor technologies and no capital to different model variants with capital accumulation, adjustment costs, and variable utilization rates. We posit the existence of a deterministic, zero-inflation steady state (with zero net exports). We log-linearize the equilibrium conditions around the steady state, and use this first-order approximation as the basis for all our simulations.[11]

As noted by Chari et al. (2002), a NOEM model that conventionally assumes international complete asset markets and additively separable preferences of the isoelastic type (as our benchmark does) also implies a very tight link between relative consumption and the RER. Using the log-linearization of the *perfect international risk-sharing* condition in (20), it can be shown that the persistence and volatility of the RER must be tied to business cycle moments on consumption. The first-order autocorrelation of the RER depends on the first-order autocorrelation of domestic consumption, given by

$$\operatorname{corr}\left(\widehat{rs},\widehat{rs}_{-1}\right)=\operatorname{corr}\left(\widehat{c},\widehat{c}_{-1}\right)\left\{\frac{1-\left(\dfrac{\operatorname{cov}\left(\widehat{c},\widehat{c}^{*}_{-1}\right)}{\operatorname{cov}\left(\widehat{c},\widehat{c}_{-1}\right)}\right)}{1-\operatorname{corr}\left(\widehat{c},\widehat{c}^{*}\right)}\right\}$$

$$\cong\operatorname{corr}\left(\widehat{c},\widehat{c}_{-1}\right)\ \text{if}\ \operatorname{corr}(\widehat{c},\widehat{c}^{*})\operatorname{cov}\left(\widehat{c},\widehat{c}_{-1}\right)\cong\operatorname{cov}(\widehat{c},\widehat{c}^{*}_{-1}). \quad \textbf{(42)}$$

In fact, the approximation noted in (42) holds pretty well in most of our simulations. In addition, RER volatility is linked to consumption volatility and the cross-country consumption correlation as follows:

$$\operatorname{var}\left(\widehat{rs}\right)=\frac{2}{\sigma^{2}}\left[1-\operatorname{corr}\left(\widehat{c},\widehat{c}^{*}\right)\right]\operatorname{var}\left(\widehat{c}\right), \quad \textbf{(43)}$$

where σ is the elasticity of intertemporal substitution.[12]

Equations (42) and (43) suggest that if the theoretical model is unable to match the properties of either consumption or the RER—both of which are determined endogenously—it likely fails to match them both. These equations also help motivate our exploration of the consumption–investment trade-off in accounting for RER movements. A model with capital accumulation, in any of its variants, modifies the incentives that households face in deciding how much to consume today and how much to save for tomorrow. Different assumptions about capital (or the exclusion of capital altogether) influence at the margin the consumption response to a given shock and that, naturally, gets reflected into potentially different RER dynamics.

To our knowledge, this is the first quantitative exploration of the CPI-based RER—through the lens of the NOEM model—that specifically highlights the contribution of popular assumptions about capital accumulation to account for the empirical evidence on the persistence, volatility, and cross-correlation of consumption, on one hand, and the persistence and volatility of the RER, on the other hand. In our investigation, we also look closely at the nature of shocks, and at different frictions in the goods and asset markets.

4.1. Productivity Shocks[13]

Rogoff (1996, p. 648) summarized the conventional view in these terms: "(i)t is not difficult to rationalize slow adjustment if real shocks—shocks to taste and technology—are predominant. But existing models based on real shocks cannot account for short-term exchange rate volatility." Steinsson (2008) has proved otherwise by showing that a barebones NOEM model with no capital and solely driven by "real" shocks can indeed account for both the volatility and the persistence of the CPI-based RER. We revisit this point of the debate in Panel 1 of Table 2, where we report our simulation results with productivity shocks. The case with no capital (NoC), which is closer to Steinsson (2008), is compared against a variant of our benchmark model with capital but no adjustment costs (NAC), a variant with investment adjustment costs (IAC), and another alternative with capital adjustment costs (CAC). We report all those simulations in Columns (3)–(6). We conduct extensive sensitivity analysis in Columns (7)–(14).[14]

RER persistence. We observe that persistent exogenous productivity shocks tend to imply persistent endogenous RERs. In the model with capital but no adjustment costs (NAC), RER persistence stands at 0.76, compared to 0.78 in the data. In all other variants of the model with or without capital (NoC, IAC, and CAC), RER persistence is higher than what is empirically observed (ranging from 0.84 to 0.85). Figure 1 illustrates that the model with adjustment costs implies a strong propagation mechanism and hump-shaped dynamics for consumption, investment, and the RER in response to a productivity shock.

Adjustment costs make investment costlier to carry out. Under those conditions, investment peaks with a lag of 3 to 6 periods after the productivity shock occurs–as can be seen from the impulse response functions (IRFs) in Figure 1—and its persistence increases from 0.40 in the NAC case to 0.88–0.94 in the IAC and CAC variants of the model (compared to 0.91 in the data). However, whether we include capital or not has quantitatively negligible effects on the endogenous persistence of consumption and the RER.

As can be seen in Panel 1 of Table 2, our findings on persistence are robust to the parameterization of the adjustment costs [the high adjustment cost scenario in Columns (7)–(8)], the inclusion of variable capital utilization [Columns (9)–(10)], incomplete international asset markets [Columns (11)–(12)], or producer-currency pricing [Columns (13)–(14)]. Factors other than capital accumulation

TABLE 2. RER, investment, and consumption

		Capital specs.				High adj. costs		Var. capital utiliz.		Incomp. markets		PCP	
	U.S. data	NoC $\to +\infty$	IAC $\kappa = 3.35$	CAC $\chi = 11.15$	NAC $\to 0$	IAC $\kappa = 29$	CAC $\chi = 113$	IAC + CU $\kappa = 3.85$	CAC + CU $\chi = 10.55$	IAC $\kappa = 3.2$	CAC $\chi = 10.9$	IAC $\kappa = 2.82$	CAC $\chi = 9.35$
						Productivity shocks							
Std. dev. to GDP													
Consumption	0.81	0.91	0.39	0.34	0.14	0.81	0.81	0.41	0.33	0.39	0.34	0.35	0.31
Investment	3.38	—	3.38	3.38	4.60	1.89	1.32	3.38	3.38	3.38	3.38	3.38	3.38
RER	5.14	3.17	1.63	1.47	0.57	2.88	2.94	1.72	1.42	1.67	1.46	1.16	1.05
Autocorrelation													
Consumption	0.87	0.84	0.82	0.83	0.75	0.83	0.83	0.82	0.84	0.82	0.83	0.81	0.83
Investment	0.91	—	0.94	0.88	0.40	0.95	0.87	0.94	0.88	0.94	0.88	0.94	0.87
RER	0.78	0.85	0.84	0.85	0.76	0.85	0.84	0.84	0.85	0.84	0.85	0.85	0.87
Cross-correlation													
Consumption	0.33	0.76	0.65	0.63	0.69	0.75	0.73	0.65	0.62	0.64	0.61	0.79	0.77
Investment	0.33	—	0.57	0.55	0.37	0.73	0.73	0.57	0.53	0.58	0.55	0.64	0.63

TABLE 2. Continued

		Capital specs.				High adj. costs		Var. capital utiliz.		Incomp. markets		PCP	
	U.S. data	NoC $\rightarrow +\infty$	IAC $\kappa = 2.34$	CAC $\chi = 34.3$	NAC $\rightarrow 0$	IAC $\kappa = 3.72$	CAC $\chi = 92.7$	IAC + CU $\kappa = 1.1$	CAC + CU $\chi = 25.85$	IAC $\kappa = 2.3$	CAC $\chi = 34.15$	IAC $\kappa = 0.88$	CAC $\chi = 20.3$
						Monetary shocks							
Std. dev. to GDP													
Consumption	0.81	1.06	0.67	0.48	0.03	0.81	0.81	0.39	0.37	0.66	0.48	0.35	0.28
Investment	3.38	—	3.38	3.38	5.07	2.92	2.14	3.38	3.38	3.38	3.38	3.38	3.38
RER	5.14	6.42	4.11	2.98	0.19	5.00	5.00	2.36	2.26	4.27	3.10	1.26	1.08
Autocorrelation													
Consumption	0.87	0.45	0.34	0.38	0.72	0.37	0.42	0.28	0.37	0.34	0.38	0.24	0.32
Investment	0.91	—	0.81	0.37	−0.06	0.83	0.41	0.76	0.36	0.81	0.37	0.73	0.32
RER	0.78	0.46	0.36	0.40	0.72	0.39	0.44	0.31	0.39	0.37	0.41	0.24	0.31
Cross-correlation													
Consumption	0.33	0.27	0.24	0.23	0.36	0.23	0.23	0.29	0.24	0.25	0.24	0.74	0.71
Investment	0.33	—	0.09	0.25	0.29	0.08	0.24	0.15	0.26	0.10	0.25	0.69	0.68

