An international economy with country-specific money and productivity growth processes

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Abstract. This paper analyses a stochastic international growth model with money and country-specific forcing processes for productivity and money growth rates. Monies are required, owing to cash-in-advance constraints for consumption goods, but the liquidity constraints need not be binding for all periods. An individual can trade claims on future currency units for both countries through government bond markets. Each country specializes in the production of one of the goods, but individual agents can invest, subject to installation costs, in any available technology. The forcing processes are calibrated to a sample of U.S. and Canadian data. An equilibrium *growth* solution is computed numerically using the Marcet method of parameterized expectations. The interdependence implied by the model is illustrated by a series of impulse responses. Particular attention is focused on the asymmetry of the forcing processes across countries and the interaction between the real and the nominal components of the model.

Une économie internationale avec des processus de monnaie et de croissance de productivité qui sont particuliers aux pays. Ce mémoire analyse un modèle stochastique de croissance d'une économie internationale monétarisée où chaque pays est encastré dans des processus qui définissent les taux de croissance de la monnaie et de la productivité. La monnaie est requise pour faire face aux contraintes de paiement d'avance pour les biens de consommation mais les contraintes de liquidité ne jouent pas à plein pour toutes les périodes. Un individu peut utiliser les marchés des obligations des gouvernements des deux pays pour faire le commerce de titres permettant de se donner accès à des sommes de monnaie pour un moment futur. Chaque pays se spécialise dans la production d'un des biens mais les individus peuvent investir dans n'importe quelle technologie disponible pour autant qu'ils peuvent payer les coûts d'installation. Les processus que imposent la croissance de la monnaie et de la

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productivité ont été calibrés à partir d'un échantillon de données canadiennes et américaines. On calcule une solution numérique d'équilibre de croissance à l'aide de la méthode des anticipations paramétrées de Marcet. L'interdépendance impliquée par le modèle est illustrée à l'aide d'une série de réponses à des chocs. Les auteurs portent une attention particulière à l'asymmétrie des processus qui imposent la croissance de la monnaie et de la productivité entre pays et à l'interaction entre les composantes réelles et nominales du modèle.

I. INTRODUCTION

This paper analyses a stochastic international growth model with money. By integrating stochastic growth with the intertemporal pricing of nominal assets in a model in which money has an explicit role, and by allowing country-specific forcing processes for productivity and money growth rates, this international artificial economy extends the existing literature in several ways.

First, we build on recent international *real* business cycle models. For example, Backus, Kehoe, and Kydland (1992) construct an international real business cycle model in which countries have different technology shocks. They also analyse the effect of allowing international borrowing. Baxter and Crucini (1990) focus on various savings/investment correlations. Head (1990) analyses a multi-country real growth model that distinguishes between tradable and non-tradable goods. Stockman and Tesar (1990) concentrate on the open-economy aspects of real business cycles in a two-country model that also incorporates traded and non-traded goods sectors. They find that shocks to tastes are required to replicate some features of the data.

Our international monetary growth model extends this real business cycle literature by incorporating money and also by introducing steady-state growth with country-specific forcing processes for both money and productivity growth rates. These processes exhibit cross-country correlations but also are allowed to have asymmetric international diffusion rates as well as different degrees of persistence across countries. The productivity shocks are parameterized as being integrated in levels but stationary in growth rates. This structure generates processes for aggregate quantities that are integrated in levels as suggested by historical data.

The structure of endogenous production and steady-state growth also builds on the international monetary *endowment* economy models, for example, Bansal (1989), Hodrick (1989), Lucas (1982), Macklem (1991), and Svensson (1985a). As in many closed-economy stochastic general equilibrium monetary models – for example, Coleman (1988); Cooley and Hansen (1989); Giovannini (1989); Labadie (1989); Hodrick, Kocherlakota, and Lucas (1991); Lee (1989); and Svensson (1985b) – money enters the model through cash-in-advance constraints (CIA).

In our international case, consumption goods produced in a particular country must be purchased with that country's currency. The timing of markets and arrival of new information is that of Svensson, which leads to the possibility of non-binding liquidity constraints. In order to get explicit solutions, most models in this genre impose a strict equality for the liquidity constraints. Using the Marcet (1989) numerical solution technique, we are able to solve the model with the liquidity constraints binding in some periods but not others.[1] As in Hodrick, Kocherlakota, and Lucas (1991), these constraints are invariably binding for our baseline parameterization. Therefore, we also solve the model with a counter-factual parameter setting (lower domestic money growth), which leads to a significant number of realizations of non-binding liquidity constraints. This feature is also asymmetric across countries. These simulations give some indication of the impact of scarce money and the implications of allowing the velocity of money to vary in CIA models.[2]

In this version of the model there is no government spending on goods and no taxation, so that the governments' budget constraints equate net changes in stocks of government bonds (claims on future currency units) with the exogenous innovations to the respective money supplies. This method of injecting new money into the economies and the opportunity to trade in markets which allow diversification of risk associated with monetary innovations is one way in which our model differs from the international monetary growth model of Cho and Roche (1991).[3]

In our model each country specializes in the production of one of the goods. This output can be either consumed or reinvested subject to an installation cost. Individual agents can invest in any available technology by setting up their own firm in either country or both countries (our substitute for equity markets). Agents can also import or export investment goods such that they are allocated to the most productive technology. This assumption that investment goods are perfect substitutes implies that purchasing power parity will obtain in equilibrium. We also report some results for a version of the model in which agents must use output from a particular technology to augment the capital for that technology (no substitutability of country 1 and country 2 goods for investment purposes). Such a restriction on the international mobility of investment goods can result in deviations from absolute purchasing power parity in equilibrium.

The moments of the forcing processes are calibrated to a sample of U.S. and Canadian data. The structure of the model is such that we are able to compute a perfectly pooled equilibrium solution for this stochastic international monetary growth model. That solution is computed numerically, using the Marcet (1989) method of parameterized expectations, and the moments of the endogenous variables are compared with those of the actual data.

The interdependence implied by the model is illustrated by a series of impulse responses. Particular attention is focused on the asymmetry of the forcing processes across countries and on the interaction between the real and nominal components of the model. For example, with endogenous production, we find that monetary fluctuations cause business cycle behaviour in consumption and investment and the effect on goods and asset prices can be substantially different from that in endowment models (e.g., Svensson 1985a, b). We also find that the effects of

1 Christiano and Fisher (1994) discuss alternative algorithms for numerical solutions in the presence of constraints that are not always binding.

2 An alternative method of addressing such issues is to extend the CIA structure to incorporate money using a transactions costs structure, as in Bansal (1989) and Marshall (1992).

3 Other differences are that we introduce country-specific forcing processes and allow diversification of risk associated with productivity shocks.

monetary policy are transmitted to other countries via exchange rate and terms-of-trade adjustments.

