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The Exchange Rate in a Dynamic-Optimizing Current Account Model with Nominal Rigidities: A Quantitative Investigation

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Abstract

This paper studies dynamic-optimizing model of a semi-small open economy with sticky nominal prices and wages. The model exhibits exchange rate overshooting in response to money supply shocks. The predicted variability of nominal and real exchange rates is roughly consistent with that of G-7 effective exchange rates during the post-Bretton Woods era. The model predicts that a positive domestic money supply shock lowers the domestic nominal interest rate, that it raises output and that it leads to a nominal and real depreciation of the country's currency. Increases in domestic labor productivity and in the world interest rate too are predicted to induce a nominal and real exchange rate depreciation.

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Summary

During the last 15 years, much effort was devoted to developing open-economy business cycle models with explicit microfoundations. With rare exceptions (discussed below), that literature considered models without money or in which money is neutral (or almost neutral), with prices and wages assumed fully flexible. A striking limitation of these models is that the predicted variability of nominal and real exchange rates is much too small compared with actual data for periods with flexible exchange rates.

Recent research, however, has developed dynamic-optimizing open-economy models that do not assume fully flexible prices. This paper builds on work by Obstfeld and Rogoff (1995) and by Beaudry and Devereux (1995), who study models in which firms set their prices one period in advance. Those models, too, seem unable to generate sufficient exchange rate volatility.

In the model in this paper, nominal prices and wages are set two or four periods in advance (one period represents one quarter in calendar time). In addition, a mechanism inspired by Calvo (1983) is considered that assumes that nominal prices and wages are changed after random time intervals. A semi-small open economy model with four types of exogenous shocks is assumed: shocks to the domestic money supply, to domestic labor productivity, to the world price level, and to the world interest rate.

The predicted variability of nominal and real exchange rates is roughly consistent with that of G-7 effective exchange rates during the post-Bretton Woods era. The model exhibits exchange rate overshooting in response to money supply shocks. A positive shock to the domestic money supply is predicted to lower the domestic nominal interest rate, to raise domestic output, and to trigger a nominal and real depreciation of the country's currency. In the model, money supply changes are the dominant source of exchange rate fluctuations.

I. Introduction

During the last decade, much effort has been devoted to the development of dynamic open economy business cycle models with explicit microfoundations. This work is often referred to as the dynamic-optimizing approach to the current account or as the international Real Business Cycle approach (see, e.g., Razin (1995) and Backus, Kehoe and Kydland (1995) for detailed surveys of that work). That research studies models with forward-looking rational agents who trade in international goods and asset markets. With rare exceptions (see discussion below) that literature has either considered models without money or models in which money is neutral (or almost neutral) as prices and wages are assumed fully flexible.[2] In these models, non-monetary shocks (shocks to technologies, preferences, fiscal policy or the terms of trade) are the main source of economic fluctuations.

One of the most striking limitations of models of this type is that they tend to generate a predicted variability of nominal and real exchange rates that is much too small, when compared to actual data for periods with flexible exchange rates.[3]

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[4]Examples of the non-monetary approach can be found in, e.g., Dellas (1986), Frenkel and Razin (1987), Cantor and Mark (1988), Ravn (1990), Stockman and Tesar (1990), Kollmann (1991, 1995a,b; 1996a), Mendoza (1991), Backus, Kehoe and Kydland (1992), Bianconi and Turnovsky (1992), Costello and Praschnik (1992), Devereux, Gregory and Smith (1992), Reynolds (1992), Baxter and Crucini (1993), Boileau (1993), Bruno and Portier (1993), Canova (1993), Macklem (1993), Marrinan and van Wincoop (1993), Yi (1993), Bec (1994), Eudy (1994), Senhadji (1994), Correia, Neves and Rebelo (1995), Helbling and Turtelboom (1995) and Zimmermann (1995). Most of these authors use quantitative (calibrated) stochastic models in their analysis.

Quantitative dynamic-optimizing monetary open economy models with flexible prices and wages are presented by, e.g., Cardia (1991), McCurdy and Ricketts (1991), Cho and Roche (1993), Bekaert, Hodrick and Marshall (1994), Schlagenhauf and Wrase (1995), Chin and Miller (1995), Bruno (1995) and Miller and Todd (1995). These monetary models build on the theoretical research of, among others, Stockman (1980, 1988), Helpman (1981), Lucas (1982), Svenson (1985) and Grilli and Roubini (1992).

[5]For example, the recent flexible-price monetary model studied by Schlagenhauf and Wrase (1995) generates standard deviations of nominal and real exchange rates that are roughly five to ten times smaller than the actual standard deviations observed for industrialized countries since the end of the Bretton Woods system; non-monetary models generate standard deviations of (real) exchange rates that are smaller still; see, e.g.,

It has repeatedly been suggested that models with nominal rigidities might be needed for a proper understanding of exchange rate behavior (see, e.g., Mussa (1990)), and recently several authors have begun to study dynamic-optimizing open economy models that depart from the assumption that nominal prices are fully flexible. The present paper contributes to this recent research effort.

Specifically, the work here builds on papers by Obstfeld and Rogoff (1995) and by Beaudry and Devereux (1995) who develop dynamic-optimizing monetary open economy models in which nominal goods prices are fixed in the short run, as firms set their prices one period in advance.[6] However, these recent models too seem unable to generate sufficient nominal and real exchange rate volatility.[7]

The present paper studies a dynamic-optimizing open economy model in

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Backus, Kehoe and Kydland (1995).

[8]Sticky prices are a key ingredient of Keynesian exchange rate models developed during the 1970s and 1980s (e.g., Dornbusch (1976)). However, those models lack the rigorous micro-foundations regarding the private sector's consumption and investment decisions that characterize the dynamic-optimizing approach.

The work by Obstfeld and Rogoff and by Beaudry and Devereux is also closely related to recent research that has introduced money and nominal rigidities into *closed* economy Real Business Cycle models (see, i.a., Cho and Cooley (1990), Cho (1993), Cho and Phaneuf (1993), Hairault and Portier (1993), Yun (1994), Benassy (1995), Bordo, Erceg and Evans (1995) and Ohanian, Stockman and Kilian (1995)).

[9]The Beaudry and Devereux (1995) model predicts that nominal and real exchange rates are *less* volatile than output, whereas the reverse is observed historically. Obstfeld and Rogoff (1995) show that (at least in the baseline version of their model) the assumption of preset prices *reduces* exchange rate volatility due to money supply shocks.

While working on the present project, papers by Hau (1995), Betts and Devereux (1996) and Sutherland (1996) came to my attention that also explore the effect of nominal rigidities in open economies, using models closely inspired by Obstfeld and Rogoff (1995). Unfortunately, these authors do not present stochastic model simulations, and hence it is difficult to evaluate how well their models match actual exchange rate data. Only the model proposed by Hau seems to have the potential for generating highly volatile exchange rates, as in his model (in contrast to those of Betts and Devereux and of Sutherland) money supply shocks can generate strong short-run responses of the exchange rate; however, this is only the case when the share of non-tradables in the households' consumption basket is relatively high.

which, in contrast to the work that was just discussed, nominal prices and nominal *wages* are set two or four periods in advance (the model is calibrated to quarterly data, i.e. one period represents one quarter in calendar time). In addition, a price and wage adjustment process inspired by Calvo (1983 a,b; 1987) is considered that assumes that nominal prices and wages are changed after time intervals of random length. The paper assumes a semi-small open economy with four types of exogenous shocks: shocks to the domestic money supply, to domestic labor productivity, to the price level in the rest of the world and to the world real interest rate.

It appears that the predicted variability of nominal and real exchange rates generated by the model is roughly consistent with that of Hodrick-Prescott filtered quarterly G7 effective exchange rates during the post-Bretton Woods era. The nominal rigidities assumed in this paper allow also to generate improved model predictions for other business cycle statistics. For example, the version of the model in which prices and wages are set four periods in advance captures better the observed variability of output, consumption and the nominal interest rate than a version of the model without nominal rigidities.

In the model with nominal rigidities studied here, money supply changes are the dominant source of exchange rate fluctuations, among the four types of shocks mentioned above. Like Keynesian open economy models with sticky prices (Dornbusch (1976)), the model exhibits exchange rate overshooting, in response to money supply shocks.

The model predicts that a positive shock to the domestic money supply lowers the domestic nominal interest rate, that it raises domestic output and that it leads to a nominal and real depreciation of the country's currency. Likewise, an increase in the foreign interest rate is predicted to induce a nominal and real depreciation of the country's currency. These predictions seem consistent with recent empirical evidence on the effects of monetary policy shocks (see, e.g., Eichenbaum and Evans (1995) and Grilli and Roubini (1995)). The model here predicts furthermore that an increase in domestic labor productivity triggers a nominal and real depreciation of the country's currency, while an increase in the price level in the rest of the world induces a nominal appreciation (foreign

price shocks have little impact on the real exchange rate).

The structure of the remainder of the paper is as follows: the model is outlined in Section 2. Section 3 discusses empirical regularities that characterize international business cycles. Section 4 presents simulation results. Section 5 concludes.

II. The Model

The paper assumes a semi-small open economy with a representative household, with firms and a government.[10]

1. Preferences

Household preferences are described by:

$$E_0 \sum_{t=0}^{t=\infty} \beta^t \, U(C_t, \mathcal{M}_t/P_t, L_t). \qquad (1)$$

E_0 denotes the mathematical expectation conditional on information available in period t=0. $0<\beta<1$ is a subjective discount factor and U(.) is an instantaneous utility function. C_t is an index of period t consumption. $\mathcal{M}_t/P_t$ represents real balances, where $\mathcal{M}_t$ is nominal balances held at the beginning of period t, while P_t is a consumption price index for period t. L_t represents labor effort in period t. The utility function U is of the following form:

$$U(C,\mathcal{M}/P,L) = (1/(1-\Psi)) \left\{ \left[C^{\sigma} + \kappa \, (\mathcal{M}/P)^{\Gamma} \right]^{1/\sigma} \right\}^{1-\Psi} - L,$$

where Ψ, σ, Γ and κ are parameters.[11]

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[10]In contrast, existing dynamic-optimizing open economy models with nominal rigidities have assumed a two-country world. The work here builds on Real Business Cycle models of (semi-)small open economies (e.g., Cardia (1991), Mendoza (1991), Schmitt-Grohé (1993) and Akitoby (1995)).

The economy considered here is *semi-small* in the sense that (as discussed below) it faces a downward-sloping aggregate export demand function, while import prices and the international interest rate are exogenous (this distinguishes the model here from models of *small* economies that face exogenous prices in all international markets).

[11]Note that labor effort enters linearly in the period utility

The consumption index C_t is defined as

$$C_t = D_t^{1-\alpha} F_t^{\alpha},$$

where D_t is an index of consumption goods produced in the country, while F_t is an index of imported consumption goods (α is a parameter; $0<\alpha<1$). There exists a continuum of home produced goods indexed by $s \in [0, 1]$ and a continuum of imported goods indexed by $\tau \in [0, 1]$. All consumption goods are perishable. D_t and F_t are defined as follows:

$$D_t = \left\{ \int_0^1 d_t(s)^{1/(1+\nu)}\, ds \right\}^{1+\nu} \quad \text{and} \quad F_t = \left\{ \int_0^1 f_t(\tau)^{1/(1+\nu)}\, d\tau \right\}^{1+\nu},$$

where $\nu>0$ is a parameter. $d_t(s)$ and $f_t(\tau)$ denote the date t consumption of home produced and of imported goods of types s and τ, respectively. Let $p_t^d(s)$ and $p_t^f(\tau)$ be the prices of these goods (in domestic currency) and let P_t^D and P_t^F be price indexes defined as:

$$P_t^D = \left\{ \int_0^1 p_t^D(s)^{-1/\nu}\, ds \right\}^{-\nu} \quad \text{and} \quad P_t^F = \left\{ \int_0^1 p_t^F(\tau)^{-1/\nu}\, d\tau \right\}^{-\nu}.$$

The consumption price index P_t is defined as:[12]

$$P_t = (1-\alpha)^{\alpha-1}\, \alpha^{-\alpha}\, (P_t^D)^{1-\alpha}\, (P_t^F)^{\alpha}.$$

Optimal consumption behavior implies:

$$D_t = (1-\alpha)\, P_t C_t / P_t^D \quad \text{and} \quad F_t = \alpha\, P_t C_t / P_t^F \quad \text{as well as}$$

$$d_t(s) = D_t \left[p_t^D(s)/P_t^D \right]^{-(1+\nu)/\nu} \quad \text{and} \quad f_t(\tau) = F_t \left[p_t^F(\tau)/P_t^F \right]^{-(1+\nu)/\nu}. \qquad (2)$$

The household can provide labor services of different types. There exists a continuum of labor types, indexed by $h \in [0, 1]$. Let $l_t(h)$ denote the number of hours of type h labor. The variable L_t that appears in the

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function. Such a specification is widely used in the Real Business Cycle literature, as it seems best suited for capturing the observed volatility of hours worked (e.g., Hansen (1985)).