Note: This table reports the theoretical moments for each series given our parameterization. All statistics are computed after each series is H-P filtered (smoothing parameter = 1600). NAC denotes the no adjustment cost case, CAC denotes the capital adjustment cost case, IAC denotes the investment adjustment cost case, and +CU indicates that capital utilization is variable. NoC is the model stripped of capital where technologies are linear-in-labor. We use Matlab 7.4.0 and Dynare v3.065 for the stochastic simulation.
Data Sources: The OECD's Quarterly National Accounts, OECD's Economic Outlook, and OECD's Main Economic Indicators. Some series are complemented with data from the Bureau of Economic Analysis, the Bureau of Labor Statistics, the Federal Reserve System, the European Central Bank (ECB), and WM/Reuters. Sample period: 1973:I-2006:IV. GDP, consumption and investment are in per capita terms. All series are logged, multiplied by 100, and H-P filtered (smoothing parameter = 1600). The data set can be obtained from the authors upon request.

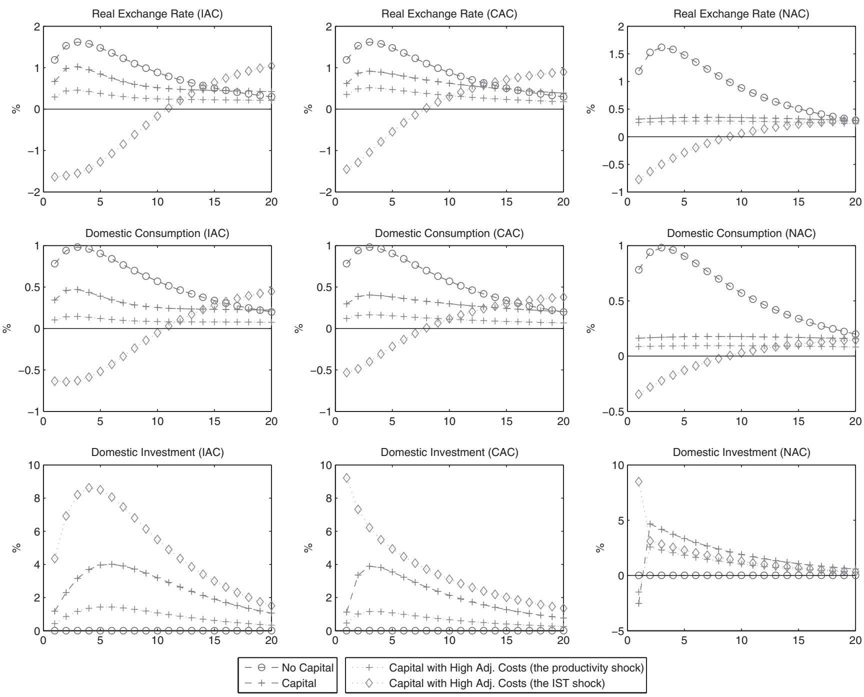

FIGURE 1. Impulse response functions (domestic productivity and IST shocks). These graphs report the selected impulse response functions (IRFs) for each series given our parameterization. The IRFs represent the response of endogenous variables to a one-time, one standard deviation of the domestic productivity shock innovation. The magenta lines describe the high adjustment costs scenario, where productivity and IST shocks are combined. In that case, we report the IRFs for a one-time, one standard deviation of the domestic IST and the domestic productivity shock innovations. "Capital" identifies all variants of the model with capital, including the no adjustment cost case (NAC), the capital adjustment cost case (CAC), and the investment adjustment cost case (IAC). "No Capital" identifies the NoC model without capital (or IST shocks), where technologies are linear-in-labor. In all experiments domestic output increases in response to the given shock. We use Matlab 7.4.0 and Dynare v3.065 for the stochastic simulation.

have a more significant role in sustaining endogenous persistence in the NOEM model. Benigno (2004), for instance, emphasizes the role of monetary policy inertia, which we revisit in Section 5.3.

RER volatility. The model without capital (NoC) implies RERs that are 3.17 times more volatile than output (compared to 5.14 times in the data). This is roughly twice the RER volatility ratio of 1.47–1.63 with capital and adjustment costs (CAC and IAC), and more than five times the volatility ratio of 0.57 with capital but no adjustment costs (NAC). Figure 1 illustrates that the size of the RER response noticeably declines as it gets easier to accumulate capital over time. Our findings show that the RER volatility (unlike its persistence) varies significantly depending on whether capital is included in the model or not.

We expect the RER to be less volatile relative to output whenever consumption is smoother, unless the cross-country consumption correlation falls enough to reverse that effect (see equation (43)). Without capital (NoC), consumption becomes roughly as volatile as output (0.91 times the volatility of output compared to 0.81 in the data) whereas the consumption cross-correlation is twice as high (0.76 vs. 0.33 in the data).[15] In turn, models with capital accumulation (NAC, CAC, and IAC) generate a consumption path much smoother than output even in the presence of adjustment costs (0.14–0.39 compared to 0.91 in the NoC case) with only a slight decline in the consumption cross-correlations (0.63–0.69 vs. 0.76 in the NoC case).

The *quantity puzzle* [see, e.g., Backus et al. (1992)] is apparent across all variants of the NOEM model driven by productivity shocks. In fact, the simulated consumption cross-correlation is systematically higher than the cross-country output correlation of 0.44 found in our data set (and matched in all our simulations), whereas the empirical consumption cross-correlation tends to be smaller (0.33 in our data set). The robustness of the *quantity puzzle* to different specifications of capital is noteworthy. However, the main take-away is that capital accumulation is as powerful a channel for intertemporal consumption smoothing in an open economy as it is in a closed economy [see Jermann (1998) on the closed-economy case]. Therefore, the resulting lower consumption volatility ends up being the dominant factor in the RER volatility decomposition (equation (43)).

In other words, incorporating capital into the NOEM model makes it harder to account for the RER volatility. The results under high adjustment costs [Columns (7)–(8)] also illustrate the deep connection between investment, RER, and consumption volatility. In those experiments we follow Chari et al. (2002) and select the adjustment cost parameter, either χ or κ, to ensure that the consumption volatility ratio roughly matches the data (0.81 times the volatility of U.S. real GDP). That setup makes investment costlier, which impedes households from utilizing as effectively the intertemporal channel provided by capital accumulation to smooth their consumption. The model with high adjustment costs replicates exactly the consumption volatility ratio in the data (0.81 vs. 0.91 in the NoC case). It also returns consumption cross-correlations that are closer to the ones in a model without capital (0.73–0.75 vs. 0.76 in the NoC case) and RER volatility ratios that are closer as well (2.88–2.94 vs. 3.17 in the NoC case). In turn, investment becomes much smoother relative to output than what we observe (1.32–1.89 vs. 3.38 in the data).

Adding variable capital utilization [Columns (9)–(10)] or modeling incomplete international asset markets [Columns (11)–(12)] has only modest effects. Producer-currency pricing (PCP) [Columns (13)–(14)] implies that the law of one price holds, so volatility is significantly smaller, as we discuss in Section 5.2.

