Technology Shocks: Novel Implications for International Business Cycles *

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Abstract

This paper studies the effects of neutral and investment-specific technology shocks in a standard international business cycle model. When investment-specific shocks explain a large fraction of fluctuations, as recently suggested by the empirical literature, our theoretical framework can account quantitatively for 1) the negative correlation between real exchange rates and relative consumption (Backus-Smith puzzle) 2) the negative correlation between terms of trade and relative output and 3) the large volatility of the terms of trade and trade flows. The main insight of this exercise is that investment-specific technology shocks in a open economy generate effects similar to taste-shocks: they raise production and domestic prices together with an appreciation of the terms of trade and large inflows of foreign goods. Our findings entail a reconsideration of the international transmission of technology shocks: the reponse of international prices depends critically on the type of technology shocks.

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*Preliminary and incomplete.

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1 Introduction

This paper studies the implications of neutral and investment-specific technology shocks for international business cycles. Since the seminal work by Kydland and Prescott [1982], many authors have analyzed business cycles positing that neutral technology shocks are the main source of fluctuations. More recently, however, a growing empirical literature finds evidence that neutral and investment-specific technology shocks jointly account for a large fraction in the variation of output and hours at business cycle frequencies[1]. In this broader interpretation about technology shocks, investment shocks are often found to play a major role in driving business cycles.

From the perspective of the theory, our starting point is a standard two-country model à la Backus *et al.* [1994] (BKK henceforth) which has been extensively used in modern international macroeconomics. Following Greenwood *et al.* [1988], we introduce a class of preferences with no intertemporal substitution on labor effort (GHH preferences) and endogenous capacity utilization. We then consider disturbances to both neutral and investment-specific technologies and investigate weather quantitatively the model can reduce the gap between the theory and some important patterns observed in the data about international prices and quantities.

Three empirical features motivates our analysis. First, the correlation between the real exchange rate and relative consumption across countries is generally low and often negative in the data. In theoretical models, however, this correlation is large and positive in that the real exchange rate is proportional to the ratio of marginal utilities of consumption (Backus-Smith [1993], Chari *et el.* [2002]). This failure turns out to be robust to many deviations from the standard model and is commonly interpreted as evidence of low international risk-sharing. Second, the terms of trade are generally negatively correlated with relative output across countries (BKK, Corsetti *et al.* [2007]). This property, which appears as the production counterpart of the relationship between real exchange rate and relative consumption, is in sharp contrast with the predictions of

[1] See, for example, Fisher [2006] and Justiniano *et al.* [2008]. Justiniano and Primiceri [2007] show that changes in the volatility of investment shocks can explain most of the decline in volatility of macroeconomic variables in the U.S. during the postwar period.

the theory as well. It indicates that expansions are associated with terms of trade appreciations, while a relative scarcity argument would predict the opposite outcome. Third, both net exports and the terms of trade display sizable volatility at business cycle frequencies: net exports are half as volatile as output whereas the terms of trade are almost twice as volatile as output. When in models the trade structure is defined by a Armington aggregator over domestic and foreign goods, however, general equilibrium effects introduce a trade-off between the volatility of relative prices and the volatility of quantities.

The main insight of the paper is that investment-specific shocks affect the economy like demand shocks, in that they generate increases in domestic absorption that do not originate from shifts in aggregate production. As a response to these shocks, production increases (via variable capacity utilization and labor input) together with output prices, as so does consumption. This mechanism ultimately has interesting implications for the external sector of the economy: the terms of trade appreciates while the trade balance deteriorates. Quantitatively, we find that if investment-specific shocks explain most of the fluctuations in output and the trade elasticity is low, the model can successfully account for the features observed in international data.

Shocks to the marginal efficiency of investment are associated with strong substitution effects away from current consumption. In a standard closed economy model without frictions and isoelastic preferences, consumption is countercyclical. In a open economy setting, the possibility of importing goods from abroad mitigates, but does not resolve this issue. The incentives to invest remain strong and consumption is acyclical. We deal with this issue by introducing variable capacity utilization and GHH preferences, which represent a reduced form for a model that includes home production. In response to changes in market technologies, firms increase utlization of installed capital whereas agents increase market hours of work relatively to home work and, as a consequence, market consumption. The strong response of labor supply and consumption to technology shocks embedded in this class of preferences provides a reconciliation between theory and data.