Section II outlines the structure of our international model including the optimization problem faced by private-sector agents, and section III summarizes a stationary equilibrium. Section IV and tables 1 and 2 summarize the calibration of the preference and technology parameters as well as those of the forcing processes. Section V and table 3 report various summary statistics for the historical sample and for the artificial economy. Section VI and the figures illustrate some interdependencies implied by the model using impulse response plots. Section VII concludes with some comments about shortcomings and work to be done.

II. STRUCTURE OF THE INTERNATIONAL ARTIFICIAL ECONOMY AND AGENT OPTIMIZATION

1. Market and information structure

We construct a two-country international growth model with money and bonds. There are two goods. Each country specializes in the production of one of the goods. There is trade in goods, monies, and bonds between countries.

Goods can be either consumed or invested in physical capital accumulation. National goods are imperfect substitutes from the perspective of consumption. Allocating output to augment or maintain capital stock involves installation costs. In the main version of our model, output from a particular country can be invested in either country. We refer to this version as the cross-investment (CI) case. We also report some results for a no-cross-investment (NCI) version in which goods installed as capital stock in a particular country must be produced in that country. That is, in the CI version investment goods are perfect substitutes, whereas in the NCI version the substitutability of goods produced in different countries is zero for investment purposes.

Factor markets are not explicit. Production is by self-employed entrepreneurs such that revenue is imputed to the capital and managerial/labour factors. We abstract from equity market issues by allowing agents to invest in any available technology by setting up their own firms in either or both countries.

Country-specific monies are required in the model by the cash-in-advance (CIA) restrictions that all purchases of the goods for consumption must be paid for in the currency of the producing country. The trading and information structure is the same as that in Svensson (1985b). Goods markets open at the beginning of the period when all information regarding realizations of the stochastic variables during the period is revealed. Asset markets open at the end of the period. In the goods market the agent uses money carried over from the previous period's asset markets to purchase desired levels of the consumption goods. This structure introduces a potential precautionary demand for money, since the amount of money available to purchase consumption goods in any period must be determined in the previous period before the uncertainty concerning the state of the world is resolved. The solution technique we use allows the CIA constraints to be binding in some periods but not others.

2. A government's problem

The assumption that agents can set up factories in either country allows them to share risk associated with technological shocks by diversification of production. Analogously, we allow agents to share risk associated with the country-specific money rates by trading bonds issued by the governments of both countries. These one-period discount bonds pay one unit of the country's currency in the following period.[4]

We abstract from fiscal policy and do not distinguish between governments and central banks. In this case, the budget constraint for the government of country i is

$$(M_{it+1} - M_{it}) + (P^b_{it}B_{it+1} - B_{it}) = 0, \qquad i = 1, 2, \tag{1}$$

where M_i and B_i are the aggregate stocks of money and government bonds, respectively, and P^b_i is the price of the discount bond. This extreme simplification of the role of governments implies that, given the exogenous forcing processes for the growth rates of country-specific monies, governments will issue debt such that their budget constraints given in (1) obtain.

3. A private sector agent's optimization problem

Resident in each country is a continuum of identical, infinitely lived agents or households that integrate to a representative agent for each country. Where necessary, variables associated with a particular country are subscripted with a 1 or a 2, while variables associated with a particular representative agent are superscripted with a d or an f. Lower-case variables are associated with a representative agent. This subsection describes the optimization problem faced by the domestic representative agent, who is assumed to be resident in country 1.

a. Consumption

Each domestic agent maximizes expected discounted utility over an infinite horizon,

$$E_0 \left\{ \sum_{t=0}^{\infty} \beta^t u(c_{1t}, c_{2t}) \right\}, \tag{2}$$

where c_1 and c_2 are the individual's consumption of domestic and foreign goods, respectively. Intraperiod utility is specified as a homothetic function of a bundle of domestic and foreign goods. That is,

$$u(c_{1t}, c_{2t}) = \frac{(c^{\sigma}_{1t}c^{1-\sigma}_{2t})^{(1-\gamma)}}{1-\gamma}, \qquad [= \log(c^{\sigma}_{1t}c^{1-\sigma}_{2t}) \text{ if } \gamma = 1], \tag{2'}$$

in which γ is the coefficient of relative risk aversion, $1/\gamma$ is the elasticity of intertemporal substitution, and σ is the share of country 1's goods in the domestic agent's consumption bundle.

4 Hodrick (1989) introduces state-contingent government bonds.

As stipulated above, all purchases of goods for consumption must be paid for in the currency of the producing country. Denoting P_{1t} and P_{2t} as the own-currency prices of domestic and foreign goods, respectively, this restriction implies cash-in-advance (CIA) constraints.

$$P_{1t}c_{1t} \leqq m_{1t}, \tag{3}$$

$$P_{2t}c_{2t} \leqq m_{2t}, \tag{4}$$

In conformity with the market and information structure described above, the m_{it}, $i = 1, 2$, are the domestic agent's country 1 and country 2 money balances carried over from asset market transactions at the end of period $t-1$ and thus available at the start of period t to purchase desired levels of the consumption goods.

b. Production

Output produced in country 1 by the domestic agent is denoted y_1 while that produced by the domestic agent in the foreign country is denoted y_2. The production technologies available in the two countries are given by

$$y_{1t} = f_1(k_{1t-1}, \theta_{1t}) = \theta_{1t} k_{1t-1}^{\alpha_1}, \tag{5}$$

$$y_{2t} = f_2(k_{2t-1}, \theta_{2t}) = \theta_{2t} k_{2t-1}^{\alpha_2}, \tag{6}$$

where k_{it-1} is the domestic agent's capital stock in place in country i at the end of period $t-1$ and thus available for production in that country in period t, α_i is the capital share parameter in country i, and θ_i is the level of the productivity shock realized in period t in country i.

Output not sold for consumption is invested in the available production technologies. New investment becomes productive in the period following the decision to invest. The capital stock depreciates at a rate of $1-\delta$ per period. Gross investment in country i in period t is denoted i_{it}, so that

$$i_{1t} = k_{1t} - \delta k_{1t-1}, \tag{7}$$

$$i_{2t} = k_{2t} - \delta k_{2t-1}. \tag{8}$$

Investment is costly to install. In particular, a decision in period t to invest i_t units of capital for use in period $t+1$ requires $(i_t + \phi(i_t^2/2\delta k_{t-1}))$ units of output in period t. This formulation means that the marginal cost of investment is increasing in the rate of investment. We define output net of installation costs as y^n. That is,

$$y_{it}^n = y_{it} - \phi \frac{i_{it}^2}{2\delta k_{it-1}}, \qquad i = 1, 2. \tag{9}$$

We assume that *installed* capital cannot be consumed. In the version of our model that allows cross-investment (CI), output from a particular country can be invested in either country. In this case, there is a resource constraint on investment,

$$q_{1t} + q_{2t} = i_{1t} + i_{2t}, \tag{10}$$

in which q_1 and q_2 are investments goods available from home and foreign production respectively, while i_1 and i_2 are the desired allocations of those goods. In the no-cross-investment (NCI) version of our model, goods installed as capital stock in a particular country must be produced in that country so that there is no distinction between q_{it} and i_{it} in that case.

