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ABSTRACT

Closing Small Open Economy Models*

The small open economy model with incomplete asset markets features a steady state that depends on initial conditions. In addition, equilibrium dynamics possess a random walk component. A number of modifications to the standard model have been proposed to induce stationarity. This Paper presents a quantitative comparison of these alternative approaches. Five different specifications are considered: (1) A model with an endogenous discount factor (Uzawa-type preferences); (2) A model with a debt-elastic interest-rate premium; (3) A model with convex portfolio adjustment costs; (4) A model with complete asset markets; (5) A model without stationarity-inducing features. The main finding of the Paper is that all models deliver virtually identical dynamics at business-cycle frequencies, as measured by unconditional second moments and impulse response functions. The only noticeable difference among the alternative specifications is that the complete-asset-market model induces smoother consumption dynamics.

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1 Introduction

Computing business-cycle dynamics in the standard small open economy model is problematic. In the standard model, domestic residents have only access to a risk-free bond whose rate of return is exogenously determined abroad. As a consequence, the steady state of the model depends on initial conditions. In particular, it depends upon the country's initial net foreign asset position.¹ Put differently, transient shocks have long-run effects on the state of the economy. That is, the equilibrium dynamics posses a random walk component.

The random walk property of the dynamics implies that the unconditional variance of variables such as asset holdings and consumption is infinite. Thus, endogenous variables in general wonder around an infinitely large region in response to bounded shocks. This introduces serious computational difficulties because all available techniques are valid locally around a given stationary path.

To resolve this problem, researchers resort to a number of modifications to the standard model that have no other purpose than to induce stationarity of the equilibrium dynamics. Obviously, because these modifications basically remove the built-in random walk property of the canonical model, they all necessarily alter the low-frequency properties of the model. The focus of the present study is to assess the extent to which these stationarity-inducing techniques affect the equilibrium dynamics at business-cycle frequencies.

We compare the business-cycle properties of five variations of the small open economy. In section 2 we consider a model with an endogenous discount factor (Uzawa (1968) type preferences). Recent papers using this type of preferences include Obstfeld (1990), Mendoza (1991), Schmitt-Grohé (1998), and Uribe (1997). In this model, the subjective discount factor, typically denoted by β , is assumed to be decreasing in consumption. Agents become more impatient the more they consume. The reason why this modification makes the steady state independent of initial conditions becomes clear from inspection of the Euler equation $\lambda_t = \beta(c_t)(1+r)\lambda_{t+1}$. Here, λ_t denotes the marginal utility of wealth, and r denotes the world interest rate. In the steady state, this equation reduces to $\beta(c)(1+r) = 1$, which pins down the steady-state level of consumption solely as a function of r and the parameters defining the function $\beta(\cdot)$. We close this section by considering a simplified specification of Uzawa preferences where the discount factor is assumed to be a function of aggregate per capita consumption rather than individual consumption. This specification is arguably no more arbitrary than the original Uzawa specification and has a number of advantages. First, it also induces stationarity since the above Euler equation still holds. Second, the modified Uzawa preferences result in a model that is computationally much simpler than the standard Uzawa model, for it contains one less Euler equation and one less Lagrange multiplier. Finally, the quantitative predictions of the modified Uzawa model are not significantly different from those of the original model.

In section 3 we study a model with a debt-elastic interest-rate premium. This stationarity inducing technique has been used, among others, in recent papers by Senhadji (1994), Mendoza and Uribe (2000), and Schmitt-Grohé and Uribe (2001). In this model, domestic agents are assumed to face an interest rate that is increasing in the country's net foreign debt. To see why this device induces stationarity, let $p(d_t)$ denote the premium over the world interest rate paid by domestic residents, and d_t the stock of foreign debt. Then in the steady state the Euler equation implies that $\beta[1+r+p(d)] = 1$. This expression determines the steady-state net foreign asset position as a function of r and the parameters that define the premium function $p(\cdot)$ only.

¹If the real rate of return on the foreign bond exceeds (is less than) the subjective rate of discount, the model displays perpetual positive (negative) growth. It is standard to eliminate this source of dynamics by assuming that the subjective discount rate equals the (average) real interest rate.

Section 4 features a model with convex portfolio adjustment costs. This way of ensuring stationarity has recently used by Neumeyer and Perri (2001). In this model, the cost of increasing asset holdings by one unit is greater than one because it includes the marginal cost of adjusting the size of the portfolio. The Euler equation thus becomes $\lambda_t[1 + \psi'(d_t)] = \beta(1 + r)\lambda_{t+1}$, where $\psi(\cdot)$ is the portfolio adjustment cost. In the steady state, this expression simplifies to $1 + \psi'(d) = \beta(1 + r)$, which implies a steady-state level of foreign debt that depends only on parameters of the model.