4.2. Monetary Shocks

As discussed by Rogoff (1996, p. 647), "(m)ost explanations of short-term exchange rate volatility point to financial factors such as changes in portfolio preferences, short term asset price bubbles, and monetary shocks (...)." Following on the last point, Chari et al. (2002) motivate their paper as a quantitative assessment of the interaction between monetary shocks and sticky prices in explaining RER fluctuations—an idea they trace back to Dornbusch (1976). Monetary shocks have featured prominently in the NOEM literature and can have large effects on RER volatility, but the prevailing view—based on the work of Chari et al. (2002)—is that RER fluctuations damp out too quickly in response to a monetary shock to be able to account for the persistence of RERs observed in the data. We revisit this issue in Panel 2 of Table 2, which contains our simulation results where business cycles are driven by monetary shocks alone. We investigate the same specifications as before in Columns (3)–(6) with no capital (NoC), with capital but no adjustment costs (NAC), with investment adjustment costs (IAC), and with capital adjustment costs (CAC). We conduct extensive sensitivity analysis in Columns (7)–(14).

RER persistence. Chari et al. (2002) and Steinsson (2008), among others, illustrate the inability of the NOEM model with non-persistent monetary shocks to match the high persistence of the CPI-based RER observed in the data. Our findings confirm that the transmission mechanism tends to be weak with or without capital. We showcase the existing trade-off between investment persistence and both consumption and RER persistence. This trade-off depends critically on how capital and adjustment costs are modeled.

The NoC model without capital produces low endogenous persistence of consumption (0.45 compared to 0.87 in the data) and the RER (0.46 compared to 0.78 in the data). Adding capital with no adjustment costs (NAC) generates more persistent consumption and RER series (both at 0.72) with a low persistence of investment that closely approximates the exogenous monetary shock first-order autocorrelation of 0. Domestic households have an incentive to invest aggressively on impact after a (temporary, non-persistent) domestic monetary shock and to return to their long-run investment steady state immediately afterward (see Figure 2). The buildup of new capital helps propagate the effects of the monetary shock over time and sustains its contribution to consumption longer. This also explains why the persistence of consumption and the RER is much higher than for investment (and much higher than in the NoC case).

Introducing adjustment costs (IAC or CAC) makes the strategy of front-loading investment on impact too costly and calls for a more gradual investment response to monetary shocks (which also requires a much larger consumption reaction during the initial periods). With adjustment costs these incentives translate into more endogenous persistence in investment (0.37–0.81 vs. −0.06 in the NAC case) and less persistence in consumption (0.34–0.38 vs. 0.72 in the NAC case

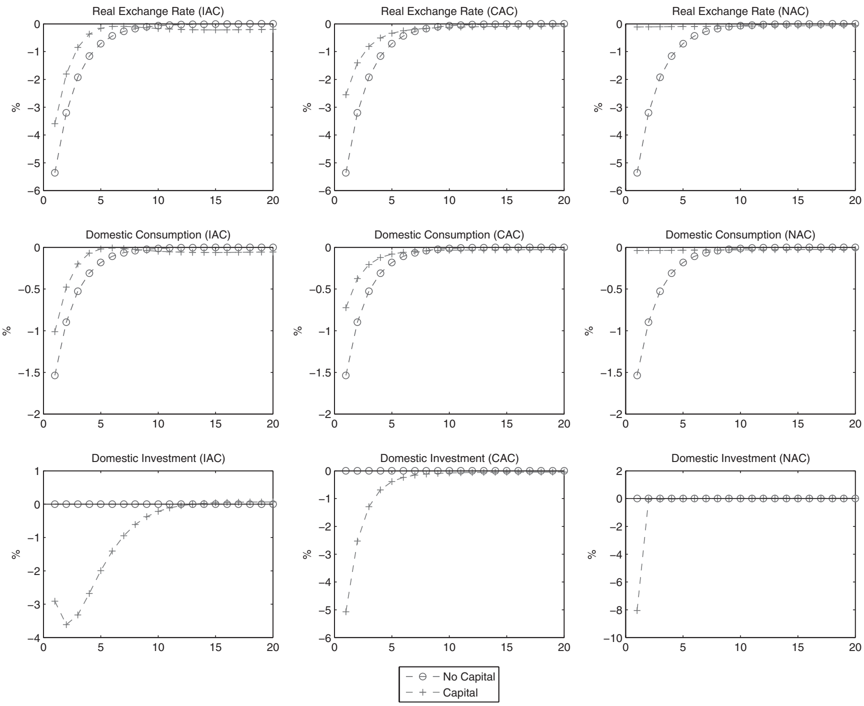

FIGURE 2. Impulse response functions (domestic monetary shock). These graphs report the selected impulse response functions (IRFs) for each series given our parameterization. The IRFs represent the response of endogenous variables to a one-time, one standard deviation of the domestic monetary shock innovation. In all experiments domestic output falls in response to the shock. "Capital" identifies all variants of the model with capital, including the no adjustment cost case (NAC), the capital adjustment cost case (CAC), and the investment adjustment cost case (IAC). "No Capital" identifies the NoC model without capital, where technologies are linear-in-labor. We use Matlab 7.4.0 and Dynare v3.065 for the stochastic simulation.

and 0.45 in the NoC case) and in the RER (0.36–0.40 vs. 0.72 in the NAC case and 0.46 in the NoC case).

The persistence of investment is considerably higher in the IAC case than in the CAC case (0.81 vs. 0.37). The IAC specification generates a hump-shaped response of investment to a non-persistent monetary shock, whereas investment responds swiftly under the CAC specification (see Figure 2). This hump-shaped response of investment is consistent with the empirical macro evidence and one of the main reasons to favor the IAC adjustment cost function highlighted by Christiano et al. (2005). But whereas investment exhibits hump-shaped dynamics, consumption and the RER do not. So the IAC model still fails to generate sufficiently persistent consumption and RERs.

These findings are robust to higher adjustment costs [Columns (7)–(8)] and the inclusion of variable capital utilization rates [Columns (9)–(10)]. The results are largely unaffected by the assumptions of incomplete international asset markets [Columns (11)–(12)] or producer-currency pricing [Columns (13)–(14)].

RER volatility. Chari et al. (2002) and Steinsson (2008) show that monetary shocks can trigger RER movements that are quite volatile within the class of NOEM models investigated in this paper. We show that intertemporal consumption smoothing through capital accumulation tends to reduce the endogenous RER volatility generated by the model also in response to monetary shocks. Hence, matching the RER volatility ratio requires either high adjustment costs in the CAC case [as in Chari et al. (2002)], IAC costs [as in Christiano et al. (2005)], or an NoC model that features no capital [as in Steinsson (2008)]. In turn, investment volatility is underpredicted except in the IAC case.

In our NoC variant without capital, consumption is highly volatile (1.06 times as volatile as output vs. 0.81 in the data) and closely replicates the empirical cross-country consumption correlation (0.27 vs. 0.33 in the data). Hence, by the mechanics at play in (43), the RER volatility relative to output reaches 6.42 versus 5.14 in the data. Capital accumulation is especially effective to smooth consumption intertemporally in response to a non-persistent monetary shock. With capital and no adjustment costs (NAC), investment absorbs the impact of the shock and helps distribute the effects on consumption very gradually and smoothly over time. The consumption volatility drops to 0.03 times that of output (compared to 0.81 times in the data), whereas the consumption cross-correlation of 0.36 is somewhat higher than in the NoC case (at 0.27) but still in line with the data (at 0.33). The lower consumption volatility ratio and the slightly higher consumption cross-correlation work together to bring the RER volatility ratio down to merely 0.19.

Adding adjustment costs makes intertemporal consumption smoothing costlier and, naturally, causes higher consumption and RER volatility. In the IAC and CAC cases, the cross-country consumption correlation drops to 0.23–0.24 from 0.36 in the NAC case and 0.27 in the NoC case. However, the consumption volatility ratio jumps significantly to 0.48 in the CAC case and 0.67 in the IAC case (compared to 0.03 in the NAC case and 0.81 in the data). Lower cross-correlation and higher consumption volatility are associated with higher RER volatility (4.10 times the volatility of output in the IAC model and 2.98 times in the CAC model vs. 5.14 in the data). Besides the hump-shaped response of investment to monetary shocks noted before, the IAC model implies roughly 40% more consumption and RER volatility than the CAC variant.

