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TECHNOLOGY SHOCKS: NOVEL IMPLICATIONS FOR INTERNATIONAL BUSINESS CYCLES

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ABSTRACT

Technology Shocks: Novel Implications for International Business Cycles*

Understanding the joint dynamics of international prices and quantities remains a central issue in international business cycles. International relative prices appreciate when domestic consumption and output increase more than their foreign counterparts. In addition, both trade flows and trade prices display sizable volatility. This paper incorporates Hicks-neutral and investment-specific technology shocks into a standard two-country general equilibrium model with variable capacity utilization and weak wealth effects on labor supply. Investment-specific technology shocks introduce a source of fluctuations in absorption similar to taste shocks, thus reconciling theory and data. The paper also presents implications for the transmission mechanism of technology shocks across countries and for the Barro and King (1984) critique of investment shocks.

JEL Classification: E32, F32 and F41
Keywords: Backus-Smith puzzle, international business cycles and investment-specific technology shocks

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1 Introduction

Since the seminal work by Backus, Kehoe and Kydland [1992, 1994] (BKK henceforth), general equilibrium models driven by Hicks-neutral technology shocks (or TFP shocks) have provided valuable insights on a wide range of international business cycle features. Notably, the countercyclical behavior of the trade balance is well understood within the realm of these models. Accounting for the joint dynamics of international prices and quantities, however, remains a central issue of international business cycles. Two features of the data have received much attention in the literature. First, international relative prices tend to appreciate when domestic consumption and output increase more than their foreign counterparts.[1] Second, both international relative prices and trade flows are volatile over the business cycle.[2] These stylized facts bear implications for the transmission of shocks across countries, the degree of international risk-sharing, and the sources of business cycle fluctuations.

This paper shows that understanding the joint dynamics of international prices and quantities requires generating large shifts in domestic absorption relative to output. I then propose a theory that involves an additional source of technological variation (investment-specific technology or IST shocks), a transmission mechanism with higher short-run response of output to shocks (through changes in the utilization of installed capital), and weak wealth effects on labor supply. Interestingly, the two features of data of interest turn out to be properties of the efficient allocation chosen by a social planner.

Recent empirical evidence suggests that TFP and IST shocks jointly account for a large fraction of the variation in output and hours over the business cycle.[3] In this broader interpretation

[1] See, for instance, Backus-Smith [1993], Kollman [1995], Stockman and Tesar [1995], Chari, Kehoe and McGrattan [2002], Benigno and Thoenissen [2008] and Corsetti, Dedola and Leduc [2008].

[2] See the original Backus, Kehoe and Kydland [1994] work, Baxter [1995], Boileau [1999], Heathcote and Perri [2002], Engel and Wang [2008].

[3] Early studies on the importance of investment-specific technology shocks include Greenwood *et al.* [1988], Hansen and Prescott [1993] and Greenwood *et al.* [2000]. More recently, Fisher [2006] estimates that neutral and investment-specific technology shocks account for almost eighty percent of the variation of output in the post-1982 period. Justiniano *et al.* [2008] find similar results estimating a medium-scale DSGE model that includes several shocks and frictions. Justiniano and Primiceri [2008] argue that changes in the volatility of investment shocks can

of technology shocks, investment shocks often drive business cycles. The empirical literature, however, typically abstracts from open economy considerations: one contribution of the paper is to explore the theoretical and quantitative implications of this view of technology shocks for international business cycles.

From the perspective of the theory, I modify an otherwise standard two-country model à la BKK along two dimensions. First, I introduce variable capacity utilization. Hence, technology shocks stimulate output and the accumulation of capital through a more intensive utilization of installed capital. Second, I consider a class of preferences with no intertemporal substitution on labor efforts (GHH preferences), as in Greenwood, Hercowitz, and Huffman [1988].[4] I show that this framework is quantitatively consistent with the empirical properties of international relative prices and trade flows documented, without affecting the standard business cycle regularities.