The models discussed thus far all feature incomplete asset markets. Section 5 presents a model of a small open economy with complete asset markets. Under complete asset markets, the marginal utility of consumption is proportional across countries. So one equilibrium condition states that $U_c(c_t) = \alpha U^*(c_t^*)$, where U denotes the period utility function and stars are used to denote foreign variables. Because the domestic economy is small, c_t^* is determined exogenously. Thus, stationarity of c_t^* implies stationarity of c_t .

For the purpose of comparison, in section 6 we also study the dynamics of the standard small open economy model without any type of stationarity-inducing features, such as the economy analyzed in Correia et al. In this economy, the equilibrium levels of consumption and net foreign assets display a unit. As a result unconditional second moments are not well defined. For this reason, we limit the numerical characterization of this model to impulse response functions.

All models are calibrated in such a way that they predict identical steady states. The functional forms of preference and technologies are also identical across models. The basic calibration and parameterization is taken from Mendoza (1991). The business-cycle implications of the alternative models are measured by second moments and impulse responses. The central result of the paper is that all models with incomplete asset markets deliver virtually identical dynamics at business-cycle frequencies. The complete-asset-market model induces smoother consumption dynamics but similar implications for hours and investment.

2 Model 1: Endogenous Discount Factor

Consider a small open economy populated by a large number of identical households with preferences described by the following utility function:

$$E_0 \sum_{t=0}^{\infty} \theta_t U(c_t, h_t), \quad (1)$$

$$\theta_0 = 1, \quad (2)$$

$$\theta_{t+1} = \beta(c_t, h_t)\theta_t \quad t \geq 0, \quad (3)$$

where $\beta_c < 0$, $\beta_h > 0$. This preference specification allows the model to be stationary, in the sense that the non-stochastic steady state is independent of initial conditions (namely, the initial level of financial wealth, physical capital, and total factor productivity).

The evolution of foreign debt, d_t , is given by

$$d_t = (1 + r_{t-1})d_{t-1} - y_t + c_t + i_t + \Phi(k_{t+1} - k_t) \quad (4)$$

where r_t denotes the interest rate at which domestic residents can borrow in international markets in period t , y_t denotes domestic output, c_t denotes consumption, i_t denotes gross investment, and k_t denotes physical capital. The function $\Phi(\cdot)$ is meant to capture capital adjustment costs and

is assumed to satisfy $\Phi(0) = \Phi'(0) = 0$. Small open economy models typically include capital adjustment costs to avoid excessive investment volatility in response to variations in the domestic-foreign interest rate differential. The restrictions imposed on Φ ensure that in the non-stochastic steady state adjustment costs are zero and the domestic interest rate equals the marginal product of capital net of depreciation. Output is produced by means of a linearly homogeneous production function that takes capital and labor services as inputs,

$$y_t = A_t F(k_t, h_t), \quad (5)$$

where A_t is an exogenous stochastic productivity shock. The stock of capital evolves according to

$$k_{t+1} = i_t + (1 - \delta)k_t, \quad (6)$$

where $\delta \in (0, 1)$ denotes the rate of depreciation of physical capital.

Households choose processes $\{c_t, h_t, y_t, i_t, k_{t+1}, d_t, \theta_{t+1}\}_{t=0}^{\infty}$ so as to maximize the utility function (1) subject to (2)-(6) and a no-Ponzi constraint of the form

$$\lim_{j \rightarrow \infty} E_t \frac{d_{t+j}}{\prod_{s=1}^j (1 + r_s)} \leq 0 \quad (7)$$

Letting λ_t denote the Lagrange multiplier on the resource constraint (4) and η_t the multiplier on $\theta_{t+1}/\theta_t - \beta(c_t, h_t)$, the first-order conditions of the household's maximization problem are (3)-(7) holding with equality and:

$$\lambda_t = \beta(c_t, h_t)(1 + r_t)E_t \lambda_{t+1} \quad (8)$$

$$\lambda_t = U_c(c_t, h_t) - \eta_t \beta_c(c_t, h_t) \quad (9)$$

$$\eta_t = -E_t U(c_{t+1}, h_{t+1}) + E_t \eta_{t+1} \beta(c_{t+1}, h_{t+1}) \quad (10)$$

$$-U_h(c_t, h_t) + \eta_t \beta_h(c_t, h_t) = \lambda_t A_t F_h(k_t, h_t) \quad (11)$$

$$\lambda_t [1 + \Phi'(k_{t+1} - k_t)] = \beta(c_t, h_t) E_t \lambda_{t+1} [A_{t+1} F_k(k_{t+1}, h_{t+1}) + 1 - \delta + \Phi'(k_{t+2} - k_{t+1})] \quad (12)$$