In the high adjustment cost scenarios [Columns (7)–(8)], the IAC and CAC models are able to replicate the RER volatility ratio (5.00 times compared with 5.14 in the data) at the expense of underpredicting investment volatility (2.14–2.92 times compared to 3.38 in the data).[16] However, the investment volatility ratio is 36% higher with the IAC than with the CAC specification and it is possible

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to roughly approximate the investment, consumption and RER volatility ratios simultaneously—it suffices to set κ somewhere between 2.32 and 3.68 to get a close match for all. This promising result, however, is not robust to the alternative assumption of producer-currency pricing [Columns (13)–(14)]—see Section 5.2 for a more detailed discussion—or, for that matter, to the inclusion of variable capital utilization [Columns (9)–(10)].

Capital services are inelastically supplied in the short run even with variable capital utilization, because the desired stock of physical capital and the utilization rate are set before today's shocks are realized [as in Christiano et al. (2005)]. However, variable utilization adds an extra margin through which households can more effectively manage the path of investment. That is nowhere more evident than with a combination of non-persistent monetary shocks and IAC costs–where the cost is tied to changes in the flow of investment—because investment is more constrained to act as a shock absorber on impact and, therefore, consumption adjusts by more and becomes more volatile than in the CAC case (see Figure 2). Columns (9)–(10) illustrate that the consumption volatility ratio is lower (0.39 in the IAC case and 0.37 in the CAC case) and the RER volatility ratio falls (by up to 40% in the IAC case) relative to the benchmark with fixed utilization rates. In contrast, variable utilization has a more limited effect in response to persistent productivity shocks, because the gains from managing investment to smooth consumption are also smaller (see Panel 1 of Table 2).[17]

A salient finding of our experiments is that the cross-country consumption correlation with monetary shocks is always significantly smaller than that with productivity shocks. The simulated cross-country consumption correlation is also lower than the output cross-correlation of 0.44 in all our simulations [except under producer-currency pricing in Columns (13)–(14)]. That helps address the *quantity puzzle*—so pervasive with productivity shocks—without having to abandon the assumption of complete international asset markets [Columns (11)–(12)]. These findings suggest that the low cross-country consumption correlations found in the data may not necessarily be conclusive evidence of limited or imperfect international risk-sharing, because they might be the result of frictions in the goods market leading to large deviations in the law of one price as well.

5. SENSITIVITY ANALYSIS

In our sensitivity analysis of the NOEM model with capital, we explore further the nature of shocks, the structure of asset and goods markets, and the role of monetary policy. First, we introduce IST shocks in combination with productivity shocks [see, e.g., Raffo (2010)], and argue that the model predictions in this case are difficult to reconcile with the evidence on RERs and investment (more so under international asset market incompleteness). We also show that our analysis of the contribution of monetary shocks to RER movements is fairly robust to the addition of productivity shocks [as long as monetary shocks remain the main driver of the cycle, as in Chari et al. (2002)]. Second, we consider alternative competing assumptions about the asset and goods markets. We observe that a standard bond economy with international borrowing costs closely replicates the persistence and volatility of the RER under complete markets [see also Chari et al. (2002)], except when IST shocks drive the cycle. By reestablishing the law of one price (under producer-currency pricing), we show that the contribution to RER movements of deviations from the law of one price (under local-currency pricing) is quantitatively significant and more so in response to monetary shocks. Finally, we highlight the importance of monetary policy inertia for the endogenous propagation of shocks [see, e.g., Benigno (2004)], especially in conjunction with the costs of capital accumulation.

5.1. Shock Processes

IST and productivity shocks. Raffo (2010) shows that IST shocks can help reconcile the international real business cycle model with certain hard-to-match stylized facts—the negative correlation between the RER and relative consumption (the *Backus–Smith puzzle*) and the volatility of terms of trade and trade flows—while preserving countercyclical trade balances. Raffo (2010) does not feature nominal rigidities or other imperfections in the goods markets, so RER fluctuations are due solely to differences in the consumption baskets across countries (a channel also present in our benchmark NOEM model). Raffo (2010) goes on to explain that in this context the RER is a function of terms of trade and its volatility is lower than the terms of trade volatility, unlike what we observe in the data. He suggests that incorporating a richer market structure that allows for pricing-to-market (local-currency pricing) and large deviations from the law of one price could reverse this puzzling implication.

Our benchmark model offers a framework with which to evaluate Raffo's (2010) conjecture. Panel 1 of Table 3 presents our results with both productivity and IST shocks. We observe that adding persistent IST shocks tends to imply fairly persistent endogenous consumption and RERs—but less so than with persistent productivity shocks alone. Moreover, we also observe smaller consumption cross-correlations and higher consumption and RER volatilities than with persistent productivity shocks alone—although not enough to resolve the *quantity puzzle* or to match the empirical RER volatility. The first-order autocorrelation of the RER stands at 0.70 in the NAC case with IST shocks (compared against 0.76 with productivity shocks and 0.78 in the data), whereas the RER volatility is more than 2.5 times higher at 1.49 times the volatility of output (compared against 0.57 times with productivity shocks and 5.14 in the data).

In turn, the tension between consumption and investment is greatly exacerbated, with investment persistence falling to 0.26 (compared to 0.40 with productivity shocks and 0.91 in the data) and investment volatility going up to 5.87 times the volatility of output (compared to 4.60 times with productivity shocks and 3.38 in the data). A positive IST shock makes investment temporarily more productive. Households invest more to take advantage of that, but do so partly by working

TABLE 3. RER, investment, and consumption

		Capital specs.				High adj. costs		Var. capital utiliz.		Incomp. markets		PCP	
	U.S. data	NoC $\to +\infty$	IAC $\kappa = 0.04$	CAC $\chi = 0.2$	NAC $\to 0$	IAC $\kappa = 2.35$	CAC $\chi = 18.85$	IAC + CU $\kappa = 0.04$	CAC + CU $\chi = 0.2$	IAC $\kappa = 0.04$	CAC $\chi = 0.2$	IAC $\kappa = 0.04$	CAC $\chi = 0.2$
						Productivity + IST shocks							
Std. dev. to GDP													
Consumption	0.81	—	0.47	0.32	0.31	0.76	0.56	0.45	0.32	0.47	0.32	0.46	0.31
Investment	3.38	—	6.71	5.90	5.87	7.87	7.04	6.38	5.83	6.64	5.87	7.72	6.37
RER	5.14	—	2.36	1.54	1.49	3.68	2.75	2.25	1.52	1.58	1.11	2.18	1.34
Autocorrelation													
Consumption	0.87	—	0.75	0.71	0.70	0.84	0.78	0.75	0.71	0.75	0.71	0.75	0.71
Investment	0.91	—	0.60	0.28	0.26	0.91	0.62	0.62	0.29	0.60	0.28	0.63	0.31
RER	0.78	—	0.75	0.71	0.70	0.83	0.76	0.74	0.71	0.80	0.75	0.76	0.71
Cross-correlation													
Consumption	0.33	—	0.49	0.53	0.55	0.53	0.52	0.50	0.54	0.47	0.51	0.55	0.63
Investment	0.33	—	0.28	0.33	0.34	0.22	0.28	0.29	0.33	0.31	0.34	−0.03	0.14