Real exchange rates in the data appreciate when domestic consumption is higher than foreign consumption, leading to a low and often negative correlation between real exchange rates and relative consumption. Therefore, consumption is higher where it is more expensive. Theoretical models produce large and positive correlations between the real exchange rate and relative consumption, as the real exchange rate is tightly linked to the ratio of marginal utilities of consumption. The standard theory implies that consumption is higher wherever it is cheaper, in stark contrast with the data. The literature often refers to this failure of the theory as the Backus-Smith puzzle (see Backus-Smith [1993]) or consumption-real exchange rate anomaly (see Chari, Kehoe and McGrattan [2002]).

Fluctuations in the terms of trade are also difficult to reconcile with standard models of international business cycles. In the data, the terms of trade tend to appreciate when domestic output increases more than foreign output, as documented in Corsetti, Dedola and Leduc [2007] among others. In the standard models, the terms of trade reflect primarily the relative scarcity in pro-

explain most of the changes in volatility of U.S. macroeconomic variables during the post-war period.

[4]GHH preferences are commonly used in open economy models. See Raffo [2008] for a survey. For an early contribution on the role of variable capacity utilization in the transmission of neutral technology shocks across countries, see Baxter and Farr [2005].

duction across countries. An increase in domestic production induced by a change in total factor productivity is associated with a depreciation of the terms of trade, as domestic goods are more abundant than foreign goods in international markets.

Last, in the data both net exports and the terms of trade display sizable volatility over the business cycle: net exports are half as volatile as output and the terms of trade are almost twice as volatile as output. In the model, general equilibrium effects introduce a trade-off between the volatility of relative prices and the volatility of trade flows. When the trade structure is defined by a constant-elasticity-of-substitution aggregator over domestic and foreign goods, as in Armington [1969], the model inherits an inverse relationship between the volatility of trade flows and international prices. The higher (lower) the elasticity of substitution between traded goods, the larger (smaller) the response of prices to shocks, whereas the opposite is true for quantities.

Accounting for the aforementioned properties of the data requires large changes in absorption over the business cycle. The main insight of the paper is that IST shocks provide a plausible source of variation in domestic absorption, since they do not affect directly aggregate efficiency. In this dimension, they resemble taste shocks. The economy accommodates a positive shift in absorption by (i) increasing production of intermediate goods, (ii) increasing prices, and (iii) increasing imports of goods from abroad. As a consequence, the terms of trade appreciate and the trade balance deteriorates. When IST shocks account for a significant fraction of business cycle fluctuations, as suggested by the empirical literature, the model generates an appreciation of international relative prices during expansions and large volatility of international relative prices and quantities, consistent with the data.

I then present two implications derived from this theory. The first is about the *direction* of terms of trade changes associated with different technology shocks. In response to TFP shocks, the terms of trade primarily reflect relative changes of traded goods production across countries. The terms of trade depreciate when the economy expands. In response to IST shocks, in contrast, shifts in domestic absorption affect directly the relative demand of traded goods across countries. The terms of trade appreciate when the economy expands. So, these findings suggest a reconsideration of the international transmission of technology shocks as typically interpreted in the empirical literature.[5]

The second implication is about domestic comovement. In a frictionless closed economy model, shocks to the marginal efficiency of investment stimulate labor effort and output through intertemporal substitution of leisure. However, agents choose to postpone consumption as well, resulting in a negative comovement of consumption with labor and investment, which is counterfactual. This observation, originally due to Barro and King [1984], points toward a limited role of investment shocks in accounting for business cycle fluctuations. I show that the transmission mechanism exploited in the paper, which relies on variable capacity utilization and weak wealth effects on labor supply, can preserve comovement among domestic variables. Perhaps surprisingly, I find that the possibility of importing goods from abroad has very little quantitative impact on comovement. Thus, despite the strong response of output to investment shocks, the benchmark model reproduces the typical business cycle features observed in the data.