These first-order conditions are fairly standard, except for the fact that now the marginal utility of consumption is not given simply by $U_c(c_t, h_t)$ but rather by $U_c(c_t, h_t) - \beta_c(c_t, h_t)\eta_t$. The second term in this expression reflects the fact that an increase in consumption lowers the discount factor ($\beta_c < 0$). In turn, a unit decline in the discount factor reduces utility in period t by η_t . Intuitively, η_t equals the present discounted value of utility from period $t + 1$ onward. To see this, iterate the first-order condition (10) forward to obtain: $\eta_t = -E_t \sum_{j=1}^{\infty} \left(\frac{\theta_{t+j}}{\theta_{t+1}}\right) U(c_{t+j}, h_{t+j})$. Similarly, the marginal disutility of labor is not simply $U_h(c_t, h_t)$ but instead $U_h(c_t, h_t) - \beta_h(c_t, h_t)\eta_t$.

In this model, the interest rate faced by domestic agents in world financial markets is assumed to be constant and given by

$$1 + r_t = 1 + r. \quad (13)$$

The law of motion of the productivity shock is given by:

$$\ln A_{t+1} = \rho \ln A_t + \epsilon_{t+1}; \quad \epsilon_{t+1} \sim N(0, \sigma_{\epsilon}^2); \quad t \geq 0. \quad (14)$$

A competitive equilibrium is a set of processes $\{d_t, c_t, h_t, y_t, i_t, k_{t+1}, \eta_t, \lambda_t\}$ satisfying (4)-(12) all holding with equality, given (13), (14), A_0 , d_{-1} , and k_0 .

We parameterize the model following Mendoza (1991), who uses the following functional forms for preferences and technology:

$$U(c, h) = \frac{[c - \omega^{-1}h^\omega]^{1-\gamma} - 1}{1 - \gamma}$$

$$\beta(c, h) = [1 + c - \omega^{-1}h^\omega]^{-\psi_1}$$

$$F(k, h) = k^\alpha h^{1-\alpha}$$

$$\Phi(x) = \frac{\phi}{2} x^2; \quad \phi > 0$$

As is well known, the functional forms of the period utility function and the discount factor imply that the marginal rate of substitution between consumption and leisure depends only on labor. In effect, combining equations (9) and (11) yields

$$h_t^{\omega-1} = A_t F_h(k_t, h_t) \tag{15}$$

The right-hand side of this expression is the marginal product of labor, which in equilibrium equals the real wage rate. The left-hand side is the marginal rate of substitution of leisure for consumption. The above expression thus states that the labor supply depends only upon the wage rate and in particular that it is independent of the level of wealth.

We also follow Mendoza (1991) in assigning values to the structural parameters of the model. Mendoza calibrates the model to the Canadian economy. The time unit is meant to be a year. The parameter values are shown on table 1.

Table 1: Model 1: Calibration

γ	ω	ψ_1	α	ϕ	r	δ	ρ	σ_ϵ
2	1.455	.11	.32	0.028	0.04	0.1	0.42	0.0129

All parameter values are standard in the real-business-cycle literature. It is of interest to review the calibration of the parameter ψ_1 defining the elasticity of the discount factor with respect to the composite $c - h^\omega/\omega$. Given the focus of our paper, this parameter is important because it determines the stationarity of the model and the speed of convergence to the steady state. The value assigned to ψ_1 is set so as to match the average Canadian trade-balance-to-GDP ratio. To see how in steady state this ratio is linked to the value of ψ_1 , use equation (12) in steady state to get

$$\frac{h}{k} = \left(\frac{r + \delta}{\alpha} \right)^{\frac{1}{1-\alpha}}$$

It follows from this expression that the steady-state capital-labor ratio is independent of the parameter ψ_1 . Given the capital-labor ratio, equilibrium condition (15) implies that the steady-state value of hours is also independent of ψ_1 and given by

$$h = \left[(1 - \alpha) \left(\frac{\alpha}{r + \delta} \right)^{\frac{\alpha}{1-\alpha}} \right]^{\frac{1}{\omega-1}}$$

Given the steady-state values of hours and the capital-labor ratio, we can find directly the steady-state values of capital, investment ($i = \delta k$), and output ($k^\alpha h^{1-\alpha}$), independently of ψ_1 . Now note that in the steady state the trade-balance-to-GDP ratio, $tb/F(k, h)$, is given by $1 - (c + i)/F(k, h)$. Then, equilibrium condition (8) implies the following steady state condition relating the trade-balance-to-GDP ratio to ψ_1 : $\beta(F(k, h) - tb - i, h)(1 + r) = 1$. Using the specific functional form for the discount factor, this expression can be written as:

$$\frac{tb}{F(k, h)} = 1 - \frac{i}{F(k, h)} - \frac{[(1 + r)^{1/\psi_1} + \frac{h^\omega}{\omega} - 1]}{F(k, h)}$$

This expression can be solved for ψ_1 given $tb/F(k, h)$, α , r , δ , and ω . All other things constant, the larger is the trade-balance-to-output ratio the larger is the required value of ψ_1 .