[12]The price indices P_t^D, P_t^F and P_t represent the minimal expenditure (in domestic currency) needed to buy one unit of the composite D, F and C goods in period t, respectively.

utility function is defined as: $L_t = \int_0^1 l_t(h)\, dh$.

2. Firms and the Structure of Goods Markets

There are two types of firms in the country: (i) producers of consumption goods (home produced goods can be sold in the domestic market or exported); (ii) firms that import foreign consumption goods in order to sell them in the domestic market. All firms are owned by the domestic household.

Following Obstfeld and Rogoff (1995) and Beaudry and Devereux (1995), monopolistic competition in goods markets is assumed: each good is produced (or imported) and sold by a single firm (consumers purchase all goods from the country's firms--they cannot buy goods directly in foreign markets).

Domestic producers have identical technologies that use domestic labor as the only input (labor is immobile internationally). The period t production function of the firm producing domestic good s is:

$$y_t(s) = \theta_t \, \mathcal{L}_t(s), \tag{3}$$

where $y_t(s)$ is the firm's output, while θ_t is period t labor productivity (N.B. productivity is identical for all domestic producers). θ_t is an exogenous random variable. $\mathcal{L}_t(s)$ is an index of the different types of labor used by the firm in period t:

$$\mathcal{L}_t(s) = \left\{ \int_0^1 l_t(h;s)^{\phi}\, dh \right\}^{1/\phi},$$

where $l_t(h;s)$ represents the quantity of type h labor used by the firm at date t; $\phi<1$ is a parameter. Cost minimization implies that the demand for type h labor by the producer of good s satisfies:

$$l_t(h;s) = (y_t(s)/\theta_t) \left(w_t(h) \,/\, W_t \right)^{1/(\phi-1)}, \tag{4}$$

where $w_t(h)$ is the wage rate for type h labor, while

$$W_t = \left\{ \int_0^1 w_t(h)^{\phi/(\phi-1)}\, dh \right\}^{(\phi-1)/\phi}$$

is an aggregate wage index.[13]

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[13] W_t represents the minimal expenditure (in domestic currency) needed to purchase one unit of the composite labor input $\mathcal{L}$ in period t.

The date t profit of the firm that produces good s is given by:

$$\pi_t^D(s) \equiv p_t^D(s)\, d_t(s) + e_t\, p_t^X(s)\, x_t(s) - \int_0^1 w_t(h)\, l_t(h;s)\, dh,$$

where e_t is the country's exchange rate in period t, quoted as the local currency price of one unit of foreign currency. $p_t^X(s)$ is the price (in foreign currency) of good s in the export market, while $x_t(s)$ represents exports of the good (the determinants of export demand are discussed below).

The period t profit of the firm that sells the imported good of type τ is:

$$\pi_t^F(\tau) \equiv (p_t^F(\tau) - e_t\, P_t^*)\, f_t(\tau),$$

where P_t^* is the foreign currency price of the imported good in period t (the foreign currency prices of all imported goods are identical). It is assumed that P_t^* equals the price level in the rest of the world. P_t^* is treated as an exogenous variable in the following analysis.

The producer of domestic good s maximizes

$$\Pi_t^D(s) \equiv \sum_{i=0}^{i=\infty} E_t \rho_{t,t+i}\, \pi_{t+i}^D(s)/P_{t+i},$$

while the importer of foreign good τ maximizes

$$\Pi_t^F(\tau) \equiv \sum_{i=0}^{i=\infty} E_t \rho_{t,t+i}\, \pi_{t+i}^F(\tau)/P_{t+i}.$$

Here, $\rho_{t,t+i}$ is the pricing kernel used to value random date t+i pay-offs (that are expressed in units of the composite consumption good). As firms are owned by the representative household, it is assumed that firms value future payoffs according to the household's intertemporal marginal rate of substitution in consumption. Hence, $\rho_{t,t+i} = \beta^i U_{C,t+i}/U_{C,t}$ is assumed, where $U_{C,t+i}$ is the household's marginal utility of consumption in period t+i (see, e.g., Sargent (1987), Blanchard and Fischer (1989) and Romer (1996) for discussions of this pricing kernel).

3. Foreign Demand

Let P_t^X and X_t be an index of date t export prices (in foreign currency) and a quantity index of date t exports, respectively. P_t^X and X_t are defined analogously to the indices P_t^D and D_t:

$$P_t^X = \left\{ \int_0^1 p_t^X(s)^{-1/\nu} \, ds \right\}^{-\nu}, \qquad X_t = \left\{ \int_0^1 x_t(s)^{1/(1+\nu)} \, ds \right\}^{1+\nu}.$$

It is assumed that aggregate exports are determined by

$$X_t = (P_t^X/P_t^*)^{-\eta}, \ \eta>0.$$

Hence, X_t is negatively related to the ratio of export prices to the price level in the rest of the world.

It is assumed that the export demand function for good s resembles the domestic demand function for that good (see (2)):

$$x_t(s) = X_t \left(p_t^X(s)/P_t^X\right)^{-(1+\nu)/\nu}. \tag{5}$$

4. Government

The country's government prints the local currency. Increases in the money stock are paid out to the representative household in the form of lump-sum transfers. The money stock is exogenous. The government makes no attempt to influence the exchange rate, i.e. the exchange rate floats freely.

5. Household Budget Constraint

The household can hold three financial assets: local money, nominal bonds denominated in foreign currency and domestic currency bonds. The bonds are risk-free and have a maturity of one period. As all firms are owned by the domestic household, the household's budget constraint in period t is:

$$\mathcal{M}_{t+1} + e_t B_{t+1} + A_{t+1} + P_t C_t = \mathcal{M}_t + T_t + e_t B_t \, (1+i^*_{t-1}) + A_t \, (1+i_{t-1})$$
$$+ \int_0^1 \pi_t^D(s) \, ds + \int_0^1 \pi_t^F(\tau) \, d\tau + \int_0^1 l_t(h) w_t(h) \, dh \, . \tag{6}$$

Here, T_t is the government cash transfer in period t. B_t and A_t are, respectively, the household's (net) stock of foreign currency bonds and its (net) stock of local currency bonds that become due in period t. i^*_{t-1} and i_{t-1} are the nominal interest rates on these two types of bonds. The interest rate on foreign currency bonds (i^*_{t-1}) is exogenous.

6. Price and Wage Determination

Most of the discussions below assume that nominal prices and wages are set a fixed number of periods in advance. In addition, a price and wage adjustment mechanism inspired by Calvo (1983a,b; 1987) is considered that postulates overlapping price and wage contracts of random duration. Throughout the analysis, it is assumed that export prices are set in foreign currency.[14]

a. Predetermined Prices and Wages

The first framework assumes that the period t prices and nominal wages are set at date t-k (the simulations below consider k=2 and k=4).[15]

Maximizing the period t-k objective function of the domestic producer of good s ($\Pi^D_{t-k}(s)$) with respect to $p^D_t(s)$ and $p^X_t(s)$, subject to the firm's production function (equation (3)) and to the demand functions for the domestic good of type s (see (2) and (5)), and aggregating over all $s \in [0,1]$ yields the following aggregate price equations:

$$P^D_t = (1+\nu)\, W_t\, E_{t-k}\{\rho_{t-k,t}\, D_t/\theta_t\}/E_{t-k}\{\rho_{t-k,t}\, D_t\} \tag{7}$$

and

$$P^X_t = (1+\nu)\, W_t\, E_{t-k}\{\rho_{t-k,t}\, X_t/\theta_t\}/E_{t-k}\{e_t\, \rho_{t-k,t}\, X_t\}. \tag{8}$$

Similarly, maximization of $\Pi^F_{t-k}(\tau)$ with respect to $p^F_t(\tau)$, subject to the demand function for imported goods of type τ (see (2)) and aggregation

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[14] In contrast, Obstfeld and Rogoff (1995) and Beaudry and Devereux (1995) abstract from nominal wage rigidity and they assume that export prices are predetermined in terms of the exporter's currency--in their models, the export price in foreign currency adjusts instantaneously to changes in the nominal exchange rate, in a manner that ensures that the law of one price (LOP) holds. The assumption in the present paper that nominal wages are sticky is suggested by casual observation and econometric studies (e.g., Backus (1984)). The assumption that export prices are set in foreign currency is motivated by the widely documented empirical failure of the LOP (e.g., Engel and Rogers (1995)), in particular by widespread pricing-to-market behavior in international trade (e.g., Knetter (1993)).

[15] A closely related framework is considered by Bordo, Erceg and Evans (1995) who develop a dynamic general equilibrium model of a *closed* economy in which the wage is set k=4 periods in advance (prices, however, are fully flexible in that model).

over all $\tau \in [0, 1]$ yields:

$$P_t^F = (1+\nu)\, E_{t-k}\{\rho_{t-k,t}\, F_t e_t P_t^*\}/E_{t-k}\{\rho_{t-k,t}\, F_t\}. \qquad (9)$$

These price equations are based on the assumption that, although prices are fixed in advance, firms always satisfy the demand that they face.[16]

$w_t(h)$, the nominal wage rate of type h labor in period t is also set at date t-k. It is assumed that the representative household makes a commitment at date t-k to provide $l_t(h)=\xi_{t-k}(h)\cdot \text{ł}_t(h)$ hours of type h labor in period t (at the predetermined wage rate $w_t(h)$), where $\text{ł}_t(h)=\int_0^1 \text{ł}_t(h;s)ds$ is the total input of type h labor used by firms in period t. $\text{ł}_t(h)$ is not predetermined but reflects the production decisions made by firms in period t (and, hence, output demand in that period). In contrast, $\xi_{t-k}(h)$ is a choice variable for the household at date t-k, that allows the household to have an influence on her labor effort at date t. Clearly, $\xi_{t-k}(h)=1$ has to hold, in equilibrium (see discussion below). As shown in the Appendix, optimizing household behavior (regarding $\xi_{t-k}(h)$) implies that the following condition has to be satisfied, in equilibrium:

$$w_t(h)/P_t = \{E_{t-k}\, \text{ł}_t(h)\}/\{E_{t-k}\, U_{C,t}\, \text{ł}_t(h)\} \qquad (10)$$

(note that, in the absence of uncertainty, equation (10) implies $w_t(h)/P_t = 1/U_{C,t}$; this condition corresponds to the familiar first-order condition that prescribes the equalization of the marginal rate of substitution between consumption and leisure to the real wage rate[17]). As (10) has to

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[16]This assumption is standard in business cycle models with price rigidities (e.g., Mankiw (1994), Romer (1996)). Note that, as all firms have identical technologies and face identical demand functions, $p_t^D(s)=P_t^D$, $p_t^X(s)=P_t^X$ and $p_t^F(\tau)=P_t^F$ holds for all s, τ. Up to a certainty equivalent approximation, equations (7)-(9) show thus that each firm's price equals expected unit cost multiplied by a constant mark-up factor, $1+\nu>1$. Unless unanticipated shocks raise the actual unit costs in period t above the predetermined prices, it is thus not in the interest of firms to ration their customers in period t.