TABLE 3. Continued

		Capital specs.				High adj. costs		Var. capital utiliz.		Incomp. markets		PCP	
	U.S. data	NoC $\rightarrow +\infty$	IAC $\kappa = 2.32$	CAC $\chi = 31.1$	NAC $\rightarrow 0$	IAC $\kappa = 4.2$	CAC $\chi = 95.5$	IAC + CU $\kappa = 1.18$	CAC + CU $\chi = 23.75$	IAC $\kappa = 2.28$	CAC $\chi = 31.15$	IAC $\kappa = 0.99$	CAC $\chi = 19.1$
							Productivity + monetary shocks						
Std. dev. to GDP													
Consumption	0.81	1.05	0.63	0.45	0.08	0.81	0.81	0.39	0.36	0.63	0.46	0.36	0.29
Investment	3.38	—	3.38	3.38	4.91	2.83	2.05	3.38	3.38	3.38	3.38	3.38	3.38
RER	5.14	6.26	3.77	2.70	0.40	4.87	4.85	2.26	2.11	3.93	2.81	1.23	1.10
Autocorrelation													
Consumption	0.87	0.46	0.35	0.43	0.75	0.39	0.44	0.32	0.45	0.35	0.43	0.29	0.43
Investment	0.91	—	0.83	0.39	0.06	0.85	0.43	0.80	0.39	0.82	0.39	0.77	0.36
RER	0.78	0.47	0.37	0.44	0.76	0.40	0.45	0.34	0.45	0.38	0.44	0.32	0.46
Cross-correlation													
Consumption	0.33	0.30	0.29	0.29	0.52	0.27	0.28	0.33	0.31	0.29	0.29	0.77	0.71
Investment	0.33	—	0.16	0.29	0.33	0.15	0.28	0.21	0.30	0.17	0.29	0.66	0.69

Note: This table reports the theoretical moments for each series given our parameterization. All statistics are computed after each series is H-P filtered (smoothing parameter = 1600). NAC denotes the no adjustment cost case, CAC denotes the capital adjustment cost case, IAC denotes the investment adjustment cost case, and +CU indicates that capital utilization is variable. NoC is the model stripped of capital where technologies are linear-in-labor. We use Matlab 7.4.0 and Dynare v3.065 for the stochastic simulation.

Data Sources: The OECD's Quarterly National Accounts, OECD's Economic Outlook, and OECD's Main Economic Indicators. Some series are complemented with data from the Bureau of Economic Analysis, the Bureau of Labor Statistics, the Federal Reserve System, the European Central Bank (ECB), and WM/Reuters. Sample period: 1973:I-2006:IV. GDP, consumption and investment are in per capita terms. All series are logged, multiplied by 100, and H-P filtered (smoothing parameter = 1600). The data set can be obtained from the authors upon request.

and producing more and partly by sacrificing consumption in the short run (see Figure 1). As a result, consumption becomes countercyclical because of the strong intrinsic incentives to invest now and consume later.[18] Interestingly, the incentive to postpone consumption in response to a domestic IST shock is more pronounced in the home country, leading to a short-run appreciation of the RER—which reverses itself over time—in spite of the fact that domestic output is rising more than foreign output. In contrast, the RER unequivocally depreciates in response to a (positive) domestic productivity shock or an expansionary (negative) domestic monetary shock that makes domestic goods temporarily more abundant than foreign goods (see Figures 1 and 2).[19]

Adding even small adjustment costs is generally counterproductive because it requires an even larger IST shock volatility to replicate the standard deviation of U.S. real GDP, which in turn rarely lowers the endogenous volatility of investment. However, adjustment costs give households an incentive to invest more gradually and consumption and RER persistence tend to go up. The IAC model with high adjustment costs [Column (7)] seems to outperform all other variants with IST shocks because it roughly reproduces the volatility of consumption (0.76 times the volatility of output vs. 0.81 in the data) and its persistence (0.84 vs. 0.87 in the data), but still overpredicts its cross-country correlation (0.53 vs. 0.33 in the data). Moreover, the RER is 3.68 times more volatile than output (compared to 2.88 times with productivity shocks alone and 5.14 times in the data) and the RER persistence is 0.83 (compared against 0.85 with productivity shocks and 0.78 in the data). Although the persistence of investment matches the data at 0.91 and also displays a hump-shaped response (which we could not obtain with the CAC specification), the internal tension that IST shocks bring into the model shows up in investment volatility being more than twice as large as in the data (7.87 times the volatility of output compared to 3.38 in the data) and in consumption being countercyclical.[20]

Otherwise, our results appear robust to the addition of variable capital utilization [Columns (9)–(10)],[21] but they are more sensitive—especially the volatilities—to the alternative assumptions of incomplete international asset markets [Columns (11)–(12)] and producer-currency pricing [Columns (13)–(14)] that we cover in Section 5.2. Our findings suggest that adding IST shocks as the primary driver of the business cycle makes it harder to balance the competing goals of accounting for RER (and consumption) fluctuations and fitting the volatilities of output and investment. With conventional (additively separable and isoelastic) preferences and IST shocks, introducing large deviations from the law of one price—through price stickiness and local-currency pricing—does not suffice to reconcile the NOEM model with capital with the empirical evidence on RERs.

Monetary and productivity shocks. Panel 2 of Table 3 reports our results with a combination of persistent productivity shocks and non-persistent monetary shocks of the sort investigated in Chari et al. (2002), whereas Panel 2 of Table 2 collects our findings with monetary shocks alone. Although adding productivity shocks can help the NOEM model generate a bit more persistence in consumption, investment, and the RER, the quantitative effect is only marginal. The *persistence anomaly* noted by Chari et al. (2002) cannot be resolved as long as monetary shocks are the dominant source of business cycle fluctuations, unless other features of the model or the policy rule are modeled differently (see Section 5.3).

The volatility of consumption tends to be similar or a bit lower—except in the NAC case—and the cross-country correlation of consumption somewhat higher whenever monetary and productivity shocks are combined. By the mechanics of equation (43), the slightly higher cross-correlations and generally lower consumption volatilities are associated with small declines in the RER volatility ratio—except for the NAC case. Still, the RER volatility merely increases from 0.19 times the volatility of output in the NAC case with monetary shocks alone to 0.40 times with a combination of monetary and productivity shocks. We also note that in our experiments the *quantity puzzle* tends to disappear only when monetary shocks are the sole or the primary driver of the business cycle.

Summing up, we observe only a marginal loss of generality in our findings when we derive them with monetary shocks alone [e.g., Benigno (2004) or Steinsson (2008)] instead of with a combination of monetary and productivity shocks [e.g., Chari et al. (2002)], as long as monetary shocks are the predominant source of business cycle fluctuations.

5.2. Market Structure

Incomplete international asset markets.[22] The functioning of international asset markets determines the extent to which households can efficiently insure amongst themselves to smooth their consumption in the presence of country-specific shocks. Asset markets are viewed as crucial for the propagation and transmission of business cycle fluctuations across countries, but most of the NOEM literature has often abstracted from asset market frictions of any sort to focus instead on understanding the role of frictions in the goods markets.

We adopt a rather standard extension of our benchmark that restricts the financial assets available to just two uncontingent nominal bonds in zero-net supply (each issued in a different currency), adding a quadratic cost on international borrowing tied to the real net foreign asset position of the home country [see Benigno and Thoenissen (2008), Benigno (2009), and Martínez-García (2011)].[23] We use this bond economy to evaluate the robustness of our findings as we move away from the complete international asset markets assumption. The main implication is that the imperfect international risk-sharing condition that replaces our equation (20) introduces—up to a first-order approximation—deviations in the *uncovered interest rate parity* condition linked to bond trading costs and the evolution of the domestic real net foreign asset position [for more details see, e.g., Martínez-García (2011)].

Our results in Panel 1 of Table 2 [Columns (11)–(12)] illustrate that the complete and incomplete asset markets models are practically indistinguishable whenever

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persistent productivity shocks drive the business cycle. The international real business cycle literature without nominal rigidities also shows that a bond economy closely approximates the complete asset markets allocation—unless, for instance, productivity shocks are permanent without spillovers or we impose stricter financial autarky [see, e.g., Baxter and Crucini (1995) and Heathcote and Perri (2002)]. Chari et al. (2002) document a similar result in a model with nominal frictions and non-persistent monetary shocks, and so do we in Panel 2 of Tables 2 and 3 [Columns (11)–(12)].