2.1 Model 1a: Endogenous Discount Factor Without Internalization

Consider an alternative formulation of the endogenous discount factor model where domestic agents do not internalize the fact that their discount factor depends on their own levels of consumption and effort. Alternatively, suppose that the discount factor depends not upon the agent's own consumption and effort, but rather on the average per capita levels of these variables. Formally, preferences are described by (1), (2), and

$$\theta_{t+1} = \beta(\tilde{c}_t, \tilde{h}_t)\theta_t \quad t \geq 0, \quad (16)$$

where \tilde{c}_t and \tilde{h}_t denote average per capita consumption and hours, which the individual household takes as given.

The first-order conditions of the household's maximization problem are (2), (4)-(7), (16) holding with equality and:

$$\lambda_t = \beta(\tilde{c}_t, \tilde{h}_t)(1 + r_t)E_t\lambda_{t+1} \quad (17)$$

$$\lambda_t = U_c(c_t, h_t) \quad (18)$$

$$-U_h(c_t, h_t) = \lambda_t A_t F_h(k_t, h_t) \quad (19)$$

$$\lambda_t[1 + \Phi'(k_{t+1} - k_t)] = \beta(\tilde{c}_t, \tilde{h}_t)E_t\lambda_{t+1} [A_{t+1}F_k(k_{t+1}, h_{t+1}) + 1 - \delta + \Phi'(k_{t+2} - k_{t+1})] \quad (20)$$

In equilibrium, individual and average per capita variables are identical. That is,

$$c_t = \tilde{c}_t \quad (21)$$

$$h_t = \tilde{h}_t \quad (22)$$

A competitive equilibrium is a set of processes $\{d_t, c_t, h_t, \tilde{c}_t, \tilde{h}_t, y_t, i_t, k_{t+1}, \lambda_t\}$ satisfying (4)-(7), (17)-(22) all holding with equality, given (13), (14), A_0 , d_{-1} , and k_0 . Note that the equilibrium conditions include one Euler equation less, equation (10), and one state variable less, η_t , than the standard endogenous-discount-factor model. This feature facilitates the computation of the equilibrium dynamics.

We evaluate the model using the same functional forms and parameter values as in Model 1.

3 Model 2: Debt Elastic Interest Rate

In Model 2, stationarity is induced by assuming that the interest rate faced by domestic agents, r_t , is increasing in the aggregate level of foreign debt, which we denote by \tilde{d}_t . Specifically, r_t is given by

$$1 + r_t = 1 + r + p(\tilde{d}_t), \quad (23)$$

where r denotes the world interest rate and $p(\cdot)$ is a country-specific interest rate premium. The function $p(\cdot)$ is assumed to be strictly increasing.

Preferences are given by equation (1). Unlike in the previous model, preferences are assumed to display a constant subjective rate of discount. Formally,

$$\theta_t = \beta^t,$$

where $\beta \in (0, 1)$ is a constant parameter.

The representative agent's first-order conditions are (4)-(7) holding with equality and

$$\lambda_t = \beta(1 + r_t)E_t\lambda_{t+1} \quad (24)$$

$$U_c(c_t, h_t) = \lambda_t, \quad (25)$$

$$-U_h(c_t, h_t) = \lambda_t A_t F_h(k_t, h_t). \quad (26)$$

$$\lambda_t[1 + \Phi'(k_{t+1} - k_t)] = \beta E_t \lambda_{t+1} [A_{t+1} F_k(k_{t+1}, h_{t+1}) + 1 - \delta + \Phi'(k_{t+2} - k_{t+1})] \quad (27)$$

Because agents are assumed to be identical, in equilibrium aggregate per capita debt equals individual debt, that is,

$$\tilde{d}_t = d_t. \quad (28)$$

A competitive equilibrium is a set of processes $\{d_t, \tilde{d}_{t+1}, c_t, h_t, y_t, i_t, k_{t+1}, r_t, \lambda_t\}_{t=0}^\infty$ satisfying (4)-(7), and (23)-(28) all holding with equality, given (14), A_0 , d_{-1} , and k_0 .