[17]$1/U_{C,t}$ is the marginal rate of substitution between consumption and leisure, as the marginal utility of leisure equals unity (for the utility function assumed here).

hold for all $h\in[0,1]$, the aggregate wage index, W_t, satisfies the following condition (see Appendix):

$$W_t/P_t = \{E_{t-k}\, L_t\}/\{E_{t-k}\, U_{C,t}\, L_t\} \qquad (11)$$

b. Calvo-type Price and Wage Determination

In addition, a model of price determination inspired by Calvo (1983 a,b; 1987) is considered that assumes that firms are not allowed to change their prices, unless they receive a random "price-change signal". The probability that a given price can be changed in any particular period is $1-\delta$, a constant (as there is a continuum of goods, $1-\delta$ represents also the fraction of all prices that are changed in each period; furthermore, the average time between price changes is $1/(1-\delta)$).[18]

Consider a domestic producer that is "allowed" at date t to set a new sales price in the domestic market. Let $\rho_t^{\mathcal{D}}$ be the price selected by that firm. If this price is still in effect at date t+i, then the firm's sales in the domestic market at that date are given by $d_{t+i}=D_{t+i}\left(\rho_t^{\mathcal{D}}/P_{t+i}^{D}\right)^{-(1+\nu)/\nu}$, as can be seen from (2) (here, it is again assumed that firms always satisfy the demand that they face). The probability that the price $\rho_t^{\mathcal{D}}$ is still in effect at date t+i is given by δ^i. Thus, the firm selects the price $\rho_t^{\mathcal{D}}$ that maximizes the following expression (N.B. W_{t+i}/θ_{t+i} is the firm's unit cost in period t+i):

$$\sum_{i=0}^{i=\infty} \delta^i\, E_t\left\{ \rho_{t,t+i}\, D_{t+i}\, \left(\rho_t^{\mathcal{D}}/P_{t+i}^{D}\right)^{-(1+\nu)/\nu} (\rho_t^{\mathcal{D}} - W_{t+i}/\theta_{t+i}) \,/\, P_{t+i}\right\}.$$

The solution of this maximization problem is:

$$\rho_t^{\mathcal{D}} = (1+\nu)\left\{\sum_{i=0}^{i=\infty} \delta^i E_t\{\Xi_{t,t+i}^{D}\, W_{t+i}/\theta_{t+i}\}\right\}\Big/\left\{\sum_{i=0}^{i=\infty} \delta^i E_t \Xi_{t,t+i}^{D}\right\},$$

where $\Xi_{t,t+i}^{D}=\rho_{t,t+i}\,(P_{t+i}^{D})^{(1+\nu)/\nu}\, D_{t+i}/P_{t+i}$. In period t, a fraction $(1-\delta)\delta^j$ of domestic producers are posting prices in the domestic market

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[18] Calvo (1983 a,b; 1987) considers a continuous time model. Here, a discrete time version is used that builds on Rotemberg (1987), Chadha (1987) and Yun (1994), among others. The original Calvo model does not assume sluggish nominal wages; however, the wage adjustment equation derived below follows closely the spirit of Calvo's work.

that were set $j \geq 0$ periods ago. Hence, the price index for home produced consumption goods is:

$$P_t^D = \left((1-\delta) \sum_{j=0}^{j=\infty} \delta^j \, (\rho_{t-j}^{\mathcal{D}})^{-1/\nu}\right)^{-\nu}.$$

Analogously, it can be shown that a domestic producer that is allowed in period t to set a new export price (in foreign currency) selects the following price:

$$\rho_t^{\mathcal{X}} = (1+\nu) \left\{\sum_{i=0}^{i=\infty} \delta^i E_t\{\Xi_{t,t+i}^X \, W_{t+i}/\theta_{t+i}\}\right\} \Big/ \left\{\sum_{i=0}^{i=\infty} \delta^i E_t \Xi_{t,t+i}^X e_{t+i}\right\},$$

where $\Xi_{t,t+i}^X = \rho_{t,t+i} \, (P_{t+i}^X)^{(1+\nu)/\nu} \, X_{t+i}/P_{t+i}$. The index of export prices is:

$$P_t^X = \left((1-\delta) \sum_{j=0}^{j=\infty} \delta^j \, (\rho_{t-j}^{\mathcal{X}})^{-1/\nu}\right)^{-\nu}.$$

An importer of foreign goods that is allowed at date t to set a new price of its good in the domestic market selects the following price:

$$\rho_t^{\mathcal{F}} = (1+\nu) \left\{\sum_{i=0}^{i=\infty} \delta^i E_t\{\Xi_{t,t+i}^F \, e_{t+i} P_{t+i}^*\}\right\} \Big/ \left\{\sum_{i=0}^{i=\infty} \delta^i E_t \Xi_{t,t+i}^F\right\},$$

where $\Xi_{t,t+i}^F = \rho_{t,t+i} \, (P_{t+i}^F)^{(1+\nu)/\nu} \, F_{t+i}/P_{t+i}$. The price index of imported goods is:

$$P_t^F = \left((1-\delta) \sum_{j=0}^{j=\infty} \delta^j \, (\rho_{t-j}^{\mathcal{F}})^{-1/\nu}\right)^{-\nu}.$$

Wages too are changed after time intervals of random length. With an exogenously given probability $1-\Delta$, the wage rate of a given labor type is changed in any particular period (hence, in each period, the wage rate of a constant fraction $1-\Delta$ of labor types changes). Assume that the wage rate for type h labor is changed in period t and let $w_t(h)$ denote the new wage. With probability Δ^i, $w_t(h)$ is still in effect at date t+i ($i \geq 0$). It is assumed that the household makes a commitment at date t to provide $l_{t+i}(h) = \xi_t(h) \cdot l_{t+i}(h)$ hours of type h labor at date t+i at the wage rate $w_t(h)$, provided that $w_t(h)$ is still in effect at that date. $\xi_t(h)$ is a decision variable that the household sets at date t (recall that $l_{t+i}(h) = \int_0^1 l_{t+i}(h;s)ds$). Clearly, $l_{t+i}(h) = l_{t+i}(h)$ has to hold in equilibrium or, equivalently, $\xi_t(h)=1$. As shown in the Appendix, optimizing household behavior (regarding $\xi_t(h)$) implies that, in equilibrium, the wage rate $w_t(h)$ has to satisfy the following condition:

$$w_t = w_t(h) = \sum_{i=0}^{i=\infty} (\beta\Delta)^i \, E_t\chi_{t+i} \Big/ \sum_{i=0}^{i=\infty} (\beta\Delta)^i E_t\{U_{C,t+i} \, (1/P_{t+i}) \, \chi_{t+i}\}, \quad (12)$$

where $\chi_{t+i}=W_{t+i}^{1/(1-\phi)}Y_{t+i}/\theta_{t+i}$; here, $Y_{t+i}=\int_0^1 y_{t+i}(s)ds$ is total physical output of domestic producers in period t+i (note that $w_t(h)$ does not depend on the labor type h, i.e. the same wage rate is set for all labor types for which a wage change occurs in period t).

For a fraction $(1-\Delta)\Delta^j$ of labor types, the wage rate in effect at date t was set in period t-j ($j\geq 0$). Hence, the aggregate wage index is given by:

$$W_t = \left((1-\Delta) \sum_{j=0}^{j=\infty} \Delta^j \, (w_{t-j})^{\phi/(\phi-1)} \right)^{(\phi-1)/\phi}.$$

7. The Household's Intertemporal Decisions

The representative household's intertemporal consumption decisions and her demand for money can be determined by maximizing the expected life-time utility function specified in (1) subject to the restriction that the budget constraint (6) holds in all periods and for all states of the world. Ruling out Ponzi schemes, that decision problem has the following first-order conditions:

$$1 = \beta \, (1+i_t) \, E_t\left\{ \frac{c_{t+1}^{\sigma-1} \, \Omega_{t+1} \, P_t}{c_t^{\sigma-1} \, \Omega_t \, P_{t+1}} \right\}, \quad (13a)$$

$$1 = \beta \, (1+i_t^*) \, E_t\left\{ \frac{c_{t+1}^{\sigma-1} \, \Omega_{t+1} \, P_t \, e_{t+1}}{c_t^{\sigma-1} \, \Omega_t \, P_{t+1} \, e_t} \right\} \quad \text{and} \quad (13b)$$

$$\kappa \, (\Gamma/\sigma) \, E_t\left\{ \Omega_{t+1} \, (M_{t+1}/P_{t+1})^{\Gamma-1}/P_{t+1} \right\} = i_t \, E_t\left\{ \Omega_{t+1} \, c_{t+1}^{\sigma-1} \, /P_{t+1} \right\}, \quad (14)$$

where $\Omega_{t+1} = \left(c_{t+1}^{\sigma} + \kappa (M_{t+1}/P_{t+1})^{\Gamma} \right)^{-1+(1-\Psi)/\sigma}$. Equations (13 a) and (13 b) are Euler conditions, while equation (14) can be interpreted as a money demand condition.

8. Equilibrium and Solution Method

Demand equals supply in all goods markets because, by assumption, firms always satisfy the demand that they face. In equilibrium, the amount of type h labor purchased by firms has to equal the supply of type h labor by the representative household:

$$l_t(h) = \int_0^1 l_t(h;s)ds \quad \text{for all } t \text{ and all } h\in[0, 1]$$

or, equivalently, $\xi_t(h) = 1$ for all t and all $h\in[0, 1]$.

Equilibrium in the market for domestic money requires that the demand for money equals the supply. It is assumed that only residents of the country hold the local currency. Equilibrium in the money market requires thus:

$$M_{t+1} = \mathcal{M}_{t+1} \quad \text{for all } t,$$

where M_{t+1} is the money supply, while $\mathcal{M}_{t+1}$ represents the household's desired money balances, as determined by equation (14). The law of motion of the money supply is:

$$M_{t+1} = M_t + T_t,$$

where T_t is the government transfer to the household in period t (see (6)).

It is assumed that the government does not issue bonds and that foreign investors do not hold bonds denominated in domestic currency. Hence, the household's (net) stock of domestic currency bonds has to be zero, in equilibrium: $A_t = 0$ for all t.

Given a stochastic process for the exogenous variables of the model, an equilibrium can be defined as a stochastic process for the endogenous variables that satisfies the equilibrium conditions that were just stated and the equations of the model discussed earlier. An approximate model solution is obtained by taking a linear approximation of the equations of the model around a deterministic steady state (i.e. around an equilibrium in which all exogenous and endogenous variables are constant).[19]

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[19]This solution method is widely used in business cycle research; see, e.g., King, Plosser and Rebelo (1988), Rotemberg and Woodford (1992), Cooley and Hansen (1995), Uhlig (1995). In the simulations discussed below,

This approximation yields a system of expectational difference equations that can easily be solved (for example, using the method described in Blanchard and Kahn (1980)).

9. Parameterization

a. Preferences and Foreign Demand

The simulations assume a coefficient of relative risk aversion of $\Psi=2$. This value lies in the range of risk aversion coefficients usually assumed in the business cycle literature (Friend and Blume (1975) present evidence consistent with this value of the risk aversion coefficient).

The preference parameter α determines the share of consumption expenditures that is devoted to imported consumption goods. The simulations assume $\alpha=0.33$ (this value corresponds to the arithmetic average of the ratios of imports to private consumption in the G7 countries during the period 1973-91).

As mentioned above, equation (14) can be interpreted as a money demand equation. The elasticities of money demand with respect to consumption and with respect to the domestic nominal interest rate are given by $\varepsilon_{m,c} \equiv (\sigma-1)/(\Gamma-1)$ and $\varepsilon_{m,i} \equiv 1/(\Gamma-1)$, respectively.[20] The simulations assume $\varepsilon_{m,c}=0.20$ and $\varepsilon_{m,i}=-0.04$ (the values of σ and Γ that correspond to these choices for $\varepsilon_{m,c}$ and $\varepsilon_{m,i}$ are: $\sigma=-4$, $\Gamma=-24$). These values of $\varepsilon_{m,c}$ and $\varepsilon_{m,i}$ are in the range of estimates of the transactions elasticity and interest rate elasticity of money demand that can be found in econometric work on U.S. money demand (e.g., McCallum (1989) and Goldfeld and Sichel (1990)) as well in Fair's (1987) study of money demand in 27 industrialized countries.[21]

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the model is linearized around a steady state in which the country's (net) stock of foreign bonds is zero.

[20]To understand these expressions, note that, up to a certainty equivalent approximation, the money demand condition (14) can be written as: $k\ (\Gamma/\sigma)\ (M_{t+1}/P_{t+1})^{\Gamma-1} = c_{t+1}^{\sigma-1}\ i_t + \varepsilon_{t+1}$, where ε_{t+1} is a forecast error ($E_t \varepsilon_{t+1}=0$).

[21]These estimates pertain to short-run (quarterly) money demand elasticities. Estimates of short-run elasticities are used to calibrate the

The preference parameter κ is set in such a way that the steady state consumption velocity (ratio of nominal consumption expenditure to the money stock) equals unity.[22]

Business cycle models that are calibrated to quarterly data commonly assume a steady state real interest rate in the range of 1% per quarter, and that is also the value of the steady state interest rate used here (thus, β=1/1.01 is assumed--the existence of a deterministic steady in the present model requires that β (1+r)=1 holds, where r is the steady state interest rate).

The price elasticity of export demand is set to η=1.2, a value consistent with estimated export demand elasticities for industrialized countries (see, e.g., Goldstein and Khan (1978)).[23]

b. Price and Wage Adjustment

The simulations of the version of the model with predetermined prices and wages consider the following values of k: k=2, k=4 (most of the discussions below focus on the case k=4).

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model, because the focus of the present paper is on high frequency exchange rate fluctuations (long-run elasticities of money demand with respect to the transactions proxy are generally higher than short-run elasticities--e.g., estimation results presented by McCallum (1989) suggest that the long run elasticity is approximately 0.50). Note also that (as is common in the literature) the money demand functions estimated by the authors cited above use GNP as a scale variable, and not consumption per se.

[22]The key model predictions discussed below are not sensitive to the assumed steady state velocity (a unit velocity is roughly consistent with data on the M1 consumption velocity in the G7 countries; e.g., in the U.S. that velocity was 0.93 in 1994).

[23]In order to solve the model for the aggregate price and quantity variables on which the discussions below focus, no specific values need to be assigned to the parameters ν and ϕ that determine the elasticity of substitution between different types of consumption goods and different types of labor (the linearization of the model yields a system of equations in the aggregate variables that does not depend on ν or ϕ).

It can be verified that for the values of the preference parameters assumed in the simulations, the utility function is strictly increasing and concave in consumption and real balances, in the neighborhood of the steady state around which the model is linearized.