2 Empirical Motivation

This section presents the two main facts that motivate my study: that international relative prices tend to appreciate when domestic consumption and output increase more than abroad; and that both the terms of trade and trade flows are volatile over the business cycle. This section serves also the purpose of discussing related literature on this issue. I later argue that both facts require large movements in absorption - that is, something like a demand shock - and that IST shocks provide such a source of variations in absorption.

Throughout the paper, international prices are computed as the ratio of foreign prices to domestic prices, both expressed in domestic currency. All statistics refer to HP-filtered series, unless otherwise noted. The Appendix provides more details on the sources and construction of the series.

[5] See, for instance, Clarida and Galì [1994], Corsetti, Dedola and Leduc [2007, 2008], Enders and Muller [2009].

Fact 1: International relative prices tend to appreciate when domestic consumption and output increase more than foreign consumption and output.

Figure 1 presents business cycle components of the U.S. trade-weigthed real exchange rate and of U.S. consumption relative to an aggregate of its major trading partners' consumption[6]. The chart shows that there is negative relationship between the two variables (the correlation is -0.18). Hence, increases in U.S. consumption relative to foreign consumption are associated with increases in U.S. CPI relative to foreign CPI (i.e. appreciations of the real exchange rate).

[Please insert Figure 1 here]

This feature of the data has been originally documented in Backus and Smith [1993], and does not apply exclusively to the United States. Corsetti, Dedola and Leduc [2007], for instance, report that the median value for this correlation among OECD countries is -0.30. The negative relationship between relative consumption and real exchange rates represents a central puzzle of international data, since consumption smoothing implies exactly the opposite relationship between the two quantities. For simplicity, assume that there are two agents, home (H) and foreign (F), and asset markets are complete. Optimality requires equalization of (real) marginal utilities, or

$$RER = \frac{eP^F}{P^H} \propto \frac{U_{c_t}^F}{U_{c_t}^H} \tag{1}$$

Under the assumption that the utility function is logarithmic in consumption, (1) implies that the correlation between the real exchange rate and relative consumption is one. More generally, equalization of (marginal utility of) consumption requires that consumption is higher where it is cheaper. This result is preserved if one considers a production economy where the utility function includes leisure and is non-separable, as in a standard model à la BKK. Chari, Kehoe and McGrattan [2002] note that this anomaly is robust to many deviations from the standard

[6]Business cycle components are derived using Christiano-Fitzgerald band-pass filter and excluding frequencies higher than one and a half years and lower than eight years.

model and 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."

The negative correlation between the real exchange rate and relative consumption is often interpreted as evidence of low international risk-sharing. Corsetti, Dedola, and Leduc [2007] propose a model with incomplete asset markets where productivity shocks have large uninsurable wealth effects through international prices, depending on the trade elasticity and the persistence of shocks[7]. Kollmann [2009] accounts for the Backus-Smith correlation with a model where a significant fraction of agents has no access to asset markets. Stockman and Tesar [1995], instead, emphasize the role of taste shocks together with non-traded goods as an alternative explanation of the consumption-real exchange rate anomaly[8]. Notwithstanding the general problems of identifying structural disturbances, taste shocks appear to suffer the most from this criticism. Nevertheless, both lines of research suggest that absent a mechanism that either directly or indirectly generate significant shifts in domestic absorption, models driven by productivity shocks will have a hard time accounting for the observed movements in the real exchange rate and relative consumption.

The cyclical behavior of the terms of trade and relative output is also puzzling from the perspective of standard theories. Figure 2 plots business cycle components of the U.S. terms of trade and U.S. GDP relative to an aggregate of its major trading partners' output.