We adopt the same forms for the functions U , F , and Φ as in Model 1. We use the following functional form for the risk premium:

$$p(d) = \psi_2 \left(e^{d/\bar{d}} - 1 \right),$$

where ψ_2 and \bar{d} are constant parameters.

We calibrate the parameters γ , ω , α , ϕ , r , δ , ρ , and σ_ϵ using the values shown in table 1. We set the subjective discount factor equal to the world interest rate; that is,

$$\beta = \frac{1}{1+r}.$$

The parameter \bar{d} equals the steady-state level of foreign debt. To see this, note that in steady state, the equilibrium conditions (23) and (24) together with the assumed form of the interest-rate premium imply that $1 = \beta [1 + r + \psi_2 (e^{d/\bar{d}} - 1)]$. The fact that $\beta(1 + r) = 1$ then implies that $d = \bar{d}$. We set \bar{d} so that the steady-state level of foreign debt equals the one implied by Model 1. Finally, we set the parameter ψ_2 so as to ensure that this model and Model 1 generate the same volatility in the current-account-to-GDP ratio. The resulting values of β , \bar{d} , and ψ_2 are given in table 2.

Table 2: Model 2: Calibration of Parameters Not Shared With Model 1

β	\bar{d}	ψ_2
0.96	0.7442	0.000742

4 Model 3: Portfolio Adjustment Costs

In this model, stationarity is induced by assuming that agents face convex costs of holding assets in quantities different from a long-run level. Preferences and technology are as in Model 2. In contrast to what is assumed in Model 2, here the interest rate at which domestic households can borrow from the rest of the world is constant and equal to the world interest, that is, equation (13) holds. The sequential budget constraint of the household is given by

$$d_t = (1 + r_{t-1})d_{t-1} - y_t + c_t + i_t + \Phi(k_{t+1} - k_t) + \frac{\psi_3}{2}(d_t - \bar{d})^2, \quad (29)$$

where ψ_3 and \bar{d} are constant parameters defining the portfolio adjustment cost function. The first-order conditions associated with the household's maximization problem are (5)-(7), (25)-(27), (29) holding with equality and

$$\lambda_t[1 - \psi_3(d_t - \bar{d})] = \beta(1 + r_t)E_t\lambda_{t+1} \quad (30)$$

This optimality condition states that if the household chooses to borrow an additional unit, then current consumption increases by one unit minus the marginal portfolio adjustment cost $\psi_3(d_t - \bar{d})$. The value of this increase in consumption in terms of utility is given by the left-hand side of the above equation. Next period, the household must repay the additional unit of debt plus interest. The value of this repayment in terms of today's utility is given by the right-hand side. At the optimum, the marginal benefit of a unit debt increase must equal its marginal cost.

A competitive equilibrium is a set of processes $\{d_t, c_t, h_t, y_t, i_t, k_{t+1}, r_t, \lambda_t\}_{t=0}^\infty$ satisfying (5)-(7), (13), (25)-(27), (29), and (30) all holding with equality, given (14), A_0 , d_{-1} , and k_0 .

Preferences and technology are parameterized as in Model 2. The parameters γ , ω , α , ϕ , r , δ , ρ , and σ_ϵ take the values displayed in table 1. As in model 2, the subjective discount factor is assumed to satisfy $\beta(1 + r) = 1$. This assumption and equation (30) imply that the parameter \bar{d} determines the steady-state level of foreign debt ($d = \bar{d}$). We calibrate \bar{d} so that the steady-state level of foreign debt equals the one implied by Model 1 (see table 2). Finally, we assign the value 0.00074 to ψ_3 , which ensures that this model and Model 1 generate the same volatility in the current-account-to-GDP ratio. This parameter value is almost identical to that assigned to ψ_2 in Model 2. This is because the log-linearized versions of Models 2 and 3 are almost identical. Indeed, the models share all equilibrium conditions but the resource constraint (equations (4) and (29)), the Euler equations associated with the optimal choice of foreign bonds (equations (24) and (30)), and the interest rate faced by domestic households (equations (13) and (23)). The log-linearized versions of the resource constraints are the same in both models. The log-linear approximation to the domestic interest rate is given by $\widehat{1 + r_t} = \psi_2 d(1 + r)^{-1} \widehat{d}_t$ in Model 2 and by $\widehat{1 + r_t} = 0$ in Model 3. In turn, the log-linearized versions of the Euler equation for debt are $\widehat{\lambda}_t = \psi_2 d(1 + r)^{-1} \widehat{d}_t + E_t \widehat{\lambda}_{t+1}$ in model 2 and $\widehat{\lambda}_t = \psi_3 d \widehat{d}_t + E_t \widehat{\lambda}_{t+1}$ in Model 3. It follows that for small values of ψ_2 and ψ_3 satisfying $\psi_2 = (1 + r)\psi_3$ models 2 and 3 will imply similar dynamics.