Rotemberg (1987) points out that the aggregate price equations of the Calvo model are observationally equivalent to those implied by a model of price determination developed in Rotemberg (1982 a,b) that assumes that firms can freely alter their prices at any time, but that they face quadratic costs of changing their prices. Econometric results (based on aggregate U.S. price data) presented in Rotemberg (1982 a), yield the following estimate of the price adjustment parameter δ: δ=0.92. This is the value of δ used in the simulations discussed below. That value implies that the average time between price changes at the firm level is 12.5 quarters. It is assumed that the average time between wage changes too equals 12.5 quarters, i.e. Δ=0.92 is used (support for this value is provided by Backus (1984) who finds that Canadian wage contracts have a mean length of 12.7 quarters).

c. Exogenous Variables

The exogenous variables follow autoregressive processes. In the following equations, ρ^M, ρ^θ, ρ^* and ρ^R are parameters, while ε_t^M, ε_t^θ, ε_t^* and ε_t^R are white noise random errors whose standard deviation are denoted by σ^M, σ^θ, σ^* and σ^R, respectively. These error terms are assumed to be mutually independent.

The money supply process assumed in the simulations is identical to that used in a recent monetary business cycle model developed by Cooley and Hansen (1995):

$$\ln(M_{t+1}/M_t) = \rho^M \ln(M_t/M_{t-1}) + \varepsilon_t^M,$$

where M_t is the money supply at the beginning of period t. Following Cooley and Hansen, ρ^M=0.491 is assumed and the standard deviation of the money supply innovation (ε_t^M) is set to σ^M=0.0089 (Cooley and Hansen obtain these parameter values by fitting the above money supply equation to U.S. money stock data).

The stochastic process for productivity is:

$$\ln(\theta_t) = \rho^\theta \ln(\theta_{t-1}) + \varepsilon_t^\theta.$$

In the simulations, ρ^θ=0.95 is used and the standard deviation of the

productivity innovation (ε_t^{θ}) is: $\sigma^{\theta}=0.007$.[24]

The behavior of the foreign price level is described by:

$$\ln(P^*_t/P^*_{t-1}) = \rho^* \ln(P^*_{t-1}/P^*_{t-2}) + \varepsilon^*_t.$$

The simulations assume the following values of ρ^* and of the standard deviation of ε^*_t: $\rho^*=0.80$ and $\sigma^*=0.005$.[25]

Finally, a stochastic process for the foreign interest rate has to be specified. Let $R_t=(1+i^*_t)E_t(P^*_t/P^*_{t+1})-1$ denote the expected foreign real interest rate. The simulations assume that R_t follows an AR(1) process:

$$R_t = (1-\rho^R)\, r + \rho^R R_{t-1} + \varepsilon^R_t,$$

where r is the steady state real interest rate. In the simulations, $\rho^R=0.79$ is assumed and the standard deviation of the interest rate innovation ε^R_t is: $\sigma^R=0.0043$.[26]

III. Stylized Facts About Economic Fluctuations (Post-Bretton Woods Era)

Table 1 presents empirical information on the behavior of output, private consumption, total hours worked, net exports, the price level, the money supply and the short term nominal interest rate in the G7 countries since

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[24]Prescott (1986) presents empirical evidence consistent with these values of ρ^{θ} and σ^{θ}. Many business cycle studies have used the same (or very similar) values for ρ^{θ} and σ^{θ} (e.g., Hansen (1985), Gomme (1993), Ambler and Paquet (1994)).

[25]These values were obtained by taking the quarterly U.S. CPI series as a measure of the foreign price P^*_t and fitting the above equation to that series (a constant was also included in the regression; sample period 1973-94).

[26]Note that, approximately, $R_t=i^*_t-E_t\ln(P^*_{t+1}/P^*_t)$ and, hence $R_t=i^*_t-\rho^*\ln(P^*_t/P^*_{t-1})$ if the above equation for P^*_t holds. Using the U.S. interest rate on three-month Certificates of Deposit as a measure of i^*_t, the U.S. CPI as a measure of P^*_t as well as the value of ρ^* reported above to construct a quarterly time-series for R_t and fitting an AR(1) process to that series yields $\rho^R=.79$ and $\sigma^R=0.0043$ (sample period 1973-91).

1973. The Table also provides information on the effective exchange rates of the G7 countries and on exchange rates between the U.S. dollar and the currencies of the remaining G7 countries. Detailed information on the data is provided in the Appendix. Standard deviations of the variables are reported, as well as autocorrelations and correlations with domestic output. All series used in Table 1 are sampled at a quarterly frequency. The empirical series have all been detrended using the Hodrick and Prescott (1980) filter; before applying this filter, all series (with the exception of net exports and nominal interest rates) were logged. The empirical regularities discussed below do not depend on this particular filter--other detrending methods, e.g. linear detrending, lead to similar stylized facts.

In most G7 countries, the standard deviation of output is about 2%. Generally, consumption, hours worked and the price level are less volatile than output. The standard deviation of money typically exceeds that of output. Consumption and hours worked are procyclical (i.e., positively correlated with domestic output), while net exports are countercyclical. Money is procyclical, while the price level is countercyclical. The nominal interest rate is procyclical in four of the G7 countries. All variables considered in Table 1 are highly positively serially correlated (to save space, the Table only shows autocorrelations of output and effective exchange rates).

Nominal and real exchange rates are more volatile than any of the other variables considered in Table 1. The standard deviations of real exchange rates are very similar to those of nominal exchange rates. The arithmetic average of the standard deviations of the nominal effective exchange rates of the G7 countries is 4.80%, while the average standard deviation of the real effective exchange rate series is 4.75%. Bilateral U.S. dollar exchange rates are typically more volatile than the effective exchange rates of the G7 countries (the standard deviations of these bilateral exchange rates range mostly between 8% and 9%). Table 1 shows that correlations between nominal and real effective exchange rates are high, in all G7 countries (correlations of 0.95 or above).[27] The

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[27]Likewise, correlations between nominal bilateral U.S. dollar exchange

autocorrelations of effective exchange rates mostly exceed 0.70. The U.S. effective exchange rate (nominal and real) is procyclical, while the effective exchange rates of the remaining G7 countries are generally countercyclical (here, exchange rates are measured as the national currency price of foreign currency; thus, the external value of a country's currency is typically positively correlated with domestic output).

Among the G7 countries, Germany, France, Italy and Canada have the least volatile effective exchange rates. This reflects arrangements that limit exchange rate fluctuations in Europe (EMS) and attempts by the Canadian authorities to stabilize the U.S. dollar-Canadian dollar exchange rate. As the model considered here assumes a fully flexible exchange rate, it is thus of particular interest whether the model has the ability to capture the historical volatility of U.S., Japanese and U.K. effective exchange rates and that of the bilateral U.S. dollar exchange rates.

IV. Simulation Results

Simulation results are presented in Tables 2-3. The statistics reported in these Tables are averages of moments calculated for 1000 model simulations with a sample length of 89 periods each (this number of periods corresponds to the length of the empirical nominal effective exchange rate series used for Table 1).

In Tables 2 and 3, the output variable corresponds to Y_t (total output of domestic producers), consumption is C_t, hours worked is L_t, the price level is P_t and the real exchange rate is defined as $e_t P^*_t / P_t$.

All simulated series were logged (with the exception of net exports and the nominal interest rate) and passed through the Hodrick and Prescott (1980) filter. To facilitate the comparison between model predictions and the data, the column labelled "Data" in Tables 2-3 reports arithmetic averages, across the G7 countries, of the empirical statistics presented in Table 1 (the "Data" column is identical to the last column of Table 1; the

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rates and the corresponding real exchange rates are high (not reported in Table 1, to save space).

exchange rate statistics in the "Data" column pertain to effective exchange rates).

The methodology developed by Gregory and Smith (1991) is used to formally evaluate how close the model predictions are to the data. Following these authors, the frequency distribution of the simulated statistics is used to construct confidence intervals for each of the statistics considered in Tables 2 and 3. In these Tables, a § [†] next to a given theoretical statistic indicates that the 95% [99%] confidence interval for that statistic includes the historical statistic that is reported in the "Data" column (the 95% confidence intervals run from the 0.025 to the 0.975 quantiles of the frequency distributions of the simulated statistics obtained by simulating the model 1000 times, while the 99% confidence intervals run from the 0.005 to the 0.995 quantiles). When a given historical statistic is not included in the relevant 95% or 99% confidence interval, this suggests a rejection of the hypothesis that the statistic generated by the model is compatible with the data.

1. Predetermined Prices and Wages

Table 2 presents results for the version of the model with predetermined prices and wages. Results are presented for simulations in which the model is subjected to each of the four types of shocks separately, as well as for simulations in which the four types of shocks are used simultaneously. For each configuration of shocks, versions of the model with k=0 and k=4 are compared; the case k=0, i.e. absence of nominal rigidities, is considered here as most earlier dynamic-optimizing open economy models have abstracted from nominal rigidities (the simulations that just assume money supply shocks also consider a version of the model with k=2).

a. Money Supply Shocks

Columns 1-3 of Table 2 report results for the case in which just money supply shocks are assumed. When k=0 (see column 1), then money supply shocks have almost no effect on output, consumption, hours, net exports and the real exchange rate (the predicted standard deviations of these variables are all smaller than 0.03%). In contrast, the predicted standard

deviation of the domestic price level is roughly consistent with the data. As the real exchange rate shows little response to money supply shocks, the predicted standard deviation of the nominal exchange rate (1.97%) is (basically) identical to that of the price level, and it is thus much too small, when compared to the data. These results are consistent with the failure of earlier monetary open economy models without nominal rigidities to explain the historical variability of nominal and real exchange rates.

Money supply shocks have a much stronger impact on real variables when there are nominal rigidities (k=2, 4; see columns 2 and 3 of Table 2): the standard deviations of output and the real exchange rate rise from close to zero (when k=0) to 0.72% and 2.17%, respectively, when k=2 and to 1.20% and 3.64%, respectively, when k=4. Nominal rigidities increase also the standard deviation of the nominal exchange rate (from 1.97% when k=0 to 2.83% when k=4). The predictions regarding the standard deviations of consumption, hours, net exports and the nominal interest rate too improve significantly when k=4 is assumed.

For the version of the model with k=4, Figure 1 shows the impact of a one standard deviation (i.e. 0.89%) innovation to the money supply process. In these, as well as in all following Figures, the responses of all variables (with the exception of the interest rate) are expressed as relative deviations from the steady state around which the model is linearized.[28]

As prices are predetermined, an increase in the nominal money supply induces a short-run rise in the real money supply. This lowers the domestic nominal interest rate, as can be seen in Panel (b) of Figure 1 (a fall in the interest rate is required to induce an increase in the household's demand for real money balances).

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[28]The response of a given variable z_t is expressed as $(z_t-z)/z$, where z is the steady state value of that variable. In contrast, interest rate responses are shown as differences from steady state: i_t-i, where i is the steady state interest rate.

Note that, in Panel (a) of Figure 1, the money supply response shown for period t represents the reaction of M_{t+1}, i.e. it pertains to the money stock at the *end* of period t.

The drop in the interest rate induced by the money supply shock triggers a rise in the household's consumption and thus it increases output. But note that the fall in the interest rate and the increase in consumption and output are short-lived: the consumption and output "boom" only lasts four periods, i.e. until the price level starts to adjust to the rise in the money supply.

Figure 1 shows that, on impact, a 0.89% money supply innovation induces a depreciation of the nominal exchange rate by about 2.5%, when k=4 is assumed. In the periods that follow the shock, the exchange rate appreciates and converges to its new long-run level.[29] The long-run effect of the money supply shock is a depreciation of the nominal exchange rate by approximately 1.8%. As in Dornbusch's (1976) exchange rate model, the initial response of the exchange rate to a money supply shock exceeds thus the long-run response, i.e. exchange rate "overshooting" occurs (it appears, in contrast, that no exchange rate overshooting takes place when there are no nominal rigidities,[30] which explains why the nominal exchange rate is more volatile when k=4 than when k=0, as discussed above).

During the first three periods after the money supply shock, the domestic price level does not respond to that shock, but thereafter the price level converges rapidly to its new long-run value. In the long-run, the price level rises by approximately 1.8% (note that a 0.89% innovation to the money supply raises the money stock by about 1.8%, in the long-run). Thus, the money supply shock has little impact on the real exchange rate, in the long run. However, in the short-run, the nominal depreciation of the exchange rate is accompanied by a real depreciation. This explains why nominal and real exchange rates are highly positively correlated when k=4 is assumed (see Table 2, column 3).

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[29]Conditions (13 a) and (13 b) imply that, up to a certainty equivalent approximation, uncovered interest parity holds in equilibrium: $(1+i_t)\cong(1+i_t^*)(E_t e_{t+1}/e_t)$--the drop in the domestic interest rate triggered by a positive money supply shock requires thus an appreciation of the country's currency in the periods after the money supply shock.

[30]Impulse response functions for the version of the model with k=0 not shown in Figure 1 (available from the author, upon request).