In turn, Panel 1 of Table 3 shows that with IST shocks the RER becomes somewhat more persistent (0.80 under incomplete international asset markets vs. 0.75 under complete markets in the IAC case, and 0.75 vs. 0.71 in the CAC case) and significantly less volatile (1.58 under incomplete international asset markets vs. 2.36 under complete markets in the IAC case, and 1.11 vs. 1.54 in the CAC case). Equation (43) holds under complete asset markets, so the wedge between actual RER volatility and the hypothetical volatility implied by the comovement and volatility of consumption gives us a measure of the effect of international asset market incompleteness. Comparing Columns (4)–(5) and (11)–(12), RER volatility turns out to be roughly 30% lower with IST shocks due to incomplete international asset markets.

Chari et al. (2002) find that a bond economy has the potential to weaken the link between the RER and relative consumption, but show that in fact this avenue is not very successful in eliminating the consumption–RER anomaly (the Backus–Smith puzzle).[24] Not surprisingly, we also find that the correlation between relative consumption and the RER is close to one in models with persistent productivity shocks, with non-persistent monetary shocks, or with a combination of both. Only with IST shocks we are able to lower this correlation, but it still hovers around 0.92 with conventional preferences, whereas Chari et al. (2002, Table 6) put the empirical counterpart at -0.35. For further discussion on the role of preferences, see Raffo (2010).

Producer-currency pricing. Price stickiness alone does not imply that the law of one price fails in the NOEM model. For that, market segmentation and the assumption of local-currency pricing are crucial. In fact, in our experiments with producer-currency pricing, the prices of each variety must equalize across countries when expressed in the same currency and the RER fluctuates simply because we also assume different consumption baskets for the two countries. Engel (1999) provides empirical evidence supporting the view that deviations from the law of one price on traded goods account for most of the movements in the U.S. RER. Although Engel (1999) also considers the possibility that traded goods are weighted differently in the consumption basket of each country, he concludes that RER fluctuations tied to terms-of-trade movements through this channel are not very important in the data. Our results—reported in Columns (13)–(14) of Tables 2 and 3—suggest that consumption basket differences alone are not able to explain overall RER movements.

Betts and Devereux (2000) argue that local-currency pricing and staggered prices can magnify the response of the RER and distort the international transmission mechanism of monetary policy shocks resulting in lower consumption comovement across countries. We observe that pattern more clearly in Panel 2 of Tables 2 and 3 [Columns (13)–(14)], where monetary shocks are the dominant source of business cycles. Endogenous persistence tends to be mildly higher in our benchmark than in the experiments with producer-currency pricing, but the RER volatility ratio swells dramatically, aided by a large decline in the cross-country consumption correlation and by a small increase in consumption volatility. In the IAC case with monetary shocks only, for example, the RER volatility ratio jumps from 1.26 under producer-currency pricing to 4.11 in our benchmark and the consumption cross-correlation falls from 0.74 to 0.24.

By contrast, however, the consumption distortions and RER magnification are much smaller with either productivity shocks (Panel 1 of Table 2) or a combination of productivity and IST shocks (Panel 1 of Table 3). Endogenous RER persistence is still largely unaffected by the assumption of local-currency pricing or producer-currency pricing. In the IAC case with productivity shocks, the RER volatility ratio goes from 1.16 under producer-currency pricing to 1.63 in our benchmark (a roughly 40% jump) whereas the consumption cross-correlation falls from 0.79 to 0.65. With the addition of IST shocks, the RER volatility moves from 2.18 under producer-currency pricing to 2.36 in our IAC benchmark, which is a higher volatility ratio than with productivity shocks alone but still much less than with monetary shocks and local-currency pricing. Meanwhile, the consumption cross-correlation merely falls from 0.55 to 0.49. Similar patterns are documented for the CAC case as well.[25]

What these findings illustrate is that large and distortionary deviations from the law of one price depend on the nature of the shocks. Not surprisingly, most of the NOEM models that investigate the RER dynamics through this channel have focused their attention primarily on the connection between nominal rigidities, local-currency pricing and monetary shocks [see Betts and Devereux (2000) and Chari et al. (2002)].

5.3. Monetary Policy Inertia

Productivity shocks cause inflation and output to move in opposite directions on impact—as expected of a supply shock. Whereas on impact real interest rates rise on the back of an expected large fall in the inflation rate and a moderate nominal interest rate decline, a sustained monetary policy response—given by the Taylor rule in (41)—triggers a temporary real interest rate decline that gives a second-round boost to consumption. Monetary shocks, do not produce a similar policy trade-off because output and inflation move in the same direction—as expected of a demand shock. So there is no second-round boost to consumption, and propagation is faster. Although not reported here, our sensitivity analysis suggests that such policy trade-offs play a role in the transmission mechanism of the NOEM model [see Steinsson (2008)].

However, what this narrative does not articulate fully (but takes as given) is the interest rate inertia, ρ_i, which regulates the speed of the policy response and its influence on the transmission of shocks.[26] Benigno (2004) shows the importance of this smoothing parameter for the RER persistence in a model with monetary shocks and no capital. We take a broader perspective and reexamine our benchmark IAC and CAC models with capital over an ample range of policy inertia and adjustment cost parameter values. For simplicity, we keep invariant the parameterization of the shock processes and all other structural parameters as in Table 1. We also complement Benigno (2004) by including productivity as well as monetary shocks in our exploration.

We show that Benigno's (2004) insight that policy inertia matters for the endogenous persistence of monetary shocks still holds when we add capital and adjustment costs. The bottom two plots in Figure 3 suggest that RER persistence is systematically lower than in the data (i.e., 0.78) and that the IAC and CAC specifications propagate quite differently if the business cycle is primarily driven by non-persistent monetary shocks. RER persistence tends to increase with higher adjustment costs in the IAC case, whereas it is rather more stable in the CAC case (except at low values of χ). Interestingly, reducing the policy inertia, ρ_i, tends to lower the RER persistence in the IAC case, but it does just the opposite in the CAC case.

The top two plots in Figure 3 illustrate that the RER first-order autocorrelation in response to a persistent productivity shock is also quite sensitive to the policy inertia parameter, ρ_i, but less so to the adjustment cost parameter, χ or κ (except at low values). In fact, when nominal interest rates are able to respond more rapidly and aggressively (because ρ_i is smaller) to contemporaneous competing policy objectives in output and inflation, then the second-round boost to consumption is more muted, propagation is faster and we see the RER persistence fall. In turn, whenever policy inertia approximates 1, the RER persistence closely recovers the exogenous first-order autocorrelation of productivity (at 0.9).

Finally, our findings in Figure 4 qualify and extend the conventional view that NOEM models driven mainly by monetary shocks can replicate the RER volatility but not its persistence [see Chari et al. (2002)]. In fact, a lower interest rate inertia, ρ_i, contributes to produce somewhat smoother consumption and RER series, whereas higher adjustment costs, χ or κ, lead to a significantly higher RER volatility ratio. This implies that the monetary policy rule and certain capital accumulation features have a decisive effect on the RER volatility attainable from monetary shocks. In turn, lower policy inertia, ρ_i, and higher adjustment costs, χ or κ, are often associated with a higher RER volatility ratio in response to productivity shocks. In any case, adjustment costs make it costlier to use capital accumulation for intertemporal consumption smoothing, and that is of first-order importance to account for the RER volatility with productivity and monetary shocks.