5 Model 4: Complete Asset Markets

All model economies considered thus far feature incomplete asset markets. In those models agents have access to a single financial asset that pays a risk-free real rate of return. In the model studied in this section, agents have access to a complete array of state-contingent claims. This assumption per se induces stationarity in the equilibrium dynamics.

Preferences and technology are as in model 2. The period-by-period budget constraint of the household is given by

$$E_t r_{t+1} b_{t+1} = b_t + y_t - c_t - i_t - \Phi(k_{t+1} - k_t), \quad (31)$$

where b_{t+1} denotes a random variable indicating the number of assets purchased in period t to be delivered in each state of period $t+1$. The variable r_{t+1} denotes the period- t price of an asset that pays one unit of good in a particular state of period $t+1$ divided by the probability of occurrence of that state given information available in period t . Households are also subject to a no-Ponzi-game constraint of the form

$$\lim_{j \rightarrow \infty} E_t q_{t+j} b_{t+j} \geq 0, \quad (32)$$

at all dates and under all contingencies. The variable q_t represents the period-zero price of one unit of good to be delivered in a particular state of period t divided by the probability of occurrence of that state given information available at time 0 and is given by

$$q_t = r_1 r_2 \dots r_t,$$

with $q_0 \equiv 1$. The first-order conditions associated with the household's maximization problem are (5), (6), (25)-(27), (31), and (32) holding with equality and

$$\lambda_t r_{t+1} = \beta \lambda_{t+1}. \quad (33)$$

A difference between this expression and the Euler equations that arise in the models with incomplete asset markets studied in previous sections is that under complete markets in each period t there is one first-order condition for each possible state in period $t+1$, whereas under incomplete markets the above Euler equation holds only in expectations.

In the rest of the world, agents have access to the same array of financial assets as in the domestic economy. Consequently, one first-order condition of the foreign household is an equation similar to (33). Letting starred letters denote foreign variables or functions, we have

$$\lambda_t^* r_{t+1} = \beta \lambda_{t+1}^*. \quad (34)$$

Note that we are assuming that domestic and foreign households share the same subjective discount factor. Combining the domestic and foreign Euler equations—equations (33) and (34)—yields

$$\frac{\lambda_{t+1}}{\lambda_t} = \frac{\lambda_{t+1}^*}{\lambda_t^*}.$$

This expression holds at all dates and under all contingencies. This means that the domestic marginal utility of consumption is proportional to its foreign counterpart. Formally,

$$\lambda_t = \xi \lambda_t^*,$$

where ξ is a constant parameter determining differences in wealth across countries. We assume that the domestic economy is small. This means that λ_t^* must be taken as an exogenous variable. Because we are interested only in the effects of domestic productivity shocks, we assume that λ_t^* is constant and equal to λ^* , where λ^* is a parameter. The above equilibrium condition then becomes

$$\lambda_t = \psi_4, \quad (35)$$

where $\psi_4 \equiv \xi\lambda^*$ is a constant parameter.

A competitive equilibrium is a set of processes $\{c_t, h_t, y_t, i_t, k_{t+1}, \lambda_t\}_{t=0}^\infty$ satisfying (5), (6), (25)-(27), and (35), given (14), A_0 , and k_0 .

The functions U , F , and Φ are parameterized as in the previous models. The parameters γ , β , ω , α , ϕ , δ , ρ , and σ_e take the values displayed in tables 1 and 2. The parameter ψ_4 is set so as to ensure that the steady-state level of consumption is the same in this model as in models 1 to 3.

6 Model 5: The Non-Stationary Case

For comparison with the models considered thus far, in this section we describe a version of the small open economy model that displays no stationarity. In this model (a) The discount factor is constant; (b) the interest rate at which domestic agents borrow from the rest of the world is constant (and equal to the subjective discount factor); (c) agents face no frictions in adjusting the size of their portfolios; and (d) markets are incomplete in the sense that domestic households have only access to a single risk-free international bond. This specification of the model induces a random walk component in the equilibrium marginal utility of consumption and the net foreign asset position.

A competitive equilibrium in the non-stationary model is a set of processes $\{d_t, c_t, h_t, y_t, i_t, k_{t+1}, r_t, \lambda_t\}_{t=0}^\infty$ satisfying (4)-(7), (13), and (24)-(27) all holding with equality, given (14), A_0 , d_{-1} , and k_0 . We calibrate the model using the parameter values displayed in tables 1 and 2.