The impulse response functions shown in Figure 1 also help understand why the version of the model with k=4 (and just money supply shocks) predicts that consumption is procyclical and that net exports are countercyclical (see Column 3 of Table 2), as is consistent with the data.[31]

The prediction that a positive money supply shock lowers the domestic interest rate, that it induces a nominal and real depreciation of a country's currency and that it raises domestic output and the domestic price level seems consistent with recent empirical evidence on the macroeconomic effects of monetary policy shocks (see, e.g., Eichenbaum (1992), Eichenbaum and Evans (1995), Grilli and Roubini (1995)).[32]

b. Other Types of Shocks

Columns 4-10 of Table 2 report results for simulations that just assume productivity shocks, just shocks to the foreign price level or just shocks

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[31]N.B. the strong rise of consumption triggered by a positive money supply shocks drives down the country's net exports (net exports not shown in Figure 1)--hence, the predicted countercyclicality of net exports. The impulse responses also help understand why nominal and real exchange rates are predicted to be procyclical (this is consistent with the data for the U.S., but not for the remaining G7 countries), why the nominal interest rate is predicted to be countercyclical (the interest rate is countercyclical in three of the G7 countries) and why the price level too is predicted to be countercyclical (as is consistent with the data for all G7 countries).

[32]Note that the model predicts that the maximal effect of a monetary policy shock on the exchange rate occurs on impact. In contrast, empirical research suggests that the maximal effect occurs *after* the shock (following an expansionary monetary policy shock, the exchange rate appears to depreciate for some time, before it starts to appreciate). In fact, Eichenbaum and Evans (1995) argue that the maximal effect is reached after a period of two to three years. However, Grilli and Roubini (1995) present empirical results according to which the maximal effect is reached fairly rapidly (within a few months), which seems more consistent with the predictions of the model here. Note also that empirical research tends to find that monetary policy shocks have a highly persistent effect on output, but that their impact effect is rather weak. In the simulations discussed above, by contrast, the effect of money supply shocks on output is relatively short-lived and the maximal effect on output occurs on impact. As shown below, the version of the model with Calvo-type nominal rigidities generates a much more long-lasting effect of money supply shocks on output.

to the expected foreign real interest rate.[33]

It appears that technology shocks have a rather weak impact on nominal and real exchange rates, and that irrespectively of whether prices and wages are fully flexible (k=0) or not (k=4). In contrast, shocks to the expected foreign real interest rate have a sizable effect on nominal and real exchange rates: for the case k=4, the predicted standard deviations of these variable exceed 2% when just these interest rate shocks are assumed. Shocks to the foreign price level too have a non-negligible effect on the nominal exchange rate, but these shocks have almost no effect on the real exchange rate.[34]

For the case k=4, Figures 2-4 show the impact of positive innovations to domestic productivity, to the foreign price level and to the expected foreign real interest rate, respectively. It appears that a positive productivity shock causes an immediate nominal and real depreciation of the country's currency. A positive shock to the foreign price level induces an appreciation of the nominal exchange rate that matches almost exactly (in percentage terms) the increase in the foreign price level. Thus, that shock has little effect on the real exchange rate. Finally, it can be seen that, on impact, a positive shock to the expected foreign real interest rate induces a nominal and real depreciation of the country's exchange rate[35]. The prediction that positive shocks to the foreign interest rate induce a depreciation of the country's currency seems consistent with recent empirical research on the effects of monetary policy

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[33]Because of space constraints, the following discussion focuses on the effect of these three types of shocks on the exchange rate; see the working paper version of the present paper (Kollmann (1996b)) for discussions of effects on other variables.

[34]The expected foreign real interest rate is held constant in the simulations that assume that there are just shocks to the foreign price level; as foreign price shocks affect the foreign inflation rate, they thus change the foreign *nominal* interest rate.

[35]In the periods that follow the interest rate shock, the currency appreciates. This is so because, as discussed above, interest parity holds in the present model, up to a certainty equivalent approximation (N.B. the foreign interest rate shock raises the foreign nominal interest rate above the domestic nominal interest rate; Panel (b) of Figure 4).

shocks (e.g., Eichenbaum and Evans (1995), Roubini and Grilli (1995)).

c. Combined Effect of Four Types of Shocks

Finally, columns (11) and (12) of Table 2 consider the case where the model is subjected to all four types of shocks simultaneously. In that case, the predicted standard deviations of nominal and real exchange rates are 3.91% and 4.25%, respectively, when k=4 is assumed, compared to standard deviations of 3.24% and 1.61% when k=0. As in the version of the model that just assumes money supply shocks, the predicted standard deviations of nominal and (particularly) of real exchange rates are thus noticeably larger when nominal rigidities are assumed (k=4) than when k=0.

It can be noted that when k=4 is assumed, the predicted standard deviations of nominal and real exchange rates that are generated when the four types of shocks are used exceed by no more than roughly one percentage point the standard deviations reported for the case where there are only money supply shocks. Clearly, money supply shocks are the dominant source of exchange rate fluctuations, in the version of the model with predetermined prices and wages.

The version of the model with the four types of shocks and k=4 explains 80% [90%] of the *average* historical standard deviations of G7 nominal [real] effective exchange rates--the average historical standard deviations are included in the 95% confidence intervals generated by the model with k=4. In contrast, the average historical standard deviations are *not* included in the 95% (or even in the 99%) confidence intervals generated by the model with k=0. The model with k=4 captures a somewhat smaller fraction of the historical standard deviations of U.S. and U.K. effective exchange rates (between 65% and 80%)--however, the historical standard deviations of the U.S. real effective rate and of the U.K. nominal and real effective exchange rates are included in the 99%, or even 95%, confidence intervals for these statistics.[36] In contrast, the model with k=4 captures

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[36]When k=4 is assumed, the 95% confidence interval for the standard deviation of the nominal exchange rates is [2.97%, 5.04%], while that of the real exchange rate is [3.19%, 5.38%]; the corresponding 99% confidence intervals are [2.77%, 5.64%] and [2.89%, 5.90%], respectively (for k=0, the

only about 50% of the standard deviations of Japanese effective exchange rates and of bilateral U.S. dollar exchange rates.

Model performance improves also in several other dimensions (besides predicted exchange rate volatility) when nominal rigidities (k=4) are assumed, compared to the case k=0. For example, it appears that--as in the case where just money supply shocks are assumed--predicted standard deviations of output, consumption and the nominal interest rate are larger and significantly closer to the data when k=4 is assumed than when k=0.[37] The predicted correlation between nominal and real exchange rates too is higher when k=4 than when k=0; however, even when k=4 is assumed, the predicted correlation (0.77) is significantly smaller than that observed in the data (0.97). Likewise, the predicted autocorrelation of the real exchange rate (about 0.60) is sizable, but nevertheless too small compared to that observed historically (0.77), and that irrespectively of whether k=0 or k=4 is assumed;[38] in contrast, the predicted autocorrelation of the nominal exchange rate seems more consistent with the data.[39]

2. Calvo-Type Price and Wage Adjustment

Table 3 presents simulation results for the version of the model with Calvo-type nominal rigidities (to save space, results are only shown for the case in which the model is just subjected to money supply shocks and

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corresponding 99% confidence intervals are [2.11%, 4.55%] and [1.16%, 2.14%]).

[37]Also, the version of the model with k=4 is consistent with the stylized fact that consumption is procyclical, and that net exports and the price level are countercyclical; in contrast, the version with k=0 predicts that consumption is *counter*cyclical and that net exports and the price level are *pro*cyclical.

[38]After the present paper was completed, I became aware of Chari, Kehoe and McGrattan (1996) who likewise study a dynamic-optimizing open economy model with nominal rigidities; their analysis focuses on the ability of that model to generate persistent deviations of real exchange rates from purchasing power parity. Their model too underpredicts the autocorrelation of actual real exchange rate series.

[39]The average historical autocorrelation of nominal effective exchange rates is included in the 99% [95%] confidence interval generated by the version of the model with k=4 [k=0].

for the case in which the model is subjected to the four types of shocks simultaneously).

The standard deviations of exchange rates reported in Table 3 are larger than those generated by the version of the model with predetermined prices and wages: when just money supply shocks are assumed, the predicted standard deviations of nominal and real exchange rates are 5.45% and 5.33%, respectively; with the four types of exogenous shocks, the corresponding standard deviations are 6.15% and 5.78%. As in the version of the model with predetermined prices and wages, money supply changes have thus the strongest impact on nominal and real exchange rates, among the four types of shocks considered here. For the case where the four types of exogenous shocks are assumed, the average standard deviations of G7 effective exchange rates (nominal and real) as well the historical standard deviations of U.S., Japanese and U.K. nominal effective exchange rates and of U.S. and U.K. real effective exchange rates are included in the 95% confidence intervals for these statistics.[40]

Note also that the observed high serial correlation of nominal and real exchange rates as well as the observed high correlation between nominal and real exchange rates are better captured by the version of the model with Calvo-type nominal rigidities than by the version with predetermined prices and wages. However, other historical statistics, particularly the correlations between domestic output and the remaining variables considered in Tables 1-3, are less well captured when Calvo-type nominal rigidities are assumed.

Figure 5 shows the effect of a one standard deviation (i.e. 0.89%) innovation to the money supply. This shock generates substantial exchange rate overshooting. In contrast to the model with predetermined prices and wages, the domestic price level begins to rise as soon as the money supply shock occurs. Also, the adjustment of the price level to its new long-run level is much slower than in the setting with predetermined prices and

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[40]The 95% confidence intervals of the standard deviations of the nominal and of the real exchange rate are [4.60%,7.96%] and [4.39%, 7.42%], respectively.

wages.[41] This explains why the adjustment of the nominal exchange rate to its new long-run level too is much slower and why the effect of a money supply shock on the real exchange rate (as well as on output and consumption) is much less short-lived than when prices and wages are predetermined.

V. Conclusion

This paper has studied a dynamic-optimizing model of a semi-small open economy with nominal rigidities. As in the Dornbusch (1976) model, money supply shocks induce exchange rate overshooting. The predicted variability of nominal and real exchange rates is roughly consistent with that of G7 effective exchange rates during the post-Bretton Woods era.

The model predicts that a positive shock to the domestic money supply lowers the domestic nominal interest rate, that it raises domestic output and that it leads to a nominal and real depreciation of the country's currency. Increases in the world interest rate and in domestic labor productivity too induce a nominal and real exchange rate depreciation, while an increase in the price level in the rest of the world induces a nominal appreciation (foreign price shocks have little impact on the real exchange rate).

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[41]The smoother response of the price level to shocks explains why the standard deviation of the price level is much smaller with Calvo-type nominal rigidities than when predetermined prices and wages are assumed, as can be seen in Table 3.

APPENDIX

• DERIVATION OF WAGE EQUATIONS

Wage equation in version of model with predetermined prices and wages ((10), (11))

The household selects $\xi_{t-k}(h)$ for each $h\in[0,1]$ with the objective of maximizing her expected life-time utility in period t-k. An interior solution of this decision problem has to satisfy the following first-order condition: $E_{t-k}U_{L,t}l_t(h)+E_{t-k}\lambda_t(w_t(h)/P_t)l_t(h) = 0$. Here, $U_{L,t}$ is the marginal disutility of labor effort, while λ_t is the shadow value of household wealth in period t, i.e. $\lambda_t=U_{C,t}$ (to understand this condition, note that if the household changes $\xi_{t-k}(h)$ by an infinitesimal amount ε, then her labor effort in period t and her wealth in that period change by $l_t(h)\varepsilon$ and by $(w_t(h)/P_t)l_t(h)\varepsilon$, respectively).

Using the fact that $U_{L,t}=-1$ and that $w_t(h)$ and P_t belong to the period t-k information set (in the version of the model with predetermined prices and wages), it can be seen that equation (10) is equivalent to the above first-order condition. Thus (10) has to hold in equilibrium (note that only interior solutions of the household's decision problem are relevant for characterizing the equilibrium, as $\xi_t(h)=1$ has to hold, in equilibrium).

As all producers set identical prices in the version of the model with predetermined prices (see discussion in text) and as domestic producers have identical technologies that are symmetric in the different type of labor, $l_t(h)=L_t=L_t$ and $w_t(h)=W_t$ has to hold for all $h\in[0, 1]$. Thus (11) follows immediately from (10).

Wage equation in version of model with Calvo-type nominal rigidities (equation (12))

Suppose that a new wage rate for type h labor is set in period t. The household selects $\xi_t(h)$ at date t with the objective of maximizing her expected life-time utility. A reasoning similar to that used to derive (10) shows that an interior solution of this decision problem has to satisfy the following first-order condition:

$$\sum_{i=0}^{i=\infty}(\beta\Delta)^i E_t U_{L,t+i}\, l_{t+i}(h) + \sum_{i=0}^{i=\infty}(\beta\Delta)^i E_t \lambda_{t+i}\,(w_t(h)/P_{t+i}) = 0,$$

where $\lambda_{t+i}=U_{C,t+i}$.