When investment-specific shocks are the main source of business cycle fluctuations, our benchmark model presents interesting implications for international prices. With respect to the terms of trade, the magnitude of the price effects depend crucially on the trade elasticity: the lower the trade elasticity, the higher the response of the terms of trade to shocks. Many studies emphasize the critical role of low trade elasticity in order to reproduce international business cycles consistent with the data, such as Heathcote and Perri [2002] and more recently Corsetti *et al.* [2007] (CDL henceforth). The novel contribution introduced in the paper, however, consists in the study of the *direction* of terms of trade changes associated with the different technology shocks. In response to neutral productivity shocks, the terms of trade reflect primarily the relative scarcity of production in the international market: expansions are associated with terms of trade depreciations. After a positive investment-shock, instead, the increase in domestic absorption stimulates domestic production and, more importantly, it affects the relative demand of goods traded across countries. The terms of trade appreciate when the economy expands. Hence, our findings suggest a reconsideration of empirical results concerning the international transmission of technology shocks.

The negative correlation between the real exchange rate and relative consumption is often interpreted as evidence of low international risk-sharing. Under complete markets, the real exchange rate is proportional to the ratio of marginal utilities of consumption, producing almost a linear relationship between these two quantities. This property holds "in *any* model with complete asset markets, regardless of the frictions in the goods and labour markets like sticky prices, sticky wages, shipping costs, and so on." (Chari *et al.* [2002], CKM henceforth). In a recent contribution, CDL [2007] exploit the role of incomplete markets in a model in which productivity shocks have large uninsurable wealth effects through international prices, finding that these wealth effects depend critically on the trade elasticity and the persistence of shocks. Their model with incomplete asset markets is able to account for the consumption-real exchange rate anomaly. An alternative approach, however, emphasizes the role of taste (demand) shocks together with non-traded goods, as in Stockman and Tesar [1995]. Unfortunately, notwithstanding the general problems of identifying structural disturbances, taste shocks appear to suffer the most from this issue. So far, it appears that the literature has almost neglected this avenue to focus on explanations based on incomplete asset markets.

The mechanism proposed in this paper is closer in spirit to Stockman and Tesar [1995], with some important qualifications. Investment-specific shocks affect directly the marginal utility of consumption in that they alter the relative price between consumption and investment, similarly to taste shocks. However, these disturbances originate from changes in the technology to produce investment goods and their empirical interpretation appears less controversial than taste shocks. For example, Cummins and Violante [2002] and Fisher [2006] document the long-run and cyclical properties of the real price of equipment and software, often used as a proxy for investment-specific shocks. In addition, and contrary to models driven by taste shocks, the benchmark economy presented in this paper generates countercyclical net exports together with the usual comovements that characterize domestic business cycles.

The structure of the paper is as follows. Section 2 presents the model economy. Section 3 outlines the calibration strategy adopted in the paper. Section 4 presents the main quantitative predictions of the model. Section 5 reports sensitivity analysis. Section 6 concludes.

2 The Economy

Time in this model is discrete. There are two countries ($i = 1, 2$) populated by identical infinitively lived agents. Preferences of the representative agent in each country i are characterized by an expected utility function of the form

$$u_i = E_0 \sum_{t=0}^{\infty} \beta^t U(C_{it}, N_{it}) \tag{1}$$

where C_i is consumption of final goods, N_i is labor and the time endowment is normalized to one. In the benchmark economy the momentary utility function takes the functional form

$$U(C, N) = \frac{[C - \psi N^{\nu}]^{1-\gamma}}{1-\gamma} \tag{2}$$

as in Greenwood *et al.* [1988] (so called GHH preferences). Benhabib *et al.* [1991] show that this utility function can be obtained analytically as a reduced form case from a model that includes home activities. Raffo [2007] shows that in two-country models à la BKK these preferences generate sufficient volatility in consumption so that the real trade balance is countercyclical, as in the data.

The trade structure is such that each country specializes in the production of one intermediate good ($j = A, B$) and factors of production are immobile across countries. To produce the intermediate good, each countries uses a a standard Cobb-Douglas production function of the form

$$Y_{it} = e^{z_i} H_{it}^{\theta} K_{it}^{\theta} N_{it}^{1-\theta} \tag{3}$$

where K_{it} is capital and z_{it} is an exogenous neutral technology shock. The term H_{it} represents capacity utilization, which can be adjusted in response to shocks. The resource constraints associated with intermediate goods production reads as follows

$$A_{1t} + A_{2t} = Y_{1t} \tag{4}$$

$$B_{2t} + B_{1t} = Y_{2t} \tag{5}$$

in country 1 and 2 respectively. These expression simply state that production is allocated to domestic or foreign use.