7 Quantitative Results

Table 3 displays a number of unconditional second moments of interest observed in the data and implied by models 1 - 4.² In all moments, we compute the equilibrium dynamics by solving a log-linear approximation to the set of equilibrium conditions.³ Although the focus of the paper is not to assess the models' abilities to match the data, as a reference we include in the first column of the table the observed second moments using Canadian data. As pointed out by Mendoza (1991), the small open real business cycle model captures a number of features of business cycles in Canada. Specifically, as in the data, all four models predict the following ranking of volatilities, in ascending order, consumption, output, and investment. The models also correctly predict that the components of aggregate demand and hours are procyclical, and that the correlation of the trade balance with GDP is close to zero.⁴ The models overestimate the procyclicality of labor. In the data the correlation between hours and output is 0.8, whereas the models imply a perfect correlation. This implication of the models is driven by the assumed preference and technology

²Model 5 is nonstationary, and thus does not have well defined unconditional second moments.

³The Matlab computer code used to compute the unconditional second moments and impulse response functions presented in this section is available at www.econ.upenn.edu/~uribe.

⁴Indeed, models 1-3 predict correctly that the trade balance is countercyclical. The correlation is so close to zero, however, that its sign does depend on the solution method employed. Mendoza, for example, approximates the solution to model 1 by discretizing the state space and finds a small but positive correlation.

specification. In effect, using the assumed Cobb-Douglas form of the production function we can write equation (15), which holds for all models, as $h_t^\omega = (1 - \alpha)y_t$. Log-linearizing this expression we get $\omega\hat{h}_t = \hat{y}_t$, where a circumflex over a variables denotes its log-deviation from the steady-state value. It follows that $\text{corr}(\hat{h}_t, \hat{y}_t) = 1$.

The main result of this paper is that regardless of how stationarity is induced in the small open economy real business cycle model, the model's predictions regarding second moments are virtually identical. This result is evident from table 3. The only noticeable difference arises in model 4, the complete markets case, which as expected predicts less volatile consumption. The low volatility of consumption in the complete markets model introduces an additional difference between the predictions of this model and models 1-3. Because consumption is smoother in model 4, its role in determining the cyclicity of the trade balance is smaller. As a result, model 4 predicts that the correlation between output and the trade balance is positive, whereas models 1-3 imply that it is negative.

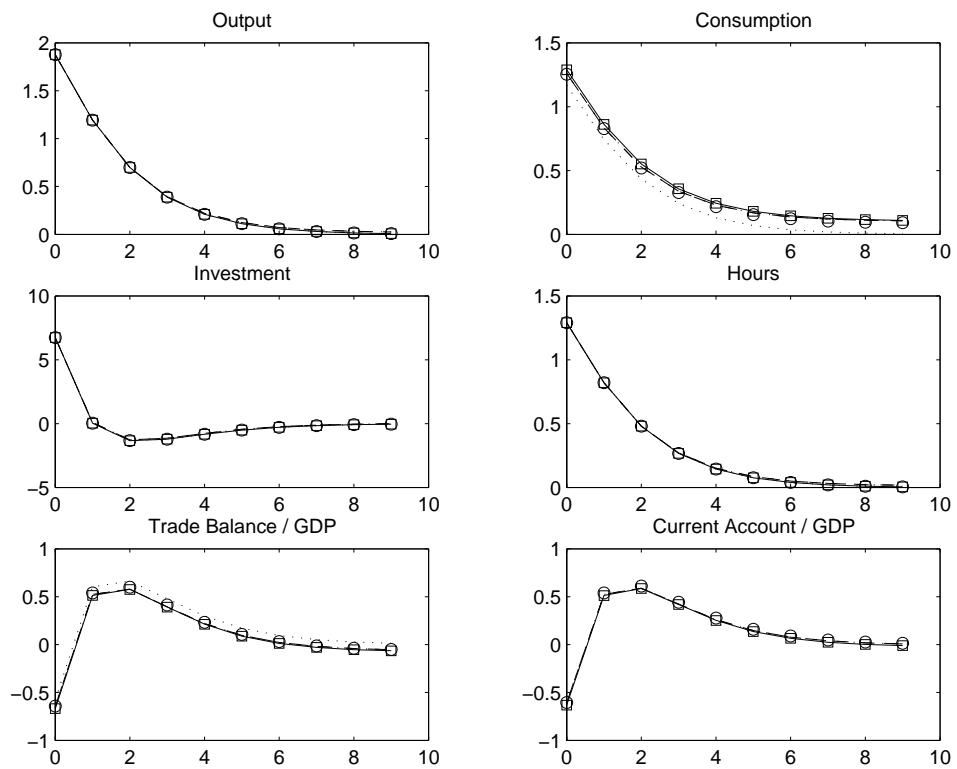
Table 3: Observed and Implied Second Moments