Equation (4)) shows that $l_{t+i}(h)=(w_t(h)/W_{t+i})^{1/(\phi-1)} Y_{t+i}/\theta_{t+i}$ holds if the wage $w_t(h)$ is in effect in period t+i (here $Y_{t+i}=\int_0^1 y_{t+i}(s)ds$). Substituting this expression into the above first-order condition, and solving the resulting expression for $w_t(h)$ yields equation (12) in the text.

N.B. Equations (2) and (5) and the fact that $y_{t+i}(s)=d_{t+i}(s)+x_{t+i}(s)$ show that Y_{t+i} can be solved for using the following expression:

$$Y_{t+i}=(1-\alpha)P_{t+i}C_{t+i}\,(P^D_{t+i})^{(1+\nu)/\nu}\,\hat{P}^D_{t+i} + X_{t+i}\,(P^*_{t+i})^{(1+\nu)/\nu}\,\hat{P}^X_{t+i},$$

where $\hat{P}^D_{t+i}=(1-\delta)\sum_{j=0}^{j=\infty}\delta^j(\rho^{\mathcal{D}}_{t+i-j})^{-(1+\nu)/\nu}$, $\hat{P}^X_t=(1-\delta)\sum_{j=0}^{j=\infty}\delta^i(\rho^{\mathcal{X}}_{t+i-j})^{-(1+\nu)/\nu}$.

• DESCRIPTION OF DATA USED TO COMPUTE HISTORICAL STATISTICS (TABLE 1)

Unless otherwise indicated, all data are taken from International Financial Statistics (published by the International Monetary Fund).

Output--Nominal GDP (for Germany: nominal GNP) deflated using domestic consumer price index (CPI). Sample period: 73:Q1-91:Q4.

Consumption--Nominal total private consumption expenditures deflated using CPI. Sample period: 73:Q1-91:Q4.

Hours worked--U.S.: total number of hours worked in non-agricultural sector (series LPHMU from Citibase).
Japan, Germany: total employment in non-agricultural sector multiplied by average weekly hours worked (from Bulletin of Labour Statistics, International Labour Office, ILO).
France: total employment in non-agricultural sector multiplied by average weekly hours worked (sources: ILO; Bulletin Mensuel des Statistiques du Travail, published by INSEE).
U.K.: total employment multiplied by average weekly hours worked (from Employment Gazette, Supplement with Historical Statistics, 1992). This source only provides average hours data at an annual frequency. A quarterly series for average weekly hours is constructed by linear interpolation.
Italy: total employment in the non-agricultural sector (ILO).
Canada: series for period 1975-1991 measures total hours worked (all jobs); for 1973-74: total employment (source: Historical Labor Force Statistics, Statistics Canada, 1991). Series for two sub-periods were multiplicatively spliced together.

The quarterly series for Italy and France pertain to the first month of a given quarter. Japanese series pertain to second month. The ILO

employment series for Italy exhibits seasonality, and it was seasonally adjusted using the Census X-11 procedure (using the EZ-X11 program available from Doan Associates, Evanston, IL.).

Sample period for hours worked series: 73:Q1-91:Q3.

Net exports--defined as *exp-imp/(exp+imp)*, where *exp* and *imp* denote the value of exports and imports (in domestic currency) of goods and services, respectively. Sample period: 73:Q1-91:Q4.

Price level--consumer price index. Sample period: 73:Q1-95:Q1.

Money supply--M1 money stock. The series for U.S. is taken from Citibase (series FM1). Sample period for U.S.: 73:Q1-93:Q3; France: 77:Q4-94:Q4; U.K.: 73:Q1-86:Q4; other countries: 73:Q1-94:Q4.

Nominal interest rate--short term rates from Citibase. U.S.: CD rate (Citibase series FYUSCD); Japan, Germany, France: call money rate (FYJPCM, FYGECM, FYFRCM); U.K.: interest rate on prime bank bills (FYGBBB); Italy: bond yields, credit institutions (FYITBY); Canada: prime corporate paper, 60 days (FYCACP). These interest rates are provided at a monthly frequency by Citibase. Observations for the second month of each quarter are used to construct quarterly series. Sample period: 73:Q1-91:Q4.

Nominal effective exchange rate--MERM effective exchange rate computed by IMF. Sample period: 73:Q1-95:Q1.

Real effective exchange rate--Sample period: 75:Q1-95:Q1. For the period 75:Q1-78:Q4, the real effective exchange rate is based on relative value added deflators, while the real effective exchange rate for 79:Q1-95:Q1 is based on relative consumer price indexes; series for two sub-periods were multiplicatively spliced together.

Nominal U.S. dollar exchange rate--Sample period: 73:Q1-95:Q1.

Real U.S. dollar exchange rate--Based on relative consumer price indexes. Sample period: 73:Q1-95:Q1.

Nominal exchange rate series (bilateral or effective) are measured as domestic currency prices of foreign currency; hence, an increase in the nominal exchange rate of a country represents a nominal depreciation of the domestic currency. Likewise, an increase in the real exchange rate (bilateral or effective) represents a real depreciation.

Table 1. Economic Fluctuations in the Post-Bretton Woods Era

	Country							
Statistic	U.S.	Japan	Germany	France	U.K.	Italy	Canada	Average
Standard deviation (in %):								
Output	2.37	1.49	1.78	1.29	2.21	2.57	2.17	1.85
Consumption	1.98	1.38	1.29	1.05	2.38	1.46	1.57	1.59
Hours	1.76	1.23	1.81	0.80	1.65	0.67	2.32	1.46
Net exports	2.84	4.05	1.39	2.07	2.19	2.78	1.63	2.42
Price level	1.66	1.91	1.05	1.26	2.31	1.75	1.40	1.62
Money supply	1.99	2.15	2.79	2.18	1.38	2.85	4.20	2.50
Nominal interest rate	0.48	0.44	0.42	0.51	0.38	0.52	0.43	0.45
Nominal effective exchange rate	5.86	7.35	3.35	3.81	5.15	4.03	4.02	4.80
Real effective exchange rate	5.15	9.05	2.81	2.85	5.65	3.34	4.30	4.75
Nominal U.S. dollar exchange rate	-	8.94	8.81	9.07	8.93	9.04	2.93	7.95
Real U.S. dollar exchange rate	-	8.93	8.43	8.40	8.54	8.28	3.18	7.63
Correlation with domestic output:								
Consumption	0.92	0.78	0.78	0.28	0.88	0.78	0.84	0.75
Hours	0.76	0.59	0.75	0.35	0.66	0.29	0.63	0.58
Net exports	-0.54	-0.08	-0.14	0.12	-0.19	-0.56	-0.30	-0.24
Price level	-0.77	-0.78	-0.76	-0.75	-0.54	-0.35	-0.48	-0.63
Money supply	0.28	0.26	0.31	0.00	0.39	0.62	0.09	0.27
Nominal interest rate	0.08	-0.28	-0.19	0.11	-0.11	0.51	0.11	0.03
Nominal effective exchange rate	0.11	-0.42	-0.45	-0.12	-0.09	-0.09	-0.06	-0.16
Real effective exchange rate	0.21	-0.31	-0.41	-0.04	-0.01	0.02	0.09	-0.06
Autocorrelation:								
Output	0.89	0.61	0.76	0.80	0.67	0.82	0.86	0.77
Nominal effective exchange rate	0.85	0.76	0.83	0.85	0.78	0.77	0.90	0.82
Real effective exchange rate	0.85	0.85	0.79	0.72	0.77	0.68	0.89	0.79
Correlation between nominal and real effective exchange rate:	0.97	0.97	0.98	0.99	0.95	0.96	0.96	0.97

Note.--Series used for Table are quarterly. All series are logged (with

TABLE 1.--continued
exception of net exports and nominal interest rates) and passed through the Hodrick and Prescott (1980) filter. Nominal interest rates are expressed at a gross quarterly rate prior to filtering. The net exports variable is defined as (*exp-imp*)/(*exp+imp*), where *exp* and *imp* denote, respectively, the value of exports and of imports of goods and services (in domestic currency). See Appendix for detailed information on data. The last column reports arithmetic average of statistics for G7 countries.

TABLE 2. Model Predictions with Predetermined Prices and Wages

Statistics	Money shocks			Productivity shocks		Data
	k=0 (1)	k=2 (2)	k=4 (3)	k=0 (4)	k=4 (5)	(6)
Standard deviation (in %):						
Output	0.01	0.72	1.20	0.70	0.48	1.85
Consumption	0.02	1.09	1.82§	0.31	0.22	1.59
Hours worked	0.01	0.72	1.20§	0.18	0.84	1.46
Net exports	0.02	1.13	1.90§	0.40	0.52	2.42
Price level	1.97§	2.12§	2.14§	0.15	0.12	1.62
Money supply	1.77†	1.77†	1.77†	0.00	0.00	2.50
Nominal interest rate	0.18	0.21	0.42§	0.02	0.03	0.45
Nominal exchange rate	1.97	2.12	2.83	0.39	0.34	4.80
Real exchange rate	0.00	2.17	3.64†	0.54	0.38	4.75
Correlation with domestic output:						
Consumption	0.99	0.99	0.99	0.99	0.65§	0.75
Hours worked	1.00	1.00	1.00	-0.99	0.22	0.58
Net exports	-0.99	-0.99	-0.99	0.99	0.78	-0.24
Price level	-0.51§	-0.51§	-0.63§	-0.99	-0.96	-0.63
Money supply	0.24§	-0.27	0.02	u	u	0.27
Nominal interest rate	-0.99	-0.39	-0.79	-0.99	-0.60	0.03
Nominal exchange rate	-0.51	0.52	0.81	0.99	0.40	-0.16
Real exchange rate	0.63	0.99	0.99	0.99	0.67	-0.06
Autocorrelation:						
Output	0.34	0.40	0.64†	0.67§	0.71§	0.77
Nominal exchange rate	0.74§	0.64†	0.58	0.67†	0.73§	0.82
Real exchange rate	0.67§	0.40	0.64	0.67§	0.76§	0.79
Correlation between nominal and real exchange rate:	-0.99	0.51	0.81	0.99	0.94†	0.97

Table 2.--continued

Statistics	Shocks to foreign price level		Shocks to expected foreign real interest rate		Simultaneous shocks to M, θ, P^*, R		
	k=0 (7)	k=4 (8)	k=0 (9)	k=4 (10)	k=0 (11)	k=4 (12)	Data (13)
Standard deviation (in %):							
Output	0.00	0.73	1.15	0.47	1.34	1.57§	1.85
Consumption	0.00	0.00	0.38	0.14	0.49	1.84§	1.59
Hours worked	0.00	0.73	1.15†	0.47	1.16†	1.71§	1.46
Net exports	0.00	0.38	2.42§	0.89	2.45§	2.20§	2.42
Price level	0.00	0.00	0.44	0.17	2.03§	2.16§	1.62
Money supply	0.00	0.00	0.00	0.00	1.77†	1.77†	2.50
Nominal interest rate	0.00	0.00	0.07	0.04	0.19	0.42§	0.45
Nom. exchange rate	1.62	1.65	1.96	2.16	3.24	3.91§	4.80
Real exchange rate	0.00	0.01	1.52	2.18	1.61	4.25§	4.75
Correlation with domestic output:							
Consumption	u	0.46	-0.99	-0.62	-0.32	0.76§	0.75
Hours worked	u	1.00	1.00	1.00	0.75§	0.85	0.58
Net exports	u	0.99	0.99	0.96	0.92	-0.40§	-0.24
Price level	u	0.67	0.99	0.99	0.14	-0.47§	-0.63
Money supply	u	u	u	u	0.00§	0.01§	0.27
Nominal interest rate	u	0.60	0.99	0.57	0.24§	-0.67	0.03
Nom. exchange rate	u	-0.13§	0.99	-0.18§	0.56	0.40	-0.16
Real exchange rate	u	-0.59	0.99	-0.25§	0.97	0.63	-0.06
Autocorrelation:							
Output	u	0.60	0.58	0.56	0.60†	0.63†	0.77
Nom. exchange rate	0.91	0.91†	0.58	0.56	0.72§	0.63†	0.82
Real exchange rate	u	0.66§	0.58	0.56	0.58	0.62	0.79
Correlation between nominal and real exchange rate:	u	0.62	0.99	0.99	0.60	0.77	0.97

Note.--The model assumes that prices are set 'k' periods in advance.

All simulated series are logged (with exception of net exports and interest rate) and passed through the Hodrick and Prescott (1980) filter. The nominal interest rate is expressed at a gross quarterly rate prior to filtering. In accordance with Table 1, the net exports variable is defined as $(exp-imp)/(exp+imp)$, where $exp \equiv X_t P^X_t e_t$ and $imp \equiv F_t P^*_t e_t$ denote, respectively, the value of exports and of imports, in domestic currency.

The "Data" column shows average (across G7 countries) of historical statistics reported in Table 1 (the exchange rate statistics in the "Data" column pertain to effective exchange rates).

u: correlation is not defined (series with zero variance).