Intermediates are then combined in each country to produce goods destined to final absorption following the Armington aggregator

$$G_{it}(A_{it}, B_{it}) = \begin{cases} \left[\varpi_i A_{it}^{1-\alpha} + (1-\varpi_i) B_{it}^{1-\alpha}\right]^{\frac{1}{1-\alpha}} & i = 1 \\ \\ \left[(1-\varpi_i) A_{it}^{1-\alpha} + \varpi_i B_{it}^{1-\alpha}\right]^{\frac{1}{1-\alpha}} & i = 2 \end{cases} \tag{6}$$

where $\varpi_i > 0.5$ determines home bias in the composition of domestic absorption. The parameter $\sigma = \frac{1}{\alpha}$ denotes the elasticity of substitution between intermediate goods A and B. Domestic absorption is then allocated to domestic consumption and investment

$$C_{it} + e^{-v_{it}} X_{it} = G_{it}(A_{it}, B_{it}) \qquad i = 1, 2 \tag{7}$$

where $e^{-v_{it}}$ represents fluctuations in the relative price between investment and consumption. This source of uncertainty is a reduced form for technology shocks that are investment-specific, that is, they affect the efficiency in producing investment goods only.

Capital is subject to a convex adjustment cost $\Psi(.)$ and evolves according to the law of motion

$$K_{it+1} = (1 - \delta(H_{it}))K_{it} + X_{it} + \Psi\left(\frac{X_{it}}{K_{it}}\right)K_{it} \tag{8}$$

where X_{it} is investment and $\delta(H_{it})$ is the depreciation rate, which can vary according to variations in the utilization rate as in Greenwood *et al.* [1988].

Finally, trade variables in country 1 are as follows. The terms of trade, defined as price of imports relative to exports, are computed from the marginal rate of substitution in the Armington aggregator

$$TOT_{1t} = \frac{q_{1t}^B}{q_{1t}^A} = \frac{1 - \varpi_1}{\varpi_1}\left[\frac{A_{1t}}{B_{1t}}\right]^{\frac{1}{\sigma}} \tag{9}$$

It is immediate to show that the real exchange rate in the model is proportional to the ratio of marginal utilities, namely

$$RER_{1,t} = \frac{U_{C_{2,t}}}{U_{C_{1,t}}} \tag{10}$$

Real net exports over GDP are defined as the difference between exports and imports

$$RNX_{1,t} = \frac{\bar{q}_1^A A_{2t} - \bar{q}_1^B B_{1t}}{\bar{q}_1^A Y_{1t}} \tag{11}$$

where $\bar{q}_1^A$ and $\bar{q}_1^B$ indicate steady state prices.

3 Calibration

Table 1 reports the parameter used in the calibration of the benchmark model.

[Please insert Table 3 here]

Many parameters are taken directly from BKK, namely the discount factor (0.99), the curvature in the utility function (2.00), the labor share in production (0.64) and the trade share (0.15) used to pin down the home bias in domestic absorption. The parameters governing variable capacity utilization are set using the steady state relationships, ensuring that the depreciation rate in steady state is 0.025 as in BKK. For the GHH preferences, the calibration follows Raffo [2007] and the curvature parameter is chosen to reproduce the same Frisch elasticity as with isoelastic preferences.

The trade elasticity is equal to 0.5, which is in the lower range of the values commonly used in the literature. This value is in the range of the estimates reported in Hooper, Jonhson and Marquez [2000] for G-7 countries. Heathcote and Perri [2002], using a time-series approach, report a value equal to 0.9. CDL [2007] provide a detailed discussion on the estimates provided by other studies as well. For our purposes, results do not change significantly to the extent that this elasticity if lower than one.

Because of limited data availability, the statistical properties of neutral and investment-specific technology shocks are calibrated to reproduce the evidence provided by the empirical macro literature for the U.S. Following Fisher [2006], two key moments of the data are used as guidelines in this exercise. First, the relative variances of the two domestic technology shocks are such that the model reproduce the variance decomposition of output reported this study. More specifically, in each country the technology shocks account for 75 percent of the variation of output, with the investment-specific shocks explaining around 50 percent and neutral technology shocks around 25 percent[2]. Justiniano *et al.* [2008] find very similar results by estimating a fully structural DSGE model that includes several shocks and frictions. Second, the correlation between innovation of the neutral and investment-specific shocks are calibrated such that the model generates a significant negative comovement between the price of investment and output within each country. In Fisher [2006], this correlation varies between -0.4 and -0.6, depending on the series used for the relative price of investment. Finally, across countries, the calibration assumes that both neutral and investment-specific shocks are persistent with some moderate spillover.