	Data	Model 1	Model 1a	Model 2	Model 3	Model 4
<u>Volatilities:</u>						
$\text{std}(y_t)$	2.8	3.1	3.1	3.1	3.1	3.1
$\text{std}(c_t)$	2.5	2.3	2.3	2.7	2.7	1.9
$\text{std}(i_t)$	9.8	9.1	9.1	9	9	9.1
$\text{std}(h_t)$	2	2.1	2.1	2.1	2.1	2.1
$\text{std}\left(\frac{tb_t}{y_t}\right)$	1.9	1.5	1.5	1.8	1.8	1.6
$\text{std}\left(\frac{cat}{y_t}\right)$		1.5	1.5	1.5	1.5	
<u>Serial Correlations:</u>						
$\text{corr}(y_t, y_{t-1})$	0.61	0.61	0.61	0.62	0.62	0.61
$\text{corr}(c_t, c_{t-1})$	0.7	0.7	0.7	0.78	0.78	0.61
$\text{corr}(i_t, i_{t-1})$	0.31	0.07	0.07	0.069	0.069	0.07
$\text{corr}(h_t, h_{t-1})$	0.54	0.61	0.61	0.62	0.62	0.61
$\text{corr}\left(\frac{tb_t}{y_t}, \frac{tb_{t-1}}{y_{t-1}}\right)$	0.66	0.33	0.32	0.51	0.5	0.39
$\text{corr}\left(\frac{cat}{y_t}, \frac{cat_{t-1}}{y_{t-1}}\right)$		0.3	0.3	0.32	0.32	
<u>Correlations with Output:</u>						
$\text{corr}(c_t, y_t)$	0.59	0.94	0.94	0.84	0.85	1
$\text{corr}(i_t, y_t)$	0.64	0.66	0.66	0.67	0.67	0.66
$\text{corr}(h_t, y_t)$	0.8	1	1	1	1	1
$\text{corr}\left(\frac{tb_t}{y_t}, y_t\right)$	-0.13	-0.012	-0.013	-0.044	-0.043	0.13
$\text{corr}\left(\frac{cat}{y_t}, y_t\right)$		0.026	0.025	0.05	0.051	

Note. The first column was taken from Mendoza (1991). Standard deviations are measured in percent per year.

Figure 1 demonstrates that models 1-5 also imply virtually identical impulse response functions to a technology shock. Each panel shows the impulse response of a particular variable in the

Figure 1: Impulse Response to a Unit Technology Shock in Models 1 - 5



Note. Solid line: Endogenous discount factor model; Dashed line: Debt-elastic interest rate model; Dash-dotted line: Portfolio adjustment cost model; Dotted line: complete asset markets model; Circles: Model without stationarity inducing elements.

six models. For all variables but consumption and the trade-balance-to-GDP ratio, the impulse response functions are so similar that to the naked eye the graph appears to show just a single line. Again, the only small but noticeable difference is given by the responses of consumption and the trade-balance-to-GDP ratio in the complete markets model. In response to a positive technology shock, consumption increases less when markets are complete than when markets are incomplete. This in turn, leads to a smaller decline in the trade balance in the period in which the technology shock occurs.

8 Conclusion

In this paper, we present five alternative ways of making the small open economy real business cycle model stationary: two versions of an endogenous discount factor, a debt-contingent interest rate premium, portfolio adjustment costs, and complete asset markets. The main finding of the paper is that once all five models are made to share the same calibration, their quantitative predictions regarding the behavior of key macroeconomic variables, as measured by unconditional second moments and impulse response functions, is virtually identical. We conclude that if the reason for modifying the canonical nonstationary small open economy model in any of the ways presented in the present study is simply technical, that is, solely aimed at introducing stationarity so that the most commonly used numerical approximation methods can be applied and unconditional second moments can be computed, then in choosing a particular modification of the model the researcher should be guided by computational convenience. In other words, the researcher should choose the variant of the model he finds easiest to approximate numerically. In this respect model 1, featuring an endogenous discount factor a la Uzawa (1968) is in disadvantage vis a vis the other models. For its equilibrium conditions contain an additional state variable.

A second result of our paper is that, in line with results previously obtained in the context of two-country real-business-cycle models by Kollmann (1996) and Baxter and Crucini (1995), whether asset markets are complete or incomplete makes no significant quantitative difference.

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