c. An agent's budget constraint and choice set

Given initial endowments of physical and financial assets, the domestic representative agent maximizes (1) by choosing,

$$z_t \equiv \{c_{1t}, c_{2t}, q_{1t}, q_{2t}, i_{1t}, i_{2t}, m_{1t+1}, m_{2t+1}, b_{1t+1}, b_{2t+1}\}_{t=1}^{\infty},$$

subject to, for all $t = 1, \infty$, the production possibilities given by (5) and (6), the CIA constraints given by (3) and (4), and the investment installation and resource constraints in (7), (8), (9), and (10). In particular, the domestic agent's period-t budget constraint can be expressed as

$$\begin{aligned} &P_{1t}c_{1t} + S_tP_{2t}c_{2t} + P_{1t}q_{1t} + S_tP_{2t}q_{2t} + m_{1t+1} + S_tm_{2t+1} + P_{1t}^b b_{1t+1} + S_tP_{2t}^b b_{2t+1} \\ &\leqq P_{1t}\left(\theta_{1t}k_{1t-1}^{\alpha_1} - \frac{\phi i_{1t}^2}{2\delta k_{1t-1}}\right) + S_tP_{2t}\left(\theta_{2t}k_{2t-1}^{\alpha_2} - \frac{\phi i_{2t}^2}{2\delta k_{2t-1}}\right) \\ &\qquad + m_{1t} + S_tm_{2t} + b_{1t} + S_tb_{2t}, \qquad (11) \end{aligned}$$

where S_t, the exchange rate, is the price of foreign currency in terms of domestic currency; P_{1t}^b and P_{2t}^b are the own-currency prices of a domestic and foreign government bond, respectively, which promise to pay one unit of the corresponding currency in period $t+1$. Note that b_{it} are the number of units of country i bonds that this agent redeems in period t. Recall that the m_{it} are the country i money balances carried over from period $t-1$ to period t that are available to this agent to purchase goods in period t.

4. Structure of the forcing processes and the state of the world economy

Each agent's choices are conditional upon her own past actions and information about the aggregate economy. The state of the economy at the beginning of time t is described by the beginning of period capital and money stocks, the current period realizations of the technology and money growth rates, and the stochastic processes governing the evolution of the technology and money growth rates.

The stochastic processes for the forcing variables are modelled as AR1 processes with cross-country correlations. Thus, letting $\theta_{it}/\theta_{it-1} \equiv \nu_{it}$ and $M_{it+1}/M_{it} \equiv \omega_{it}$ be the country i growth factors for technology and money, respectively, with

$$X_\nu \equiv \begin{pmatrix} \ln \nu_1 \\ \ln \nu_2 \end{pmatrix} \quad \text{and} \quad X_\omega \equiv \begin{pmatrix} \ln \omega_1 \\ \ln \omega_2 \end{pmatrix},$$

then the bivariate vector AR1 processes for productivity growth and money growth are

$$X_{\nu t+1} = A_\nu + B_\nu X_{\nu t} + \epsilon_{\nu t+1},$$
$$X_{\omega t+1} = A_\omega + B_\omega X_{\omega t} + \epsilon_{\omega t+1}, \tag{12}$$

in which the A_j and ϵ_j, $j = \nu, \omega$, are two-element vectors, and the B_j, $j = \nu, \omega$, are two-by-two non-symmetric matrices. For the moment, we do not allow contemporaneous correlation between the shocks-to-productivity growth rates and those to money growth rates. On the other hand, productivity shocks may be correlated across countries, as may those for money; that is,

$$\begin{pmatrix} \epsilon_{\nu 1} \\ \epsilon_{\nu 2} \end{pmatrix} \sim \text{NID}(0, \Sigma_\nu), \quad \begin{pmatrix} \epsilon_{\omega 1} \\ \epsilon_{\omega 2} \end{pmatrix} \sim \text{NID}(0, \Sigma_\omega),$$

with non-diagonal Σ_ν and Σ_ω.

5. *Stationarity-inducing transformation*

Given that the stochastic processes governing money creation and technological innovation are integrated in levels, the neoclassical model implies that consumption, investment, and output will also be integrated. The approach to solving a model with integrated driving processes is to calibrate the forcing processes in terms of their growth factors, as in (12), and to transform the system to induce stationarity. We divide real quantity variables by their productivity factor, nominal quantities by the appropriate money supply, and goods prices by the ratio of the money supply and the productivity factor. All transformed variables are indicated with an overline, for example,[5] $\bar{P}_{it} \equiv P_{it}\theta_{it}^{1/1-\alpha_i}/M_{it}$, $\bar{K}_{it} \equiv K_{it}/\theta_{it}^{1/1-\alpha_i}$, $\bar{B}_{it+1} \equiv B_{it+1}/M_{it}$, $\bar{M}_{it+1} \equiv M_{it+1}/M_{it}$ and $\bar{S}_t \equiv S_t M_{2t}/M_{1t}$.

With freely mobile capital, all quantity variables of the two economies will have a common long-run growth rate. Given the exogenous, and potentially asymmetric, processes for θ_1 and θ_2, this means choosing α_1 and α_2 so that the implied long-run growth rates for country 1 and country 2 variables are the same; that is, $\nu_{1\infty}^{1/1-\alpha_1} = \nu_{2\infty}^{1/1-\alpha_2}$, where $\nu_{1\infty}$ and $\nu_{2\infty}$ are long-run growth rates of the technological processes for θ_1 and θ_2, respectively.

6. *Solution to a private-sector agent's problem*

The vector of information about the state of the economy at time t is

$$\Omega_t = (K_{1t-1}, K_{2t-1}, \theta_{1t-1}, \theta_{2t-1}, \nu_{1t}, \nu_{2t}, M_{1t}, M_{2t}, \omega_{1t}, \omega_{2t}).$$

5 Normalization of the consumption variables in the agents' utility functions also requires transforming their subjective discount factors. Thus

$$\hat{\beta} = \beta\left(\nu_1^{\frac{\sigma}{1-\alpha_1}} \nu_2^{\frac{1-\sigma}{1-\alpha_2}}\right)^{1-\gamma}.$$

In terms of variables that have been transformed to obtain stationarity, the value function of an individual agent satisfies

$$V(\bar{k}_{1t-1}, \bar{k}_{2t-1}, \bar{m}_{1t}, \bar{m}_{2t}, \bar{b}_{1t}, \bar{b}_{2t}, \Omega_t) = \max_{\bar{z}_t} \left\{ \frac{(\bar{c}_{1t}^{\sigma}, \bar{c}_{2t}^{1-\sigma})^{1-\gamma}}{1-\gamma} + E_t[\bar{\beta}_{t+1} V(\bar{k}_{1t}, \bar{k}_{2t}, \bar{m}_{1t+1}, \bar{m}_{2t+1}, \bar{b}_{1t+1}, \bar{b}_{2t+1}, \Omega_{t+1})|\Omega_t] \right\}, \quad (13)$$

subject to transformed versions of the budget constraint, of the CIA constraints and of the resource constraints on domestic and foreign investment. A complete solution of an agent's problem for the cross-investment (CI) version of the model, including definitions of the transformed variables and first-order conditions, appears in appendix A.1 of Ricketts and McCurdy (1991).