[2]Notice that, in the exercise presented here, the remaining 25 percent is accounted for by foreign disturbances.

4 Quantitative Findings

Table 2 reports HP-filtered statistics for the data, the benchmark economy, and some variations of the benchmark economy. The data for the home country refer to U.S., while the foreign country is constructed aggregating Canada, EU-15 and Japan, which account for a large share of U.S. trade over the sample considered (1970:1-2007:3). The appendix provides the details about data sources and the construction of this aggregate. In all tables, net exports refer to the real net trade in goods and services relative to GDP.

[Please insert Table 2 here]

The top section of the table reports the statistics that are at the core of the analysis of the paper. The correlation between the real exchange rate and relative consumption is negative, as originally pointed out by Backus and Smith [1993]. CKM [2002] illustrate that this property of the data is difficult to reproduce in theoretical models, in that movements of the real exchange rate are closely linked to movements in the ratio of marginal utility of consumption across countries. This relationship induces an almost perfect correlation, which is robust to several goods and labour market frictions.

The Backus-Smith puzzle has a counterpart in terms of relative output prices and relative production: the correlation between the terms of trade and relative output is indeed negative in the data (-0.29). BKK [1995] report that this is the case for other countries as well. CDL [2007] confirm these findings for a larger set of countries and use this observation to argue that under incomplete markets, international prices amplify the consumption risk associated with (neutral) productivity shocks, thus inducing large departures from risk sharing.

The properties of net exports are also well documented. Net exports are countercyclical (-0.43) and this property of the data indicates that countries borrow from abroad during good times. In models where consumption smoothing is an important feature, it is usually difficult to reproduce this property because saving is procyclical. Finally, we observe that the correlation between the terms of trade and net exports is positive (0.51).

In terms of volatilities, international prices are almost twice as volatile as output in the data. Trade flows display some degree of variability, but less than output. For the U.S., the volatility of net exports relative to output is 0.25. In a sample of OECD countries, Engel and Wang [2007] find that this statistics is usually half as volatile as output, with the U.S. falling at the lower end of the distribution. Altogether, these observations suggest that both trade flows and trade prices display significant fluctuations at business cycle frequencies.

The remaining statistics report the usual business cycle properties for domestic variables. In terms of domestic absorption, investment is more or less three times more volatile than output while consumption volatility is around two-third the volatility of output. In terms of inputs, the volatility of labor (measure as total hours of work) is slightly lower than output and capacity utilization is more variable than output. The measure of capacity utilization adopted is constructed by the Board of Governors and include all industries. All domestic variables are strongly procyclical. Finally, consumption, output, labor input and investment are positively correlated across countries.

The next column in Table 2 presents the main findings of the paper. Overall, the benchmark economy performs quite well in reproducing the main features of domestic and international variables. In particular, the model economy generates a negative correlations between real exchange rates and relative consumption as well as between terms of trade and relative output. To understand the mechanism driving the findings, it is useful to start from the analysis of the log-linear expressions for international prices.

The approximation for the terms of trade takes the form

$$\widehat{TOT}_{1t} = \psi \left[\varphi \ \left(\widehat{y}_{1t} - \widehat{G}_{1t} \right) + \left(\widehat{y}_{1t} - \widehat{y}_{2t} \right) \right] \tag{12}$$

where both $\varphi = \frac{1-2im}{im}$ and $\psi = \frac{1}{2\sigma(1-im)}$ are positive coefficients and, under standard parameter values, $\varphi > 1$. This equation presents changes of the terms of trade as originating from two offsetting forces. The second term $(\widehat{y}_1 - \widehat{y}_2)$ is a supply effect and captures the idea that changes in domestic production relative to foreign production alter directly the relative scarcity of goods in the international markets. Hence, whenever domestic output increases it follows that foreign goods become more expensive and the terms of trade depreciate. The first term $\left(\widehat{y}_1 - \widehat{G}_1\right)$ represents a shift in domestic aggregate demand relative to domestic output. Alternatively, this expression reflects movements in the real trade balance. When neutral productivity shocks are the main source of business cycle fluctuations, as in the original BKK formulation, the relative supply effect strongly dominates and the terms of trade depreciate during booms. This mechanism is at odds with the empirical evidence, as pointed out in CDL [2007][3].