§ (†) indicates that a 95% (99%) confidence interval includes the historical statistic reported in the "Data" column.

The figures in parentheses, (1)-(13), are column numbers.

TABLE 3. Model Predictions with Calvo-type Nominal Rigidities

Statistics	Money shocks	Simultaneous shocks to M,θ,P^*,R	Data
Standard deviation (in %):			
Output	2.00§	2.07§	1.85
Consumption	2.67	2.68	1.59
Hours worked	2.00§	2.17†	1.46
Net exports	2.56§	2.61§	2.42
Price level	0.61	0.62	1.62
Money supply	1.77†	1.77†	2.50
Nominal interest rate	0.33§	0.38§	0.45
Nominal exchange rate	5.45§	6.15§	4.80
Real exchange rate	5.33§	5.78§	4.75
Correlation with domestic output:			
Consumption	0.98	0.95	0.75
Hours worked	1.00	0.91	0.58
Net exports	-0.92	-0.86	-0.24
Price level	0.29	0.28	-0.63
Money supply	0.57	0.56	0.27
Nominal interest rate	-0.59	-0.45	0.03
Nominal exchange rate	0.99	0.80	-0.16
Real exchange rate	0.98	0.87	-0.06
Autocorrelation:			
Output	0.71§	0.73§	0.77
Nominal exchange rate	0.68†	0.69†	0.82
Real exchange rate	0.68§	0.66§	0.79
Correlation between nominal and real exchange rate:	0.99	0.95§	0.97

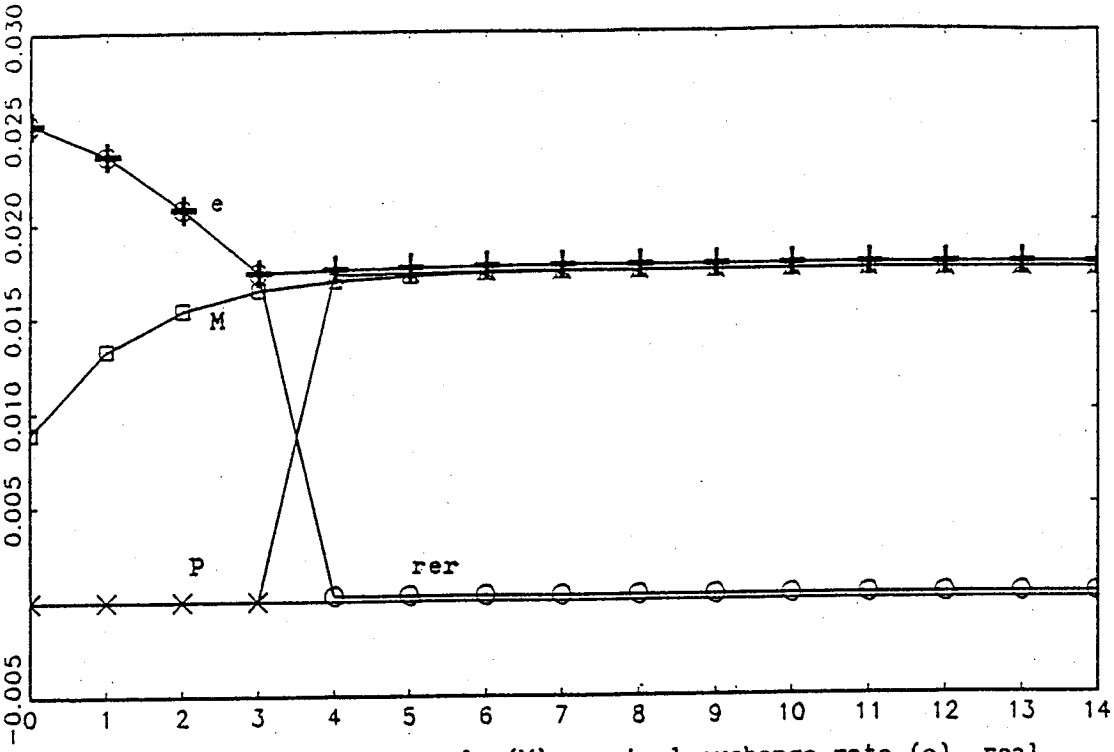
Note.--Average time between price and wage changes is 12.5 quarters ($\delta=\Delta=0.92$).

All series are logged (with exception of net exports and interest rate) and passed through the Hodrick and Prescott (1980) filter. The nominal interest rate is expressed at a gross quarterly rate prior to filtering. In accordance with Table 1, the net exports variable is defined as $(exp-imp)/(exp+imp)$, where $exp \equiv X_t P_t^X e_t$ and $imp \equiv F_t P_t^* e_t$ denote, respectively, the value of exports and of imports, in domestic currency.

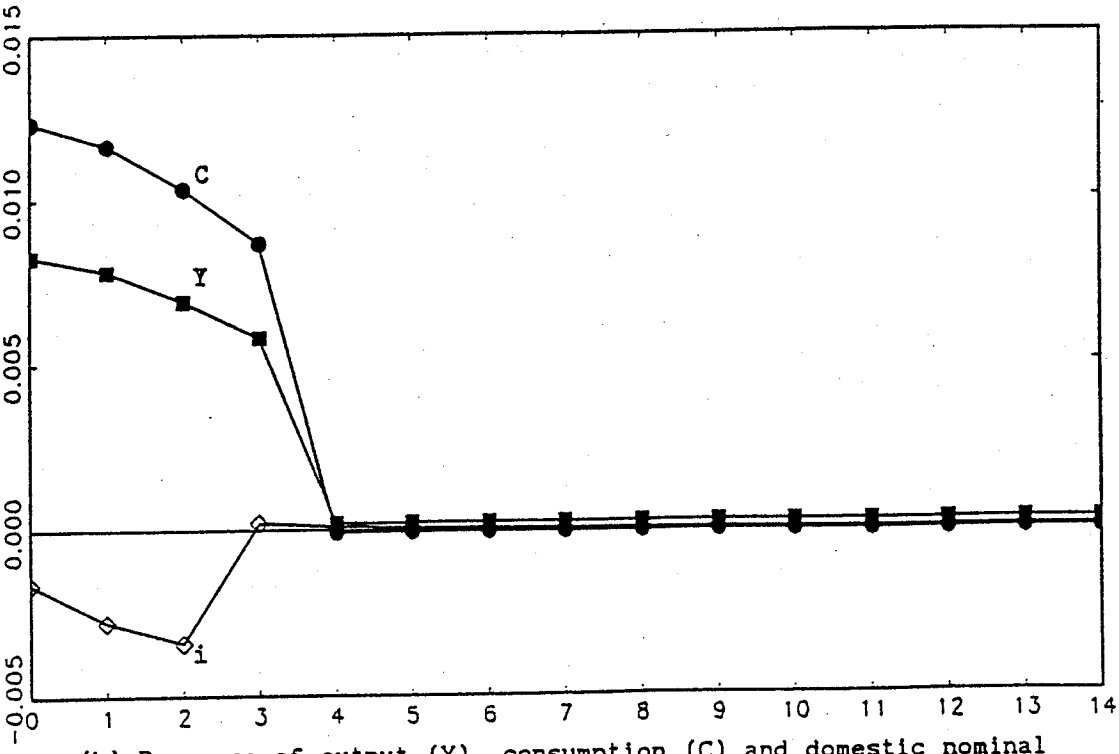
"Data" column shows average (across G7 countries) of historical statistics reported in Table 1 (the exchange rate statistics in the "Data" column pertain to effective exchange rates).

§ (†) indicates that a 95% (99%) confidence interval includes the historical statistic reported in the "Data" column.

Figure 1



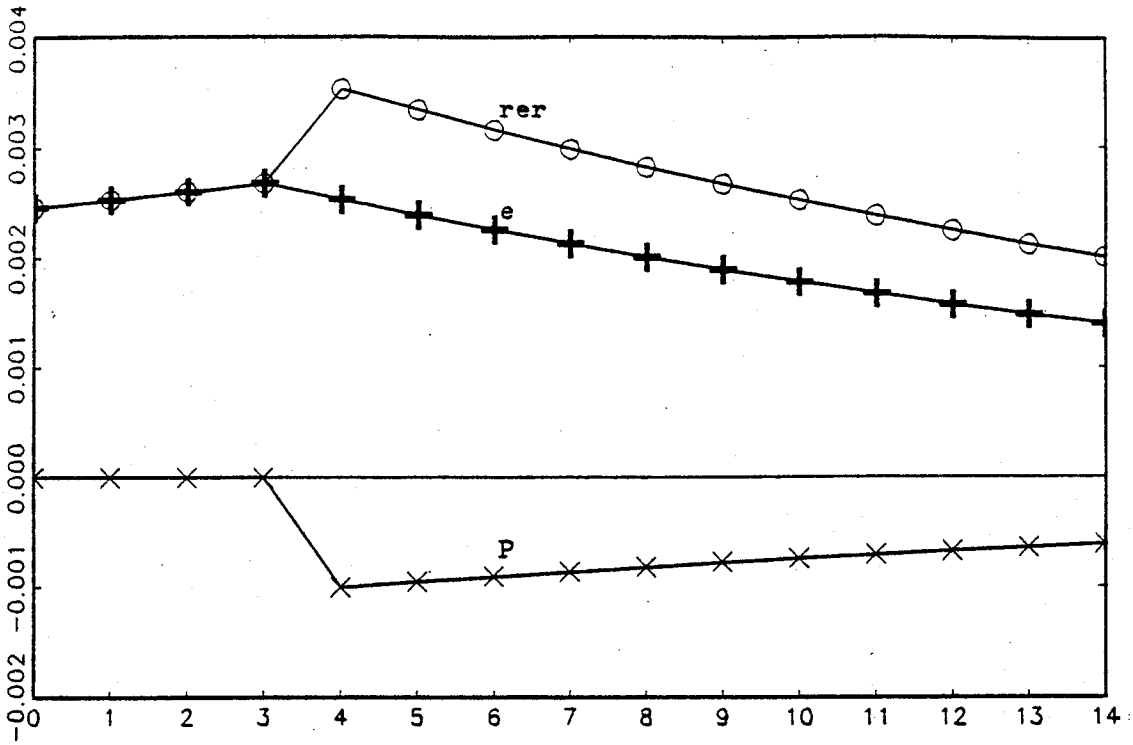
(a) Response of money supply (M), nominal exchange rate (e), real exchange rate (rer) and domestic price level (P).



(b) Response of output (Y), consumption (C) and domestic nominal interest rate (i).

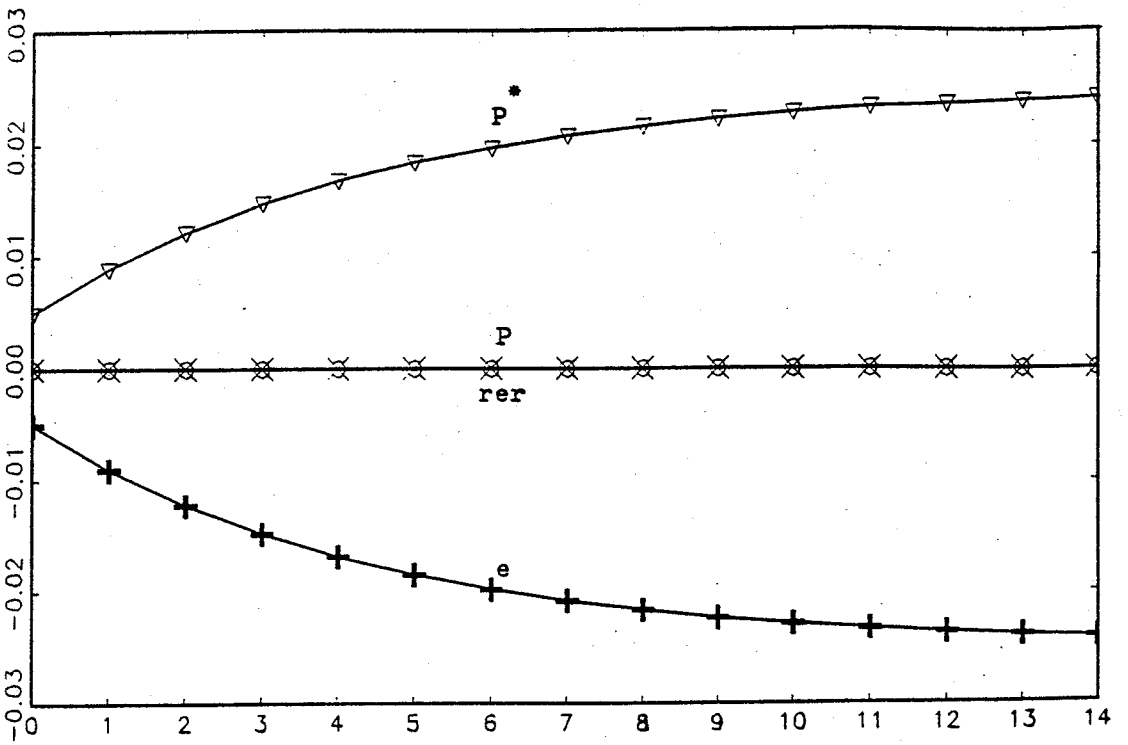
Prices and wages set 4 periods in advance. Responses to a 1 standard deviation (i.e. 0.89%) innovation to money supply process. Response of interest rate expressed as difference from steady state; responses of other variables shown as relative deviations from steady state. Money supply response (Panel (a)) pertains to end of period money stocks. Abscissa: quarters after shock.