III. A STATIONARY COMPETITIVE EQUILIBRIUM

An equilibrium in the transformed variables consists of stochastic processes for the states,

$$\Omega_t = \{\bar{K}_{it-1}, \theta_{it-1}, \nu_{it}, \bar{M}_{it}, \omega_{it};\ i = 1, 2\}, \qquad t = 1, \infty; \quad (14)$$

for the choice variables,

$$\{\bar{C}_{it}(\Omega_t), \bar{I}_{it}(\Omega_t), \bar{Q}_{it}(\Omega_t), \bar{M}_{it+1}(\Omega_t), \bar{B}_{it+1}(\Omega_t);\ i = 1, 2\}, \quad t = 1, \infty; \quad (15)$$

and for the endogenous prices,

$$\{\bar{P}_{it}(\Omega_t), P_{it}^{b}(\Omega_t), \bar{S}_t;\ i = 1, 2\}, \qquad t = 1, \infty; \quad (16)$$

such that

i. given (14) and (16), the choices for the domestic and foreign representative agents,

$$\bar{z}_t^j \equiv \{\bar{c}_{it}^j, \bar{i}_{it}^j, \bar{q}_{it}^j, \bar{m}_{it+1}^j, \bar{b}_{it+1}^j;\ i = 1, 2\}, \qquad j = d, f \text{ and } t = 1, \infty;$$

satisfy the optimization program described in section II.6 above;

ii. the government budget constraints are satisfied for all t; and

iii. the markets for money, bonds and goods clear.

The assumptions that the preferences of the representative agents for countries 1 and 2 are identical, that their initial endowments of physical and financial assets are the same, in combination with the assumed market structure that allows diversification of risks,[6] implies that their optimal choices will be identical in a perfectly

6 That is, agents have access to the technologies in both countries and can trade claims on future money issued by both countries.

pooled equilibrium. In this case, $\bar{z}_t^d(\Omega_t) = \bar{z}_t^f(\Omega_t) = \bar{Z}(\Omega_t)/2$ for each z, where z is an individual demand for a commodity or asset and Z is an aggregate demand. Then market clearing conditions can be expressed as aggregate demand equal to aggregate supply; that is, for money markets:

$$\bar{M}_{it+1}(\Omega_t) = \omega_{it} \equiv \frac{M_{it+1}}{M_{it}}, \qquad i = 1, 2; \tag{17}$$

for bond markets:

$$\bar{B}_{it+1}(\Omega_t) = \bar{B}_{it+1} \equiv B_{it+1}/M_{it}, \qquad i = 1, 2; \tag{18}$$

and for goods markets:

$$\bar{C}_{it}(\Omega_t) + \bar{Q}_{it}(\Omega_t) = \bar{Y}_{it}^n, \qquad i = 1, 2. \tag{19}$$

The world budget constraint (Walras's Law), the budget constraints for the two governments, and the six market equilibrium conditions reduce to five independent equilibrium conditions in the five prices (16).

In the CI version of the model, since aggregate investment goods produced must add up to those allocated across countries, that is,

$$\bar{Q}_{1t} + \bar{Q}_{2t}\rho_t = \bar{I}_{1t} + \bar{I}_{2t}\rho_t, \;\; \rho_t = \theta_{2t}^{1/1-\alpha_2}/\theta_{1t}^{1/1-\alpha_1}, \tag{20}$$

combined with the aggregate budget constraints and the market equilibrium conditions, implies that purchasing power parity obtains in goods; that is,

$$\rho_t\bar{P}_{1t} = \bar{S}_t\bar{P}_{2t}. \tag{21}$$

Absolute purchasing power parity will not obtain, in general, in the NCI version of the model.

The simplifications that lead to a perfectly pooled equilibrium will result in the two economies' being indistinguishable in some respects. For example, even with the heterogeneity due to country-specific forcing processes, in the CI version of the model aggregate consumption and GNP will be perfectly correlated across the two countries. On the other hand, GDP, capital stocks, investments, prices, and interest rates will differ across the countries. The exchange rate and exchange rate risk will, of course, be influenced by these heterogeneities. In equilibrium, the trade and current account balances[7] will reflect trade in goods and assets between the representative agents' domestic and foreign operations.

7 The current account balance can be measured by the change in the net asset positions across countries. Of course, this balance will be dependent on the particular financial asset market structure included in the model.

The pooled equilibrium allowed us to equate individual demands with equal shares of economy-wide aggregates, which we combine with an individual's first-order conditions to obtain the equilibrium Euler conditions. Appendix A.2 in Ricketts and McCurdy (1991) does so in detail. Eight of these conditions associated with the transformed system are reproduced below for purposes of interpretation.

$$\lambda_t \bar{P}_{1t}\left[1+\frac{\phi \bar{I}_{1t}\nu_{1t}^{1/1-\alpha_1}}{\delta \bar{K}_{1t-1}}\right] = E_t \bar{\beta}_{t+1}\lambda_{t+1}\bar{P}_{1t+1} \left[\frac{\alpha_1 \bar{K}_{1t}^{\alpha_1-1}}{\nu_{1t+1}^{\alpha_1/1-\alpha_1}} + \frac{\phi \bar{I}_{1t+1}^2 \nu_{1t+1}^{1/1-\alpha_1}}{2\delta \bar{K}_{1t}^2} + \frac{\delta}{\nu_{1t+1}^{1/1-\alpha_1}} + \frac{\phi \bar{I}_{1t+1}}{\bar{K}_{1t}}\right] \tag{22}$$

$$\lambda_t \bar{S}_t \bar{P}_{2t}\left[1+\frac{\phi \bar{I}_{2t}\nu_{2t}^{1/1-\alpha_2}}{\delta \bar{K}_{2t-1}}\right] = E_t \bar{\beta}_{t+1}\lambda_{t+1}\bar{S}_{t+1}\bar{P}_{2t+1} \left[\frac{\alpha_2 \bar{K}_{2t}^{\alpha_2-1}}{\nu_{2t+1}^{\alpha_2/1-\alpha_2}} + \frac{\phi \bar{I}_{2t+1}^2 \nu_{2t+1}^{1/1-\alpha_2}}{2\delta \bar{K}_{2t}^2} + \frac{\delta}{\nu_{2t+1}^{1/1-\alpha_2}} + \frac{\phi \bar{I}_{2t+1}}{\bar{K}_{2t}}\right] \tag{23}$$