The negative correlation between terms of trade and relative output found in the empirical evidence, however, suggests that fluctuations in international prices are accounted for primarily by fluctuations in relative aggregate demand, at least at business cycle frequencies. Raffo [2007] shows that in a standard model a la BKK with GHH preferences the stronger response of consumption to productivity shocks can quantitatively generate large movements in domestic absorption. For some parametrization, the model can also generate an appreciation of the terms of trade during booms. However, to the extent that the same (productivity) shocks is affecting relative supply and relative demand simultaneously, it turns out that the volatility of the terms of trade is close to zero.

Investment-specific technological shocks, on the other hand, provide an novel transmission mechanism in that they shift domestic absorption without affecting directly the aggregate production function, similarly to demand shock. To illustrate this point, recall that in steady state the following relationship holds

$$C + X = G(A, B) = G_a Y \tag{13}$$

[3] Raffo [2007] shows that in the standard BKK scenario, real net exports are procyclical, thus reinforcing the depreciation of the terms of trade. However, the contribution of this terms is very small in that net exports display very little variability.

Investment-specific shocks correspond to a change in the price of investment relative to consumption

$$C_t + e^{-v_t} X_t = G_t(A_t, B_t) = G_a Y_t - NX_t \tag{14}$$

that is, a shift of domestic absorption that affects the intermediate goods market like a demand shock. As a consequence, domestic output increases via variable capacity utilization and labor inputs, while domestic prices increase to meet home demand. Because of the Armington aggregator assumption (low elasticity of substitution together with the home bias), the trade balance deteriorates and the terms of trade appreciate. The findings presented in Table 2 confirm that quantitatively this mechanism can account for the cyclical pattern of the terms of trade and net exports observed in the data.

The benchmar model still presents a tight link between real exchange rate and the ratio of marginal utilities. Nevertheless, the model can account for the negative correlation between the real exchange rate and relative consumption. Consider the log-linearized expression of the real exchange rate

$$\widehat{RER}_t = \gamma \left[\alpha_C (\widehat{c}_{H,t} - \widehat{c}_{F,t}) - \alpha_N (\widehat{n}_{H,t} - \widehat{n}_{F,t}) \right] - (v_{H,t} - v_{F,t}) \tag{15}$$

Fluctuations in the real exchange rate are determined by the interactions of two terms. The first term reflects movements of the marginal utilities originating from consumption and labor, which is the standard decomposition presented in the literature. If the utility function is separable ($\alpha_N = 0$), then the real exchange rate is perfectly correlated with the ratio of consumption. If the utility function is nonseparable, like in the isoelastic case considered by BKK, then the dynamics of labor do influence the real exchange rate, but quantitatively they cannot account for the Backus-Smith puzzle. The term $(v_{H,t} - v_{F,t})$ reflects movements originating from the investment shocks, which is the new element considered here. This term appears in (15) because investment-specific shocks change directly the relative price between investment and consumption, thus affecting the marginal utility of consumption like taste shocks. The economic mechanism works as follows. After a positive investment-specific productivity shocks, the consumption good becomes more expensive than the investment good (i.e. the relative price of investment in terms of consumption falls), thus generating on impact a real exchange rate appreciation. On the production side, the economy takes advantage of this increase in productivity by varying capacity utilization and labor input, so that more resources are available to increase the capital stock. However, because of GHH preferences, the large increase in labor supply is associated with a positive increase in consumption as well. Hence, the real exchange rate appreciates during times when consumption increases, which is at the core of the Backus-Smith puzzle.

In the open economy environment presented in this paper the response of both investment and consumption to investment-specific shocks is procyclical, as in the data. This result is important because models where shocks to the relative price between consumption and investment are important sources of business cycle fluctuations often generate a negative comovement between these two variables, which is counterfactual. Following Baxter [1995], Table 3 presents the Hicksian decomposition associated with investment-specific technological shocks for three representative cases: the neoclassical RBC model as in Cooley and Prescott [1995], an open economy version of such model as adopted by BKK and the benchmark economy presented here.

[Please insert Table 3 here]

The first two columns report the wealth and the substitution effect on consumption due to an investment shocks, where the substitution effect is measured as the difference between the first period impulse response and the wealth effect. The last column report the cyclical correlation of consumption with output. In the closed economy framework, the size of the substitution effect strongly dominates the wealth effect and the two effects work in opposite directions: consumption is countercyclical. This result indicates that investment shocks, by affecting future production possibilities without shifting significantly current production, require a reduction in current consumption to take advantage of better investment opportunities. A priori, this mechanism could be overturned by simply opening the economy to foreign trade so that the economy is able to borrow from the rest of the world without having to sacrifice consumption. The results for the BKK case, however, show that quantitatively the incentives to invest are still strong and consumption is acyclical. The country uses a large share of the resources borrowed to accumulate capital. Finally, in the benchmark model considered here, both wealth and substitution effect work in the same direction to increase consumption, which is procyclical. This finding depends on two important features of the model. First, the possibility to vary capacity utilization allows the economy to increase the amount of resources available in the current period, when the shock hits. Second, the quasi-linear form of the GHH utility function implies that, absent income effect on labor supply, the response of labor to productivity shocks is stronger. As a consequence, the compensation for the increase in (market) hours of work takes the form of larger increase in consumption[4].