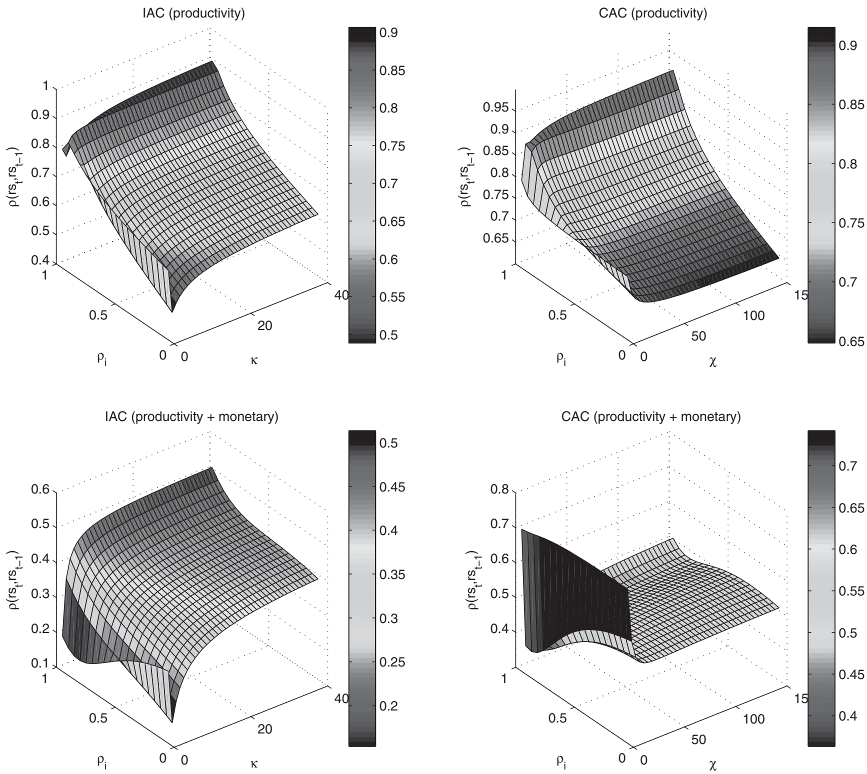

FIGURE 3. RER persistence. These graphs report the persistence of the RER whenever we allow the monetary policy inertia and the adjustment cost parameter to vary within a range that includes our benchmark parameterization. All other structural parameters remain invariant. The statistics are computed after each series is H-P filtered (smoothing parameter = 1600). CAC denotes the capital adjustment cost case, and IAC denotes the investment adjustment cost case. Within parentheses, "productivity" refers to the experiment where business cycles are entirely driven by productivity shocks, whereas "productivity + monetary" indicates the experiment where monetary and productivity shocks jointly determine the cycle. We use Matlab 7.4.0 and Dynare v3.065 for the stochastic simulation.

With low policy inertia and high adjustment costs is possible to push the RER volatility from productivity shocks above the 3.17 ratio in the NoC model (Panel 1 in Table 2), but at the expense of lowering the RER persistence below the 0.78 found in the data. Manipulating the adjustment cost parameter has other perils too, because it could lead to counterfactual investment dynamics. Hence, Figures 3 and 4 illustrate the complexity with which monetary policy—in particular the speed of the monetary policy response—and capital accumulation interact to influence the volatility and persistence of the RER.

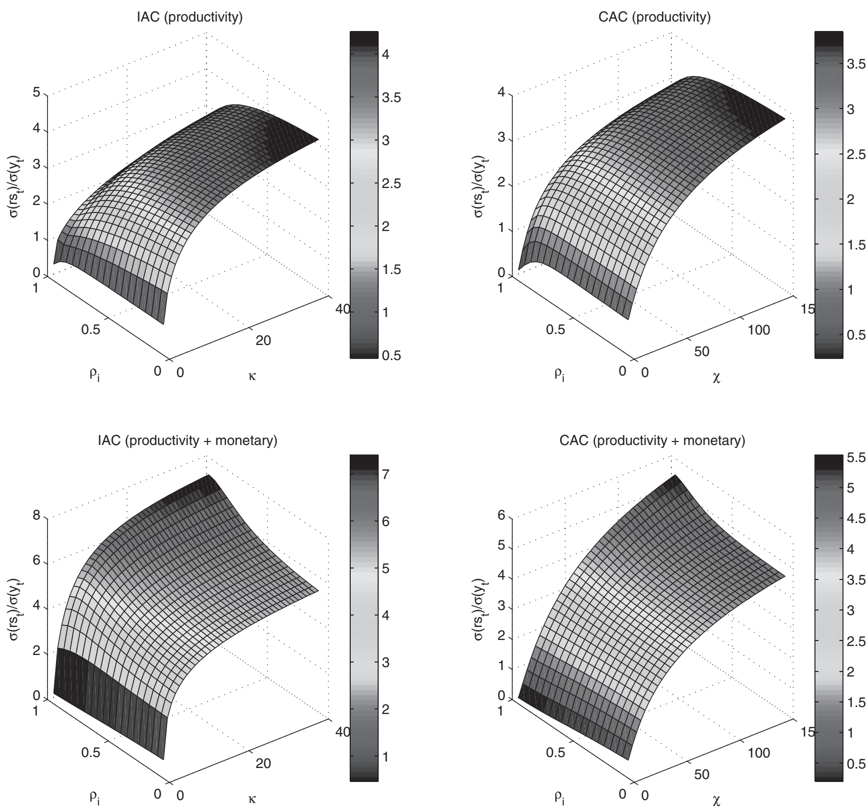

FIGURE 4. RER volatility. These graphs report the volatility of the RER whenever we allow the monetary policy inertia and the adjustment cost parameter to vary within a range that includes our benchmark parameterization. All other structural parameters remain invariant. The statistics are computed after each series is H-P filtered (smoothing parameter = 1600). CAC denotes the capital adjustment cost case, and IAC denotes the investment adjustment cost case. Within parentheses, “productivity” refers to the experiment where business cycles are entirely driven by productivity shocks, whereas “productivity + monetary” indicates the experiment where monetary and productivity shocks jointly determine the cycle. We use Matlab 7.4.0 and Dynare v3.065 for the stochastic simulation.

6. CONCLUDING REMARKS

Earlier work has extensively investigated how NOEM models with price stickiness generate volatility and persistence of the CPI-based RERs, but often those models have omitted capital entirely or made it too costly to utilize. This paper has shown that adding capital and adjustment costs (and even variable utilization rates) to the workhorse NOEM model increases the difficulty of producing volatile RERs, because capital accumulation gives households an additional margin of intertemporal adjustment, thereby leading to smoother consumption profiles and

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less volatile RERs. Our main message is, therefore, reminiscent of Jermann (1998), who has shown—albeit in a closed-economy setting—that frictions on capital impede consumption smoothing, causing greater fluctuations in the intertemporal marginal rate of substitution and generally in asset prices.

We have found that irrespective of whether the model has capital or not, productivity shocks trigger highly persistent RERs whereas monetary shocks generally do not. This finding is consistent with conventional wisdom [see, e.g., Rogoff (1996) and Chari et al. (2002)]. We also note that high persistence is more likely to occur in response to persistent productivity shocks if monetary policy—in the spirit of Taylor (1993)—is augmented with a very inertial component. With non-persistent monetary shocks, the contribution of policy inertia is more ambiguous and depends on the specification of the adjustment cost function. Policy inertia is also connected to consumption and RER volatility.

We illustrate also how a NOEM model with IST shocks as the primary driver of the business cycle—as suggested by Raffo (2010)—can approximate the observed RER dynamics better than with productivity shocks alone. But we also point out the excessive investment volatility and the countercyclical consumption associated with IST shocks as potential drawbacks of this shock-based explanation of the RER.

Our benchmark model is derived under the standard NOEM assumptions of sticky prices and local-currency pricing—which allow *deviations from the law of one price*—and of *complete international asset markets*—which imposes a tight link between the RER and relative consumption. We relax these two assumptions to broaden the quantitative exploration of the NOEM model with capital. We show that deviations from the law of one price are larger and more distortive of the RER whenever the business cycle is mainly driven by monetary shocks. We also find that a bond economy with small costs on international borrowing [see, e.g., Benigno (2009)] is almost indistinguishable from our complete asset markets benchmark whenever the cycle is driven by either non-persistent monetary shocks or persistent productivity shocks. In turn, international asset market incompleteness results into significantly lower RER volatility in response to persistent IST shocks.

NOTES

1. As has become costumary in the NOEM literature, we focus our attention on the CPI-based RER rather than on terms of trade or some alternative RER measure like the PPI-based RER [see, e.g., Rogoff (1996)].

2. Another connected strand of research has quantitatively explored or estimated small open economy (SOE) models instead [see, e.g., Kollmann (2001), Galí and Monacelli (2005), and Adolfson et al. (2007)].

3. Households in each country own the stock of physical capital and set the utilization rate one period in advance [as in Christiano et al. (2005)]. Although we can work out a model where firms accumulate capital and make all the relevant investment decisions, Christiano et al. (2005) note that modeling those as household decisions simplifies the notation and the derivations.