$$\lambda_t = E_t \bar{\beta}_{t+1}\frac{(\lambda_{t+1}+\mu_{1t+1})}{\omega_{1t}} = E_t \frac{\bar{\beta}_{t+1}\sigma(\bar{C}_{1t+1}^{\sigma}\bar{C}_{2t+1}^{1-\sigma})^{1-\gamma}}{\bar{P}_{1t+1}\bar{C}_{1t+1}\omega_{1t}} \tag{24}$$

$$\lambda_t \bar{S}_t = E_{t+1}\bar{\beta}_{t+1}\frac{(1-\sigma)(\bar{C}_{1t+1}\bar{C}_{2t+1}^{1-\sigma})^{1-\gamma}}{\bar{P}_{2t+1}\bar{C}_{2t+1}\omega_{2t}} \tag{25}$$

$$\lambda_t P_{1t}^b = E_t \frac{\bar{\beta}_{t+1}\lambda_{t+1}}{\omega_{1t}} \tag{26}$$

$$\lambda_t \bar{S}_t P_{2t}^b = E_t \frac{\bar{\beta}_{t+1}\lambda_{t+1}\bar{S}_{t+1}}{\omega_{2t}} \tag{27}$$

$$\lambda_t \bar{P}_{1t} = \min\left(\frac{\lambda_t}{2\bar{C}_{1t}}, \frac{\sigma(\bar{C}_{1t}^{\sigma}\bar{C}_{2t}^{1-\sigma})^{1-\gamma}}{\bar{C}_{1t}}\right) \tag{28}$$

$$\lambda_t \bar{S}_t \bar{P}_{2t} = \min\left(\frac{\lambda_t \bar{S}_t}{2\bar{C}_{2t}}, \frac{(1-\sigma)(\bar{C}_{1t}^{\sigma}\bar{C}_{2t}^{1-\sigma})^{1-\gamma}}{\bar{C}_{2t}}\right). \tag{29}$$

Equation (22) equates the current marginal cost of investing $\bar{I}_{1t}$ units of capital in the domestic industry with the expected future marginal return on invested capital. Equation (23) does the same for investment in the foreign industry. Marginal costs and benefits are measured in terms of utility via the factors $\lambda \bar{P}_1$ and $\lambda \bar{S}\bar{P}_2$, where λ is the marginal utility of nominal wealth, S is the exchange rate and the P_i are the money prices of the two goods. The marginal cost of additional investment reflects the decrease in current consumption and the reduction in output due to installation costs. The expected marginal benefits from investment are composed of the future

TABLE 1
Baseline parameters for preferences and technology

$\beta = 0.96$:	Annual subjective discount factor
$\sigma = 0.5$:	Share of domestic consumption in period utility
$\gamma = 1.5$:	Degree of relative risk aversion
$\phi = 2.0$:	Installation cost parameter
$\delta = 0.97$:	One minus the rate of capital depreciation
$(\alpha_1, \alpha_2) = (0.23, 0.42)$	Capital shares in domestic and foreign production that support balanced growth

marginal product of capital and the reduction in future installation costs because of the increase in the level of the depreciated capital stock next period.

Equations (24) and (25) equate the marginal utility of increased nominal wealth (adjusted for the increase in the money supply) with the expected discounted marginal utility of consumption next period. Additional money balances carried over to the next period are valued for their purchasing power in the next period's goods market. As equations (28) and (29) show, the marginal utility of consumption will be greater than the marginal utility of wealth when the agent is liquidity constrained. Changes in the growth rate of the money supply have a direct effect on the marginal utility of wealth and thus affect agents' choices of real variables as well. Our simulations show that the volatility of consumption is directly related to the volatility of the money supply. Equations (26) and (27) are the equilibrium Euler conditions associated with government bonds.

This system of eight simultaneous equations together with the resource constraint on world investment capital (20) and the purchasing power parity relation (21) can be solved for λ, $\bar{S}$, $\bar{P}_1$, $\bar{P}_2$, P_1^b, P_2^b, $\bar{I}_1$, $\bar{I}_2$, $\bar{C}_1$, and $\bar{C}_2$ at each point in time. As an analytic solution to the Euler equations and equilibrium conditions is not possible, we employ the Marcet (1989) method of parameterizing expectations and generating approximate solutions numerically.

IV. CALIBRATION

The results of the simulations are dependent upon the values chosen for the underlying preference and technology parameters as well as the parameterizations of the exogenous processes.

The values assigned to the preference and technology parameters are given in table 1. Although these parameters could have been estimated via calibration to the historical sample, in this paper we set them at values that have been used elsewhere in the literature. Of course, they can be varied across simulations to determine the sensitivity of the output to different settings of the parameters. We have found the homotopy approach described in Marcet (1989) to be useful for this exercise.

The subjective annual discount factor, β, is set at 0.96. The coefficient of relative risk aversion, γ, is initially set at 1.5. The value of α chosen for the United States has been used by Baxter and Crucini (1990). In the cross-investment (CI) version of

TABLE 2
Specification and baseline parameters for exogenous stochastic processes

Vector autoregressive specifications; that is,

$$X_{t+1} = A + BX_t + C\,E_{t+1}, \qquad E \sim \text{NID}\,(0, I),$$

$$\text{and } X = \begin{pmatrix} X_1 \\ X_2 \end{pmatrix}$$

in which X_1 is the log of a domestic (Canadian) growth rate and X_2 is the log of a foreign (U.S.) growth rate.

Productivity growth rate parameters (based on Costello 1989 data):

$$A = \begin{pmatrix} 0.0155 \\ 0.0114 \end{pmatrix} \; B = \begin{pmatrix} 0.1945 & -0.0428 \\ -0.0060 & 0.1846 \end{pmatrix} \; C = \begin{pmatrix} 0.0302 & 0.0000 \\ 0.0242 & 0.0188 \end{pmatrix}$$

$$\bar{X}_\nu = \begin{pmatrix} 0.0185 \\ 0.0139 \end{pmatrix}.$$

Monetary (M1) growth rate parameters (based on CANSIM and CITIBASE data for the period 1957–85):

$$A = \begin{pmatrix} 0.0384 \\ 0.0218 \end{pmatrix} \; B = \begin{pmatrix} 0.3394 & 0.0864 \\ -0.0832 & 0.7384 \end{pmatrix} \; C = \begin{pmatrix} 0.0340 & 0.0000 \\ 0.0070 & 0.0144 \end{pmatrix}$$

$$\bar{X}_\omega = \begin{pmatrix} 0.0663 \\ 0.0624 \end{pmatrix}.$$

the model, the value of α for Canadian technology was then chosen, as described in section II.5 above, to support equality in long-run growth rates across countries. In the NCI version, the values of α_i were chosen to be the same as those for the CI version for comparison purposes. Of course, one could also simulate the NCI version with α_i calibrated from historical data for each country.