5 Sensitivity Analysis

This section presents sensitivity analysis to three features of the benchmark economy. First, we consider a different specification of utility that includes external habit, as often used in the empirical literature. This exercise illustrates the role of GHH preferences in accounting for the response of prices to technology shocks. Next, an experiment with higher trade elasticity is presented. The main implication concerns the volatility of international prices, while the cyclical properties are minimally affected. Last, we compare the quantitative implications of the model for the two cases in which business cycles are generated by only one type of technology shocks, either neutral or investment-specific. This experiment confirms that the response of the terms of trade to technology shocks has opposite signs: the terms of trade depreciate after a neutral technology shocks, while they appreciate after an investment-specific technology shock.

[4]Benhabib *et al.* [1991] show that GHH preferences are a limiting case for a model that includes home production, where home and market activites are perfect substitutes. Raffo [2007] shows that for a sufficiently large degree of substitution between home and market activities, the quantitative performance of a BKK model with GHH preferences and a BKK model with home production are very similar.

5.1 Utility Function

The benchmark economy assumes that preferences are of GHH type. The next column in Table 2 presents the results obtained by adopting a utility function with habit persistence. The empirical macro literature deals with the negative substitution effect on consumption originating from investment-shocks by resorting to model frictions, including habit persistence. When we consider external habit, the model perform quite well with respect to quantities, but cannot yet reproduce the cyclical properties of international prices. In particular, the log-linear expression for the real exchange rate becomes

$$\widehat{RER} = A\left[(\widehat{c}_{H,t} - \widehat{c}_{F,t}) - d(\widehat{c}_{H,t-1} - \widehat{c}_{F,t-1})\right] - (v_{H,t} - v_{F,t}) \tag{16}$$

where $A = \frac{\gamma}{1-d}$ and d is the habit persistence parameter[5]. The habit persistence parameter has two effect on the real exchange rate. First, it reduces the impact of deviations in consumption from steady state. Second, it increases the response of the marginal utility of consumption, as if we were increasing the curvature parameter (through A). However, in no simulation we were able to generate the negative correlation between real exchange rate and relative consumption. Similarly, the terms of trade are slightly procyclical, which is associated with weakly countercyclical net exports. The volatility of net exports falls as well compared to the benchmark case.

An interesting feature of the economy with habit persistence is that it replicates the cross-country comevements observed in the data. More specifically, output is positively correlated across countries and the correlation exceeds consumption correlation. In addition, inputs display positive comovement as well.

5.2 Trade Elasticity

There is a lot of uncertainty about trade elasticities across countries. In their original work, BKK set this parameter equal to 1.5 referring to a study by J. Whalley [1985]. More recently, Hooper

[5]The results are presented for the case of $d = 0.8$. The utility function is now separable in leisure and labor does not enter the expression of the real exchange rate.

et al. [2000] report estimates for G7 countries in a range between 0.1 and 2. Heathcote and Perri [2002] show that with lower values the BKK model can better reproduce business cycle properties observed in the data. They also estimate a value of 0.9 for this elasticity. CDL [2007] use a model that includes a distribution sector which, by construction, lowers the implied trade elasticity. When they estimate via GMM the trade elasticity to reproduce some moments from the data, they obtain a value below 0.5.

In contrast to the business cycle literature, applied general equilibrium trade models require large trade elasticities. Yi [2003] shows that in order for trade models to match the large growth in trade after trade liberalization the trade elasticity has to be around 12 or 13. Ruhl [2005] provides an interesting perspective on these disparities by arguing that the source of variation in prices and quantities across the two models is fundamentally different: temporary shocks for business cycle models, permanent changes for trade models. He then builds a model with entry and exit that is able to reconcile this discrepancy and estimates a high frequency value of 1.4.

Based on this discussion, Table 4 presents a simulation in which the trade elasticity is equal to 1.5, as proposed by BKK and close to the value estimated by Ruhl [2005]. The performance of the model is affected along two dimensions. First, the volatility of international prices is lower than in the benchmark case, falling below the volatility of output. However, in the data, international prices are usually more volatile than output. Expression (12) provides once again guidance in understanding this result: higher trade elasticity reduces the response of the terms of trade to changes in relative supply and relative demand of intermediate goods. In other words, if intermediate goods are more substitutes, changes in productivity will have higher impact on quantities than prices[6].