4. Alternatively, variable utilization costs could be captured by movements in the depreciation rate [see Greenwood et al. (1988) and King and Rebelo (1999)]. With the inclusion of $A(U_t)$ in

the budget constraint, the utilization costs are expressed in units of output rather than in terms of capital.

5. Alternatively, the adjustment costs could have been modeled as installation costs out of the household's budget without entering explicitly into the law of motion for capital in (4) [see, e.g., Lucas (1967)]. With the inclusion of the adjustment costs in (4), they are expressed in units of capital rather than in terms of output.

6. The first-order derivatives of the cost function in (6) evaluated in steady state satisfy that $\Phi_1(\delta, 1) = \Phi_2(\delta, 1) = 0$, whereas the second-order derivatives satisfy that $\Phi_{11}(\delta, 1) = -\chi/\delta$, $\Phi_{22}(\delta, 1) = -\kappa$, and $\Phi_{12}(\delta, 1) = \Phi_{21}(\delta, 1) = 0$.

7. Domestic terms of trade can be defined as the price of imports relative to the price of exports expressed in units of the domestic currency; i.e., $ToT_t \equiv P_t^F / S_t P_t^{H*}$. If the law of one price holds, then ToT_t becomes equal to the price ratio P_t^F / P_t^H and, therefore, the expression in (14) implies that the CPI-based RER is a function of the terms of trade.

8. The returns to physical capital differ from the real rental rate net of depreciation, $Z_t/P_t + (1 - \delta)$, due to the time-variation on the marginal Q and also to variable utilization, and its associated costs.

9. Up to a first-order approximation, the monopolistic markup distortion influences the short-run dynamics only because it affects the steady state investment share, $\gamma_x \equiv (1-\psi)\delta / (\theta/\theta - 1)(\beta^{-1} - (1-\delta))$. Introducing a labor subsidy to fully eliminate this markup brings the steady state share up by 11%, but otherwise has a negligible quantitative impact on our findings.

10. Available macro estimates of the IST volatility are often smaller than 10%. For instance, Justiniano and Primiceri (2008, Tables 1 and 4) estimate a 90%-Bayesian confidence interval of [4.43, 6.76]. They also point in split samples to a decline in IST volatility after 1984. For further discussion on the price of investment relative to consumption in the U.S. data, see Fisher (2006).

11. For details on the log-linearization, see the companion technical paper in Martínez-García and Søndergaard (2008). As a notational convention, any variable identified with lowercase letters and a caret on top represents a transformation (expressed in log deviations relative to its steady state) of the corresponding variable in uppercase letters.

12. The cross-country correlation of HP-filtered consumption in our data set is 0.33 and the volatility of the HP-filtered RER relative to consumption is $5.14/0.81 = 6.35$. Based on those empirical values, the elasticity of intertemporal substitution, σ, that makes (43) hold true is $1/5.48$, which is close to the value of $1/5$ that we adopt in our benchmark parameterization.

13. In our data set, the standard deviation of the HP-filtered U.S. dollar/euro CPI-based RER is 7.91% and its first-order autocorrelation is 0.78, compared to 7.94% and 0.83 respectively in Chari et al. (2002, Table 5). In turn, GDP is slightly less volatile than in Chari et al. (2002, Table 5), 1.54% vs. 1.82%. The implication is that the volatility of the RER relative to GDP is 5.14 in our data set and 4.36 in Chari et al. (2002). The discrepancy arises mainly because our sample (1973 : I − 2006 : IV) covers more of the Great Moderation period than theirs does.

14. Columns (7)–(8) show the results when the adjustment costs are set to match the volatility of consumption rather than investment. Columns (9)–(10) present the simulations with variable capital utilization. Columns (11)–(12) show our results after replacing the assumption of complete international asset markets with a bond economy and costly international borrowing, and Columns (13)–(14) are derived under the assumption of producer-currency pricing instead of local-currency pricing.

15. A consumption volatility ratio different from one in the NoC model reflects the contribution of trade movements to consumption smoothing. Trade fluctuations in response to a persistent productivity shock make consumption less volatile than output (0.91 times), whereas the opposite happens with non-persistent monetary shocks (1.06 times).

16. Similarly, Chari et al. (2002, Tables 5 and 6) also underpredict investment volatility. With high CAC costs to match the consumption volatility ratio and a Taylor rule specification, they report a RER volatility relative to output of 4.98 in response to a combination of productivity and monetary shocks (compared to 4.36 in their data) and an investment volatility relative to output of 1.62 (compared to 2.78 in their data).

17. We also find that utilization is highly procyclical in response to monetary shocks (the correlation between current output and the utilization rate ranges from 0.51 to 0.76 depending on the adjustment cost specification), whereas it is acyclical or mildly procyclical in response to productivity shocks (ranging from −0.03 to 0.25).

18. The consumption comovement with output is −0.55 (and −0.71 with investment) in the NAC case corresponding to Column (6) of Panel 1 in Table 3. Similar negative comovements are found with adjustment costs. See Raffo (2010) for a discussion on the role of the preference specification and the wealth effects on labor supply on this and other counterfactual predictions (including the Backus–Smith puzzle).

19. In our data set, the U.S. dollar/euro RER is acyclical with a correlation of 0.04 with U.S. real GDP and −0.02 with U.S. real consumption. In turn, productivity and monetary shocks induce markedly procyclical RERs that are only partly reversed by IST shocks. For example, in the IAC benchmark [corresponding to Column (4) in Table 2], the correlations are 0.48 and 0.42 respectively for productivity shocks and 0.48 and 0.62 for monetary shocks. However, in the IAC case including IST shocks and high adjustment costs [corresponding to Column (7) of Panel 1 in Table 3], the correlations are −0.30 and 0.48 respectively.

20. The NoC model with productivity shocks alone [Column (3) in Panel 1 of Table 2] and the IAC model with high adjustment costs and IST shocks [Column (7) in Panel 1 of Table 3] pin down the persistence of the RER and give us a high RER volatility without introducing monetary shocks. But neither version simultaneously matches the persistence and volatility of investment.

21. With IST shocks, utilization rates are procyclical, with correlations between utilization and output ranging from 0.47 to 0.54 depending on the adjustment cost function.

22. International asset market incompleteness per se does not lead to RER fluctuations. For example, our benchmark under producer-currency pricing and identical consumption baskets across countries would imply a RER equal to one in every period irrespective of what we assume about the international asset markets. In turn, as Cole and Obstfeld (1991) suggest in an endowment economy, limited asset availability does not necessarily preclude full insurance and perfect risk-sharing either.

23. The international borrowing costs ensure stationarity and are modeled as

$$\frac{\mu}{2}\frac{P_t}{I_t^*}(\mathrm{NFA}_{t+1}-\overline{a})^2,$$

where NFA_{t+1} denotes the domestic real net foreign asset position. For simplicity, we assume that foreign households only participate in the foreign bond market. We maintain the same parameterization described in Table 1, but we set the cost of adjusting the foreign bond holdings at $\mu = 0.01$ as in Benigno (2009) and choose $\overline{a}$ to match the 1970–2007 average of the U.S. annual ratio of net foreign assets over GDP of −4.06% from the Lane and Milesi-Ferretti (2007) data set.

24. Benigno and Thoenissen (2008) and Corsetti et al. (2008) are more successful in tackling the *Backus–Smith puzzle* with incomplete asset markets when RER fluctuations are due to nontraded goods or tied to the value of the trade elasticity and the persistence of the productivity shocks.

25. The most notable differences with the addition of IST shocks appear on the dynamics of investment. Under local-currency pricing and IAC costs the investment volatility is significantly lower than with producer-currency pricing and IAC costs (6.71 in the benchmark vs. 7.72 under producer-currency pricing), whereas the investment cross-correlation is higher (0.28 vs. −0.03). Much the same can be said of the CAC case.

26. The trade-off for monetary policy might be different also if the Taylor rule in (41) were to respond to the output gap rather than to deviations of output from its steady state. We leave that for future research.

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