[Please insert Figure 2 here]

Once again, the data suggests that the U.S. terms of trade appreciate at times of expansion in domestic production relative to foreign production. The correlation between the two variables is

[7]Benigno and Thoenissen [2008] show that a standard two-country model with incomplete markets and a non-traded sector can reproduce the consumption-real exchange rate anomaly. Their setup, however, generates international prices that are less volatile than in the standard BKK model. The environment studied in Corsetti, Dedola, and Leduc [2007] is successful in reproducing the volatility of international relative prices observed in the data, at least for low values of the trade elasticity.

[8]See also Heathcote and Perri [2009] for a similar approach based on preference shocks.

-0.36, and it is -0.20 for the median OECD country (see Corsetti, Dedola, and Leduc [2007] for recent evidence).

From the perspective of the theory, this feature of the data is also puzzling. Let us return to our simple example and assume that the two agents have endowments of an agent-specific good but consume a bundle of the both goods. In this environment, any positive shock to the home output implies a decline of its price and a corresponding increase in the price of the foreign good. The intuition for this result relies on a relative scarcity argument: positive shocks to the supply of one good induce an increase in the demand for the other good. The subsequent appreciation of the terms of trade, whose strength depends on the elasticity of substitution between goods, has implications for risk-sharing and the transmission of shocks across countries. As pointed out by Cole and Obstfeld [1991], the movements in the terms of trade supports consumption for the agent that did not experience an increase in the supply of its good, thus providing insurance against idiosyncratic shocks. Heathcote and Perri [2002] find that in a two-country model à la BKK the allocation obtained in a bond economy is very close to the social planner solution, thus quantitatively confirming the robustness of this mechanism. The data, however, provide no support for this mechanism, suggesting that models need to generate shifts in absorption that induce expansion in production together with appreciation of the terms of trade.

Fact 2: International relative prices and trade flows are volatile over the business cycle.

Table 1 presents the standard deviation of the terms of trade and trade flows (measured as real net exports over GDP) relative to the standard deviation of output for a sample of OECD countries. As indicated by their median values, the terms of trade are about twice as volatile as output whereas trade flows are half as volatile as output. Hence, both international quantities and prices are quite volatile.

[Please insert Table 1 here]

The bottom part of Table 1 presents simulation results obtained from benchmark BKK model where cycles are driven by TFP shocks and with capital adjustment costs calibrated to reproduce the volatility of investment relative to output. Two findings emerge. First, the BKK model delivers very little volatility in trade variables, accounting for almost none of the empirical volatility of trade flows and about one third of the volatility of the terms of trade. While the dynamics of trade flows in the model reflects the incentives to invest across countries ("make hay when the sun shines"), Table 1 suggests that quantitatively this mechanism does not generate sufficient reallocation of resources across countries as in the data. Second, general equilibrium considerations introduce a trade-off between the volatility of trade prices and the volatility of traded quantities. Consider for simplicity our two-agents example presented above. When the consumption bundle is assumed to be a CES aggregator, as the literature typically does, then the terms of trade are a function of the import ratio that depends on the trade elasticity[9]. As goods become more complement (low trade elasticity), technology shocks induce a larger response in relative prices only by making the response of quantities even more muted. On the other hand, as goods become more substitute (high trade elasticity), the response of trade flows increases at the expense of the variability in international relative prices.

In her contribution to the *Handbook of International Economics*, Baxter [1995] identifies the lack of volatility of net exports and the terms of trade generated by general equilibrium models as a major challenge for traditional business cycle theory. Boileau [1999] incorporates trade in capital goods into an otherwise standard two-country model à la BKK to account for these volatilities. However, his model does not generate other typical features of international business cycles, such as the countercyclicality of net exports, and does not address *Fact 1*. More recently, Engel and Wang [2008] considers a model with trade in both capital and durable goods. Their model provides valuable insights in accounting for the volatility of trade variables and countercyclical net exports. However, the terms of trade and the real exchange rate are negatively correlated in their model, indicating that their approach would likely have difficulties in accounting for *Fact 1*.