The second important implications concern the correlation between international prices and relative output and consumption. The correlation between the terms of trade and relative output remains negative but it is much weaker than in the benchmark case. The correlation between real exchange rate and consumption is weakly positive.

[6] In the limiting case, the economy reduces to a one good model and the terms of trade do not move at all.

Overall, sensitivity analysis to the trade elasticity confirms that in order for the model to match business cycle properties observed in the data, the trade elasticity has to be in the range between zero and one.

5.3 Terms of Trade and Technology Shocks

In our benchmark economy the correlation between the terms of trade and relative output is negative, as in the data. This result depends critically on the relative importance of neutral and investment-specific shocks in generating business cycles. To illustrate this point, the last two columns of Table 2 present simulation results for the benchmark model with only one type of shock as source of fluctuations, either neutral technology (6) or investment-specific technology shocks (7).

This experiment shows that the response of the terms of trade to technology shocks is very different in the two scenarios. Under neutral technology shocks, the terms of trade reflect primarily the relative change in production in one country with respect to the other. Expansions at home are associated with terms of trade depreciations because foreign goods become more scarce relative to domestic goods. This mechanism is at the core of the idea that the terms of trade provide insurance across countries against idiosyncratic shocks, as pointed out by Cole and Obstfeld [1991] and Heathcote and Perri [2002]. In terms of expression (12), the simulation shows that the volatility of net exports is much lower than in the benchmark case, indicating that the contribution of net exports $\left[\text{term } \left(\widehat{y}_1 - \widehat{G}_1\right)\right]$ to changes in the terms of trade is smaller than the contribution of relative production $[\text{term } (\widehat{y}_1 - \widehat{y}_2)]$. Under investment-specific technology shocks, instead, movements in the terms of trade are mostly accounted for by shifts in domestic absorption. Net exports are half as volatile as output and strongly countercyclical. Expansions in domestic demand raise both output and prices together with large inflows of goods from abroad, so that the terms of trade appreciate when the production increases.

This discussion has implications for further empirical analysis about the international transmission of productivity shocks. A negative correlation between the terms of trade and output is often considered *prima facie* evidence that domestic factors other than productivity are important determinant of international prices, at least for large economic regions such as the U.S. Alternatively, Corsetti *et al.* [2008] and Enders and Muller [2007] interpret these patterns through the lenses of incomplete asset markets, concluding that in such environment international prices amplify the wealth effects associated with productivity shocks. Our findings suggest yet a different perspective on this issue. We find that the response of international prices to technology shocks depends critically on the type of technology shocks considered. In addition, our results do not depend on the assumption of asset market incompleteness or on the presence of *ad hoc* preference/demand shifters.

6 Conclusions

[to be added]

7 Appendix A. Linearization

Given that the Armington aggregator is homogenous of degree one, its log-linearized version is[7]

$$\widehat{G(.)} = \frac{\bar{G}_a \bar{a}}{\bar{G}} \hat{a}_1 + \frac{\bar{G}_b \bar{b}}{\bar{G}} \hat{b}_1 = (1 - im_1)\, \hat{a}_1 + im_1\, \hat{b}_1 \tag{A.1}$$

where im is the import share. Market clearing condition for good A, equation (4), yields

$$\hat{y}_1 = (1 - im_1)\hat{a}_1 + im_1 \hat{a}_2 \tag{A.2}$$

Combining (A.1) and (A.2) we obtain the expression for real net exports

$$\widehat{nxqty} = \hat{y}_1 - \hat{G}_1 = im_1 \left[\hat{a}_2 - \hat{b}_1 \right] \tag{A.3}$$

which is the difference between exports and imports evaluated at steady state prices.

The linear approximation of equation (9) defining the terms of trade is

$$\widehat{p} = \frac{1}{\sigma} \left[\hat{a}_1 - \hat{b}_1 \right] \tag{A.5}$$

[7] In what follows, a hat denotes percentage deviations from steady state and a bar denotes steady state values.

Combining (A.2), (A.3), (A.5) and its analogous for country 2 we obtain equation (12) in the text

$$\hat{p} = \eta \left[\phi \ \left(\widehat{y}_1 - \widehat{G}_1 \right) + \left(\widehat{y}_1 - \widehat{y}_2 \right) \right] \tag{A.6}$$

where $\eta = \frac{1}{2\sigma(1-im_1)}$and $\phi = \frac{1-2im_1}{im_1}$.