The parameterizations of the forcing processes are summarized in table 2. Parameters for the productivity growth processes were obtained from data in a study by Costello (1989). The availability of data on cross-country productivity growth rates limited the use of data to yearly periods. Monetary growth rate data were obtained from the CANSIM and CITIBASE databases using annual data (average of quarterly data) on money supply (M1) levels.

Notice, from table 2, that the bivariate forcing processes for both productivity growth (X_ν) and money growth (X_ω) exhibit contemporaneous correlation (non-diagonal C matrices) as well as asymmetric lagged spillovers (non-diagonal and asymmetric B matrices). The implied long-run growth rates reported in table 2 as $\bar{X}_\nu$ and $\bar{X}_\omega$ are also not equal across countries.

In summary, for this sample (1957–85) and frequency (annual), the volatility of shocks to productivity growth (ν) are similar across countries ($\sigma_{\nu 1} = 0.0302$, $\sigma_{\nu 2} = 0.0306$), while the volatility of shocks to money growth are higher in Canada

($\sigma_{\omega 1} = 0.0340$, $\sigma_{\omega 2} = 0.0160$). The contemporaneous correlation across countries is higher for productivity shocks (0.79) than for money shocks (0.44). Lagged spillovers of shocks to productivity are negative for both countries, although they are considerably higher from the United States to Canada than the other way around. Money growth rates were much more persistent in the United States than in Canada, and although lagged spillovers were fairly large for both countries, they had opposite signs.

V. BASELINE RESULTS

Table 3 contains summary statistics for selected variables. They include the average growth rates for real GNP (Y), private gross fixed capital investment (I), consumption of non-durables and services (C), the GDP deflator (P), and the exchange rate of Canadian for U.S. dollars (S),[8] as well as the ratios of the trade balance (NX) and the current account balance (CA) to GDP, and the rates of interest (R). The means, standard deviations, cross-correlations, and first-order autocorrelations for these percentage growth rates and ratios are presented in tables 3A to 3D, respectively. In all these cases, the summary statistics are reported for the historical sample and for both the NCI and the CI versions of the model.

As described in the previous section, the forcing processes for money growth were calibrated to historical data using a VAR process to estimate the parameters. This was also the case indirectly for the productivity growth processes, since we used Costello's parameterization of international productivity growth rates for the same sample period. The preference and technology parameters of the model were assigned values from other studies, however, rather than being calibrated to a particular sample in order to match historical moments. In other words, our objective was not to match historical data but rather to construct an artificial economy that could be simulated under alternative assumptions about the structure of the international economy in order to analyse some general equilibrium implications of such assumptions. Therefore, any comparisons of the moments of the model with those from historical data should be interpreted with appropriate caution.

Mean growth rates for the artificial economy reported in table 3A reflect the long-run equilibrium (although subject to some sample variability in the random draws, the growth rate of quantities is similar across countries and across categories, as determined by the real forcing process) and the two-country model (the trade and current account balances of one country must be the negative of that of the other). Nominal interest rates are higher than in the data, but the differentials have the correct sign. Relative purchasing power parity holds for both versions of the model, in constrast to the historical sample, but absolute PPP holds only for the CI versions of the model as indicated in (21) above.[9]

8 Note that the statistics for P will refer to the rate of inflation and those for S to the rate of depreciation.

9 We chose, for comparison purposes, to calibrate the NCI version using the capital share parameters α_1 and α_2, which were consistent with the balanced growth solution for the CI version of

TABLE 3
Summary statistics for selected variables

TABLE 3A: Mean growth rates and ratios[a] (per cent)

	Historical		NCI Model[b]		CI Model[b]	
	Domestic	Foreign	Domestic	Foreign	Domestic	Foreign
Y	2.61	1.76	2.42	2.40	2.42	2.40
I	2.57	2.03	2.42	2.40	2.41	2.40
C	2.57	1.91	2.42	2.40	2.41	2.41
NX/GNP	1.35	−0.53	−0.11	0.10	24.73	−24.73
CA/GNP	−1.29	−0.01	5.20	−5.20	1.01	−1.01
R	7.14	6.64	11.06	10.81	11.05	10.81
P	5.31	4.73	2.82	2.57	2.83	2.56
S	1.30		0.27		0.27	

[a] Y: Real Gross Domestic Product; I: Private Gross Fixed Capital Investment; C: Consumption of non-durables and Services; NX: Net Exports; CA: Current Account Balance; R: Interest Rates on one-year Treasury Bills and Government Bonds; P: GDP Deflator; S: Exchange Rate of Canadian for U.S. Dollars. Historical data are obtained from the CANSIM, CITIBASE, and IFS databases for the period 1957–85. Data are per capita and first differences of logarithms (except for NX/GNP, CA/GNP, and R).
[b] NCI Model refers to results obtained from a model in which there are no physical capital movements across countries. The two goods are distinct for investment purposes. In the CI Model cross-investment is allowed.

TABLE 3B: Standard deviations

	Historical		NCI Model		CI Model	
	Domestic	Foreign	Domestic	Foreign	Domestic	Foreign
Y	2.27	2.86	3.02	3.09	2.99	3.02
I	6.28	7.32	16.08	6.02	12.28	14.63
C	2.06	1.25	2.79	3.25	2.21	2.21
NX/GNP	1.43	1.06	1.40	1.40	33.76	33.76
CA/GNP	1.44	0.24	1.04	1.04	5.18	5.18
R	3.10	3.13	2.02	2.09	2.12	2.13
P	4.02	3.11	4.08	3.33	3.74	2.96
S	3.00		3.32		3.32	

Table 3B reports that variability of consumption relative to output is closer to what we observe in the data than is the case for many theoretical models, which often generate consumption series that are too smooth. Investment is too variable relative to output, although we could correct for this fact by increasing the cost of installation parameter ϕ. As will be clearer in the next section, the difference in

the model. We have also simulated the NCI model with α_1 and α_2 corresponding to the historical data for each country. This required $\alpha_1 = 0.38$ and $\alpha_2 = 0.35$ and resulted in a non-balanced growth solution for the NCL version. This result had implications for inflation rates, investment volatilities, and some cross-correlations.