[9] The import ratio is defined as the ratio of imports relative to output excluding exports.

3 The Economy

Consider two countries ($i = 1{,}2$) of equal size populated by identical infinitively lived agents. The representative agent in each country maximizes lifetime utility (V_{it}) defined over sequences of consumption of final goods (C_{it}) and hours worked (N_{it}) :

$$V_{it} = E_0 \sum_{t=0}^{\infty} \beta^t U(C_{it}, N_{it}) \tag{2}$$

where E_0 refers to the expectation conditional on the information available at time zero. The time endowment is normalized to one and the discount factor is such that $0 < \beta < 1$. The momentary utility function takes the functional form

$$U(C, N) = \frac{[C - \psi N^{\nu}]^{1-\gamma}}{1-\gamma} \tag{3}$$

as proposed by Greenwood, Hercowitz and Huffman [1988] (so called GHH preferences). Parameters are such that $\psi > 0, \gamma > 0$, and $\nu > 1$. 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[10]. Raffo [2008] 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.

As in a Ricardian model of international trade, each country specializes in the production of one intermediate good ($j = A, B$). The production of the intermediate good output (Y_{it}) is carried out according to a Cobb-Douglas production function that uses capital services and labor, which are immobile across countries:

$$Y_{it} = e^{z_{it}} \left(u_{it} K_{it}\right)^{\theta} N_{it}^{1-\theta} \tag{4}$$

where z_{it} is an exogenous neutral technology shock. Capital services consist of the stock of installed physical capital (K_{it}) and the rate of capacity utilization (u_{it}). The resource constraints

[10] The parametric assumptions are: $\nu = 1$ and $\gamma = 1$. In addition, capital and labor are perfect substitutes in the production of the home good. When shocks are assumed to be trend-stationary, GHH preferences are consistent with balanced growth under the assumption that productivity in the home sector grows at the same rate as market productivity.

associated with intermediate goods production in the two countries are

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

and

$$B_{2t} + B_{1t} = Y_{2t} \tag{6}$$

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

$$G_{it}(A_{it}, B_{it}) = \begin{cases} \left[\varpi_i A_{it}^{1-\alpha} + (1-\varpi_i) B_{it}^{1-\alpha}\right]^{\frac{1}{1-\alpha}} & i = 1 \\ \\ \left[(1-\varpi_i) A_{it}^{1-\alpha} + \varpi_i B_{it}^{1-\alpha}\right]^{\frac{1}{1-\alpha}} & i = 2 \end{cases} \tag{7}$$

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

$$C_{it} + I_{it} = G_{it}(A_{it}, B_{it}) \tag{8}$$

Capital accumulation evolves according to the law of motion

$$K_{it+1} = [1 - \delta(u_{it})]\, K_{it} + e^{v_{it}} I_{it} + \Psi\left(.\right) \tag{9}$$

where $\Psi(.)$ is a convex adjustment cost. The economy incurs no cost of changing capital in steady state and the function $\Psi(.)$ is increasing in the level of capital, hence $\Psi(K_{ss}) = 0$, $\Psi(.)' > 0$ and $\Psi(.)'' > 0$. As in Greenwood *et al.* [1988], capital depreciation $\delta(u_{it})$ is an increasing and convex function of the utilization rate: $\delta'(u_{it}) > 0, \delta''(u_{it}) > 0$. The term $e^{v_{it}}$ represents investment-specific technical change, as in Greenwood, Hercowitz and Krusell [2000] and Fisher [2006]. This formulation implies that IST shocks affect the productivity of new capital goods, but they do not change the productivity of installed capital.