8 Appendix B. Data

Data for the U.S. are from the Bureau of Economic Analysis (BEA) National Income and Product Account (NIPA). Real variables refer to s.a.a.r series of chained 2000 dollars. The sample covers the years 1970:Q1 to 2007:Q3. Following the OECD classification, investment includes both private and government investment. Consumption is the sum of private and public consumption. The terms of trade are the ratio of the imports to the exports price deflators, where each deflators is constructed as the ratio of nominal over real trade exports and imports. The real exchange rate is the real broad trade-weighted exchange value of the US$, indexed to March 1973=100. Data are provided by the Federal Reserve Board, Foreign Exchange Rates, G.5 (405). Monthly data are converted to quarterly by taking the average of each month in the quarter. The series is available starting 1973:Q1.

Labor input is the product of hours and the employment rate. Hours are "Non-Farm Business Hours" from the Bureau of Labor Statistics (BLS) Productivity and Cost Release. Employment is "Total Non-Farm Employees" from the BLS publication “The Employment Situation”. Monthly data, in thousands, are converted to quarterly data by taking the average of each month in the quarter. Population 15-64 is from the Bureau of the Census, Current Population reports.

Capacity Utilization data is s.a. percent of capacity for Total Industry provided by the Board of Governors of the Federal Reserve System. Monthly data are from the Industrial Production and Capacity Utilization G.17 (419) Summary Table. Monthly data are converted to quarterly data by taking the average of each month in the quarter.

Series for the construction of the rest-of-world aggregate (ROW) are from the OECD Quarterly National Account (QNA). Rest-of-world is defined as Canada, Japan, and the 15 European

Union countries (Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden and the United Kingdom), which are the major trading partner over the sample considered. Including Mexico did not affect the results. GDP and GDP component series for these countries are aggregated by summing the OECD measure VPVOBARSA (millions of US$, volume estimates and fixed PPPs, at constant 2000 prices, s.a.a.r).

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Table 1. Benchmark Parameters

Preferences	$\beta = 0.99$	$\gamma = 2.0$	$\nu = 1.65$
Production	$\theta = 0.36$	$\delta_{ss} = 0.025$	$\sigma = 1.5$
Trade	$\omega = \frac{\theta}{X/GDP}$	$im = 0.15$	
Productivity			
Transition Matrix	$\begin{bmatrix} A & 0 \\ 0 & A \end{bmatrix}$	$with$	$A = \begin{bmatrix} 0.906 & 0.088 \\ 0.088 & 0.906 \end{bmatrix}$
Std Dev innovations		$\sigma_z = 0.00352$	
		$\sigma_v = 0.00852$	
Corr innovations		$\sigma_{z_1,z_2} = 0.26$	
		$\sigma_{z_1,z_2} = 0.26$	
		$\sigma_{z_i,v_i} = 0.40$	

Table 2: BUSINESS CYCLES STATISTICS (1970:1-2007:3)

			Variations of the Benchmark Model			
	U.S. Data	**Benchmark**	**Habit**	**BKK Elasticity**	**No Z shock**	**No V shock**
Standard Deviation relative to GDP						
C	0.81	0.70	0.67	0.73	0.45	0.74
I	2.87	2.83	2.86	2.89	3.80	2.40
L	0.87	0.60	0.68	0.61	0.61	0.60
H	1.85	1.17	2.23	1.16	1.41	0.70
NX	0.25	0.36	0.19	0.47	0.47	0.15
TOT	1.72	1.29	1.36	0.84	1.01	0.44
RER	2.39	0.91	0.96	0.59	0.71	0.31
Cross-Correlations						
C and GDP	0.85	0.94	0.80	0.96	0.99	0.99
I and GDP	0.91	0.90	0.88	0.79	0.97	0.91
NX and GDP	-0.43	-0.51	-0.17	-0.27	-0.81	-0.46
TOT and NX	0.51	0.86	0.75	0.92	0.98	-0.89
TOT and relative GDP	-0.29	-0.64	0.12	-0.18	-0.98	0.94
RER and relative C	-0.21	-0.32	0.64	0.14	-0.97	0.95
Cross-Correlations Foreign and Domestic						
C	0.50	0.77	0.78	0.82	-0.12	0.72
Y	0.60	0.40	0.82	0.63	-0.34	0.57
L	0.33	0.40	0.41	0.63	-0.34	0.57
I	0.46	-0.41	0.37	-0.38	-0.73	-0.23