Figure 2



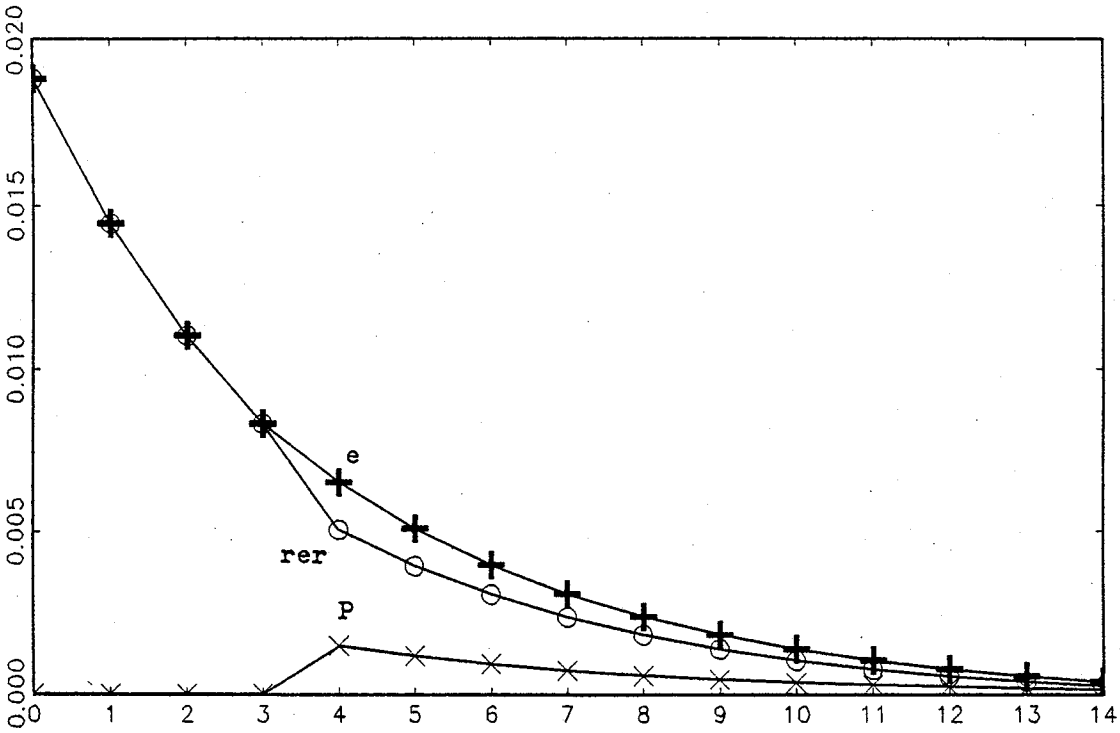
Prices and wages set 4 periods in advance. Effect of a 1 standard deviation (i.e. 0.7%) innovation to domestic labor productivity on: nominal exchange rate (e), real exchange rate (rer) and domestic price level (P). Responses expressed as relative deviations from steady state. Abscissa: quarters after shock.

Figure 3

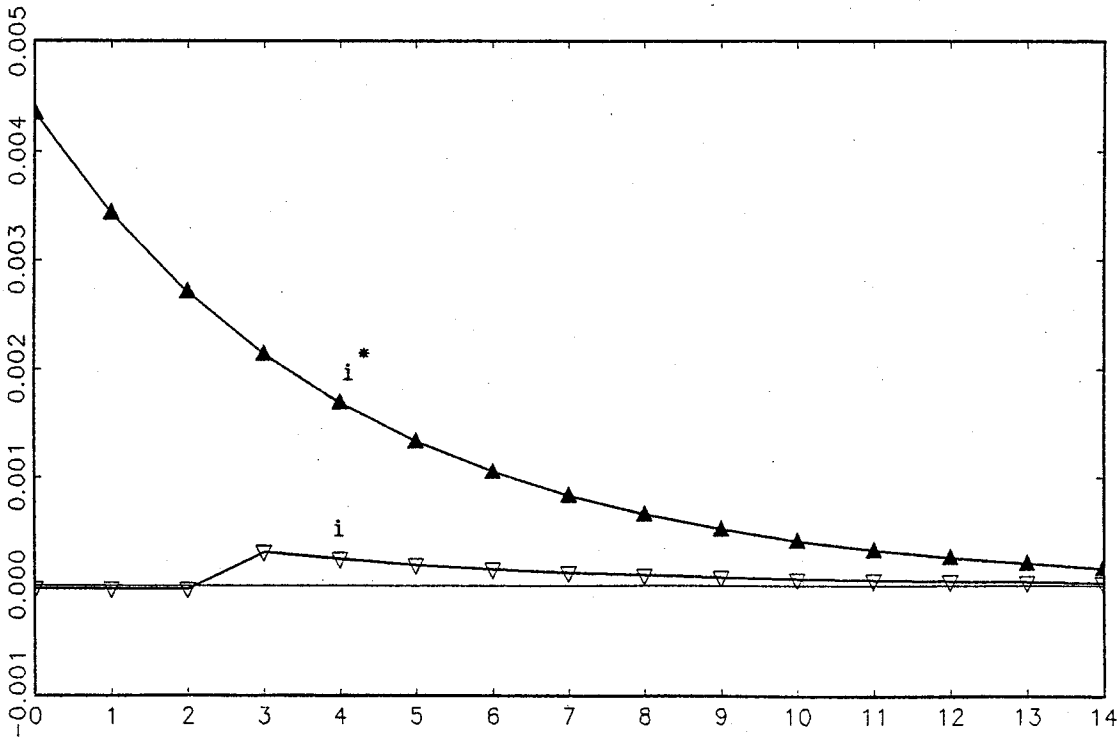


Prices and wages set 4 periods in advance. Effect of a 1 standard deviation (i.e. 0.5%) innovation to foreign price level on: foreign price level (P^*), nominal exchange rate (e), real exchange rate (rer) and domestic price level (P).
Responses expressed as relative deviations from steady state. Abscissa: quarters after shock.

Figure 4



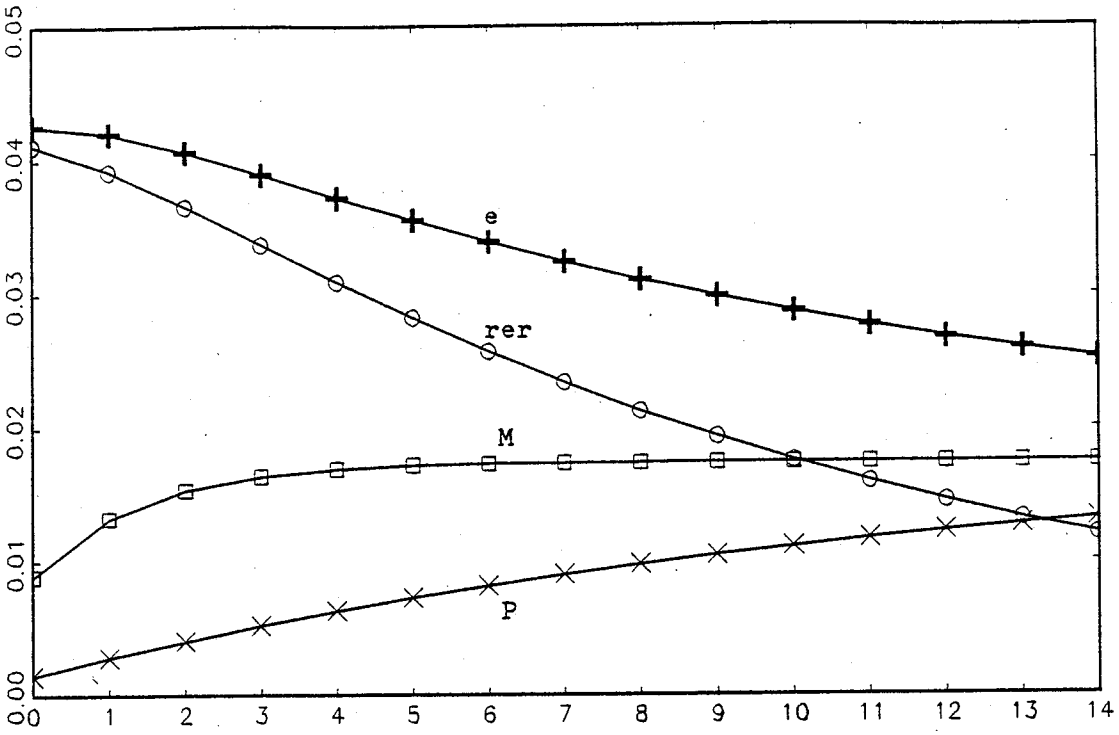
(a) Response of nominal exchange rate (e), real exchange rate (rer) and domestic price level (P).



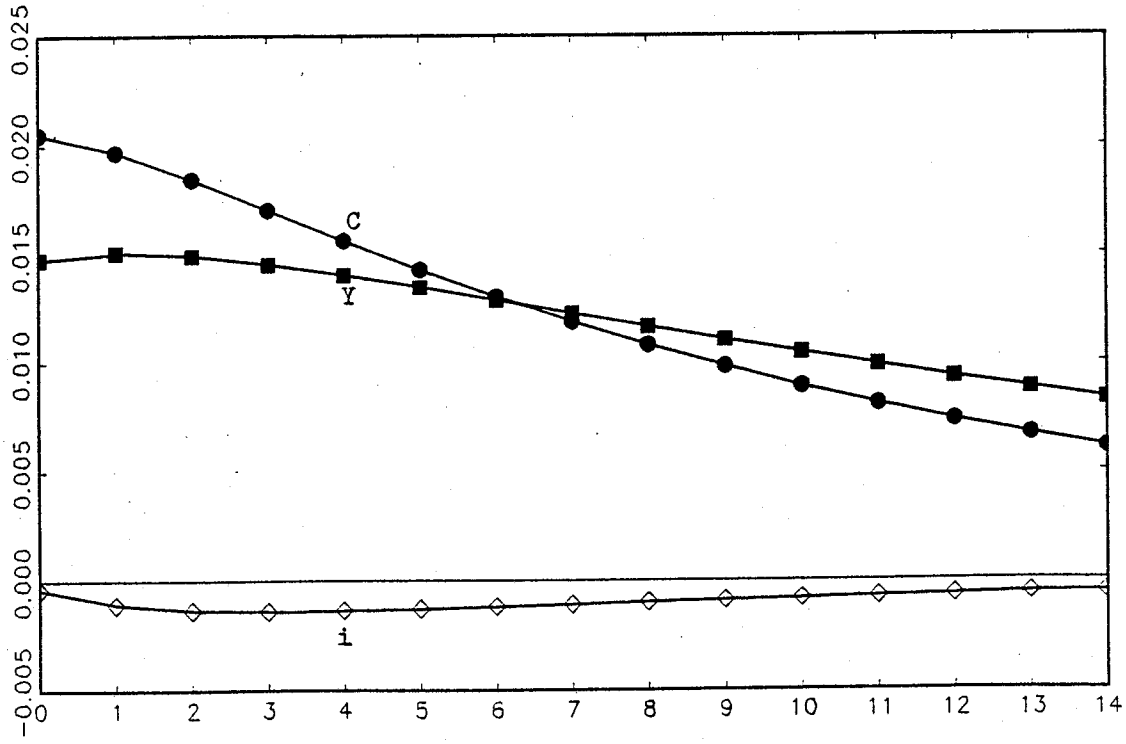
(b) Response of foreign nominal interest rate (i^*) and of domestic nominal interest rate (i).

Prices and wages set k=4 periods in advance. Responses to innovation that raises expected real foreign interest rate by 1 standard deviation (i.e. 0.43 percentage points). Response of interest rate expressed as difference from steady state; responses of other variables shown as relative deviations from steady state. Abscissa: quarters after shock.

Figure 5



(a) Response of money supply (M), nominal exchange rate (e), real exchange rate (rer) and domestic price level (P).



(b) Response of output (Y), consumption (C) and domestic nominal interest rate (i).

Model with Calvo-type price and wage adjustment. Responses to a 1 standard deviation (i.e. 0.89%) innovation to money supply process. Response of interest rate expressed as difference from steady state; responses of other variables shown as relative deviations from steady state. Money supply response (Panel (a)) pertains to end of period money stocks. Abscissa: quarters after shock.

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