TABLE 3 (*Concluded*)

TABLE 3C: Cross-correlations

	Historical		NCI Model		CI Model	
	Domestic	Foreign	Domestic	Foreign	Domestic	Foreign
Y^d, Y^f	0.65		0.78		0.77	
I^d, I^f	0.27		0.43		0.84	
C^d, C^f	0.52		0.66		1.00	
I, Q			0.93	0.85	0.94	0.92
Y, I	0.68	0.80	0.31	0.85	0.74	0.66
Y, C	0.87	0.73	0.97	0.93	0.78	0.81
Y, NX/GNP	0.25	−0.49	−0.04	−0.03	0.01	0.01
Y, CA/GNP	0.21	−0.24	−0.01	−0.16	0.01	−0.01
Y, R	−0.08	−0.16	0.06	0.09	−0.01	0.04
Y, P	−0.22	−0.54	−0.63	−0.74	−0.44	−0.53

TABLE 3D: First-order Autocorrelations

	Historical		NCI Model		CI Model	
	Domestic	Foreign	Domestic	Foreign	Domestic	Foreign
Y	0.24	0.10	0.18	0.24	0.21	0.30
I	0.31	0.14	−0.22	0.24	0.01	−0.05
C	0.38	0.35	0.14	0.01	0.21	0.21
NX/GNP	0.65	0.69	0.41	0.41	1.00	1.00
CA/GNP	0.71	0.77	0.87	0.87	1.00	1.00
P	0.44	0.52	0.46	0.44	0.57	0.58
S	0.38		0.41		0.41	

the volatility in investment across countries in the NCI version of the model is due to the asymmetric forcing processes – in particular, the higher volatility of money growth shocks in Canada. The volatility of the exchange rate matches that in the data quite closely.

One stylized fact for the international economy is that the correlation across countries for consumption is lower than that for output. This stylized fact is difficult to match using theoretical models that allow risk sharing. Indeed, as is clear from table 3C, even with the heterogeneity due to aysmmetric forcing processes, in the CI version of the model consumption across countries is perfectly correlated. On the other hand, the NCI version generates relative rankings of the cross-country correlations for Y, C, and I much closer to that in the data. Also, unlike some international business-cycle models, domestic and foreign output growth is positively correlated in our models and also is relatively close to the correlation observed in historical data. The investment-savings correlations (I, Q) within each country are high in both versions of the model.

Another stylized fact discussed in Backus, Kehoe, and Kydland (1992) is the counter-cyclical behaviour of trade balances. The correlations between GDP growth and NX/GNP ratios reported in table 3C for the NCI version are negative for both countries. Intuition for the latter is as follows. Productivity shocks produce a rising NX/GDP ratio because of the lower relative price of home-produced goods. The opposite effect occurs with a monetary shock. That is, a higher relative price reduces home and foreign consumption of the domestic good, leading to lower net exports. The negative correlation with output implies that the monetary shocks dominate.

First-order autocorrelations are reported in table 3D. They are generally of the correct sign, except for two investment cases, and in some cases are of similar size to those in the historical data. The time-series behaviour of the growth rates can be analysed using impulse responses, which we discuss in the next section.

VI. DYNAMIC RESPONSES TO IMPULSE SHOCKS

The dynamic responses of the endogenous variables to shocks to money and productivity growth rates allow us to better interpret some of the correlations seen in the tables. Figures 1 and 2 provide impulse response plots for these shocks in the domestic economy. These figures are for the cross-investment (CI) version of the model and for the baseline parameterization for which the liquidity constraints were invariably binding (BL). The shocks are once-off and one standard deviation in size, and the figures plot per cent deviations from steady-state growth rates.

The response of the economy to monetary shocks is substantially different from the Svensson endowment economy model. The reason is that in the endowment model there can be no shifts between consumption and savings, so that any desired shift induces offsetting changes in asset prices. To trace the effect of a positive monetary shock in the steady state, note that the purchasing power of money is a function of the current realization of the state vector Ω. In our case,

$$\pi(\Omega) = \frac{1}{P(\Omega)} = \frac{\theta^{1/1-\alpha}}{\bar{P}(\Omega)M}.$$

A high current realization of the growth rate of money, ω_t, means more money will be available in all states in the next period, since $M_{t+1} = \omega_t M_t$. Thus, a high ω means that the purchasing power of money will be low in the next period. Agents will therefore prefer to increase their current consumption. If agents are not currently liquidity constrained, this fact will simply bid up the current price of goods and hence lower the current purchasing power of money and current real balances. If agents are liquidity constrained or become liquidity constrained, the shadow price of liquidity, μ_t, increases, while the marginal utility of nominal and of real wealth, λ_t and $\lambda_t P_t$ respectively, decline at given prices.

The decrease in λ_t has implications for production. For fixed current output gross of installation costs, the marginal cost of investment declines relative to its expected future return. Thus saving in the form of new physical capital will be higher. Less output will be available for consumption, and since, as described above, agents wish to increase their current consumption, goods prices will increase. If the liquidity constraint is binding, current consumption will fall. This result explains why high

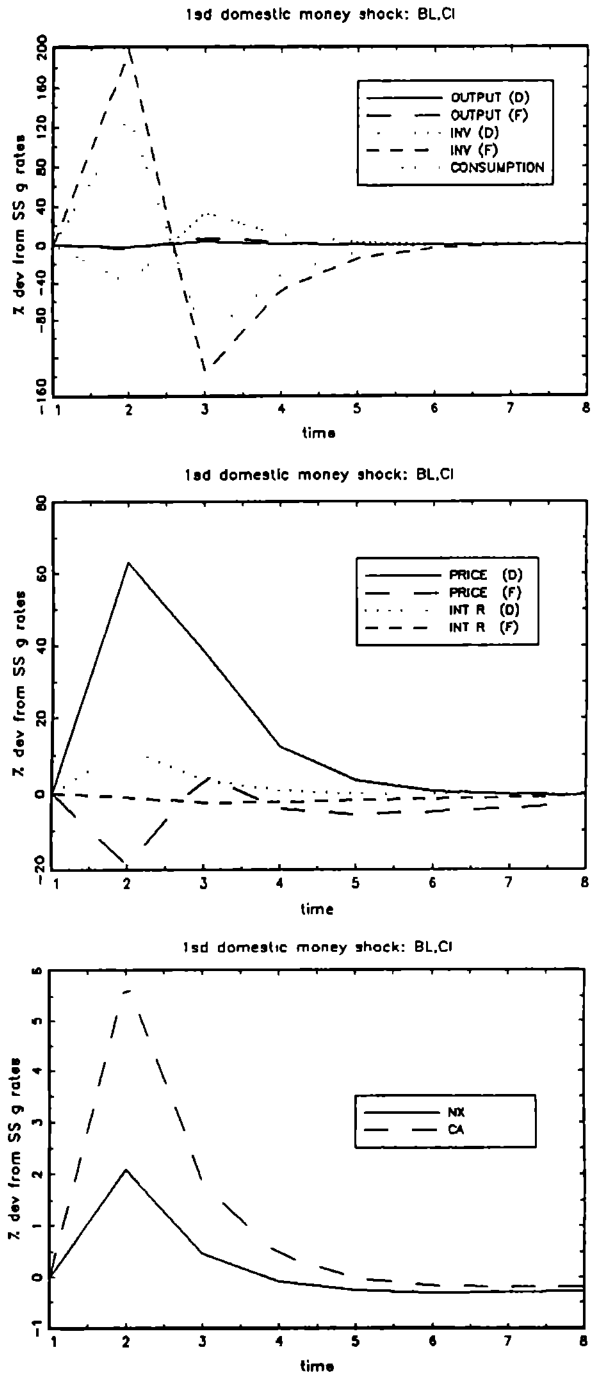
1sd domestic money shock: BL,CI
% dev from SS g rates
time
OUTPUT (D)
OUTPUT (F)
INV (D)
INV (F)
CONSUMPTION
1sd domestic money shock: BL,CI
% dev from SS g rates
time
PRICE (D)
PRICE (F)
INT R (D)
INT R (F)
1sd domestic money shock: BL,CI
% dev from SS g rates
time
NX
CA

FIGURE 1

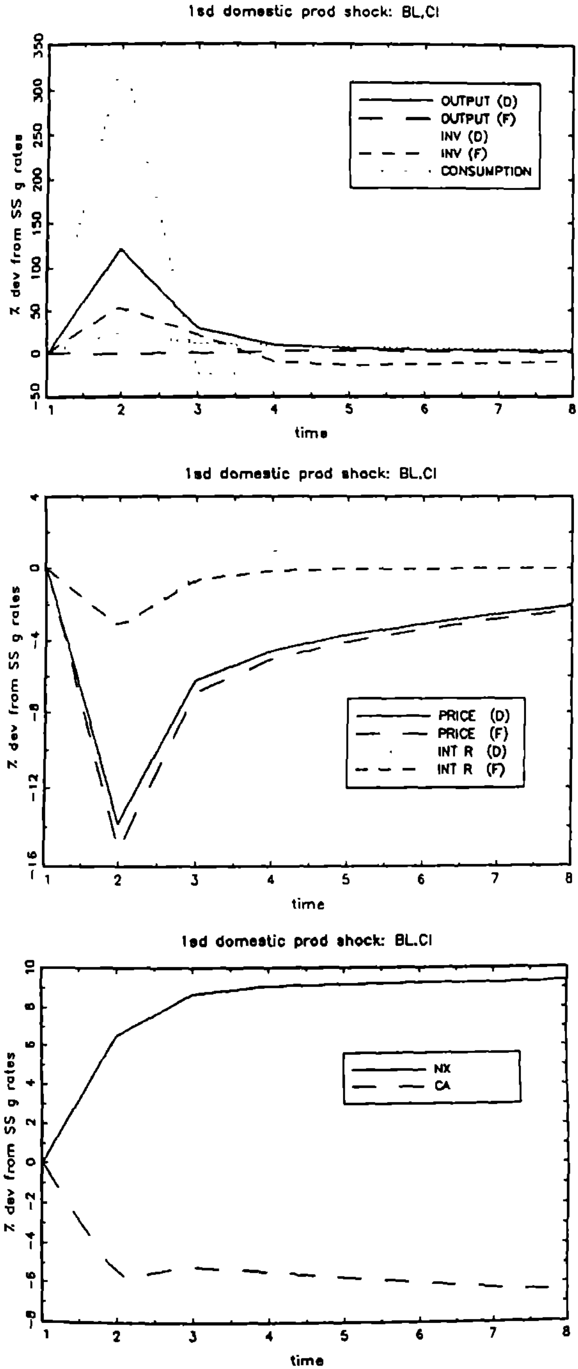
1sd domestic prod shock: BL,CI
% dev from SS g rates
time
OUTPUT (D)
OUTPUT (F)
INV (D)
INV (F)
CONSUMPTION
1sd domestic prod shock: BL,CI
% dev from SS g rates
time
PRICE (D)
PRICE (F)
INT R (D)
INT R (F)
1sd domestic prod shock: BL,CI
% dev from SS g rates
time
NX
CA

FIGURE 2

variability in money growth rates can lead to high variability in consumption and investment relative to output in the model.

The transmission mechanism for monetary shocks between countries is the exchange rate. When liquidity constraints are mostly binding, the rate of depreciation reflects the relative sizes of domestic and foreign money growth rates. In the model with physical investment flows, domestic and foreign capital savings will be adjusted until the purchasing powers of the two monies are equalized in each time period. Both countries will therefore experience similar responses to a monetary shock in either one of the countries. The effect of a money shock is more asymmetrical when no cross-investment is allowed. Prices respond in very much the same manner, but investment is more volatile and more unevenly distributed.

Productivity shocks have very little effect on exchange rates in this model. Agents respond to increased productivity by moving investment capital into the more productive technology and by increasing their current consumption. With international capital mobility, price changes must be of the same size and direction in both countries to maintain purchasing power parity. With no cross-investment, agents are unable to obtain full advantage of the productivity increase and the effects of the shock are mostly constrained to the country in which it originated.

Relaxing the liquidity constraint for the domestic economy 75 per cent of the time,[10] has a limited effect upon the magnitude of responses to real and nominal shocks and no effect on their direction. The most notable effect is on the volatility of the exchange rate. When the domestic liquidity constraint is mostly non-binding, exchange rate volatility is greatly reduced.

VII. CONCLUDING COMMENTS

Although preference and technology parameters were not calibrated to a particular historical sample, our baseline artificial economy is able to generate some of the international stylized facts. The growth model generates aggregate series that are integrated in levels and, for the most part, exhibits volatilities and correlations that are reasonable. In particular, the relative ranking of output, consumption, and investment volatilities correspond to those in the historical sample, and, at least for one version of the model, the relative ranking of the cross-country correlations for output, consumption, and investment also reflects stylized facts.

The financial structure of the model also generates sensible prices. In particular, interest rates are positive (although with higher means and lower variances than in the historical data), relative inflation rates have the correct sign for all moments, and, except for the mean rate of depreciation, the exchange rate behaviour is quite close to historical experience. The counter-factual absolute purchasing power parity result for the CI version of the model was relaxed by modifying the assumption that

10 This state was implemented by adjusting the intercepts of the VAR for money growth rates such that the long-run rate of growth for domestic money was reduced to −0.04 and that for foreign money was unchanged. The impulse response figures for this non-binding liquidity (NBL) parameterization are avialable from the authors on request.

investment goods are perfect substitutes across countries. The relative purchasing power parity result for the NCI version of the model might be relaxed by applying the CIA to investment goods. It could also be relaxed by introducing trading frictions as in Backus, Kehoe, and Kydland (1992).

The effect of the cross-country asymmetric forcing processes for money and productivity growth rates appears to have been useful in reproducing stylized facts. Their effects was also seen by comparing the dynamic responses to impulses to domestic versus foreign forcing processes (see Ricketts and McCurdy 1991 for more details). These responses also highlight the transmission channels of financial versus real shocks. Introducing contemporaneous correlation between real and nominal shocks would be interesting in this regard. It would also be interesting to investigate further the non-balanced growth solution associated with capital shares calibrated to the historical data. Further investigations of non-binding liquidity constraints or other extensions of the CIA structure might be fruitful.

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