The shock process is assumed to be VAR(1):

$$\mathbb{Z}_t = \Omega \mathbb{Z}_{t-1} + \epsilon_t \tag{10}$$

$$E(\epsilon_t \epsilon_t') = \Sigma \tag{11}$$

where $\mathbb{Z}_t = [z_{1t}, z_{2t}, v_{1t}, v_{2t}]$ and $\epsilon_t = [\varepsilon^z_{1t}, \varepsilon^z_{2t}, \varepsilon^v_{1t}, \varepsilon^v_{2t}]$. Ω is a 4x4 matrix governing the persistence and spillover of the shocks. Σ is the variance-covariance matrix associated with VAR process. Both Ω and Σ are symmetric across countries.

Trade variables in country 1 are defined as follows. Net exports over GDP are the difference between real exports and real imports relative to real output[11]

$$RNX_{1,t} = \frac{A_{2t} - B_{1t}}{Y_{1t}} \tag{12}$$

Relative prices can be derived from the first order conditions associated with the optimization problem. The terms of trade, defined as price of imports relative to exports, are computed from the marginal rate of substitution in the Armington aggregator:

$$TOT_{1t} = \frac{\partial G_1(A_1, B_1)/\partial B_1}{\partial G_1(A_1, B_1)/\partial A_1} = \frac{1-\varpi_1}{\varpi_1}\left[\frac{A_{1t}}{B_{1t}}\right]^{\frac{1}{\sigma}} \tag{13}$$

The real exchange rate is proportional to the ratio of marginal utilities:

$$RER_{1,t} = \frac{U_{C_{2,t}}}{U_{C_{1,t}}} \tag{14}$$

4 Parameterization

Table 2 reports the parameters used in the calibration of the benchmark experiment.

[Please insert Table 2 here]

The discount factor is 0.99, consistent with a real interest rate in steady state of about 1 percent. The coefficient of relative risk aversion (γ) is 2. The curvature parameter in the GHH preferences (ν) is set to 1.64, so that the implied Frisch elasticity is the same as in the isoelastic preferences considered by BKK (about 1.5).

[11] Exports, imports and output are evaluated using steady state prices.

The share of labor in production $(1-\theta)$ is 0.64. Consistent with long-run values for the United States, the import share is 15 percent, which pins down the home bias in domestic absorption (ϖ).

The specification of the depreciation function follows Greenwood *et al.* [1988]:

$$\delta(u) = \frac{\kappa}{\omega} u_t^{\omega} \tag{15}$$

I calibrate the parameters κ and ω as follows. The first order condition with respect to u_t and the law of motion of capital, both evaluated in the steady state, imply the two relationships

$$\theta \frac{Y}{u} = \kappa u^{\omega-1} K \tag{16}$$

and

$$\frac{\kappa}{\omega} u^{\omega} = \frac{I}{K} \tag{17}$$

I set the long-run quarterly depreciation rate to 0.025, as implied by the average investment-to-capital ratio, and the long-run utilization rate to 0.75, which is the average value in the U.S. data. Given that investment is about 25 percent of output, the solution to equations (16) and (17) determines the values of ω and κ.

The trade elasticity in the benchmark case is equal to 0.5.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, estimate a value of 0.9. In the baseline calibration, Corsetti, Dedola, and Leduc [2007] estimate the trade elasticity using method of moments targeting the empirical volatility of the real exchange rate. In their bechmark case - given the calibrated value for the share of the distribution sector - the implied trade elasticity falls below 0.5.

Turning to the shock process, I approximate IST shocks with the changes in the relative price between investment and consumption, as it is often assumed in the literature[12]. However, in

[12]The relationship between IST shocks in a two-sector model and changes in the relative price of investment is exact under some (quite restrictive) assumptions, namely equal factor shares in production and no impediments in the reallocation of inputs across sectors. Nevertheless, it is widely used in the empirical literature. See Guerrieri *et al.* [2009] for an interesting quantitative analysis of this issue.

estimating the dynamic effects of TFP and IST shocks for the United States, Fisher [2006] argues that neglecting quality adjustments in the investment price deflator has important quantitative implications for his estimates. Hence, Fisher constructs an investment price series alternative to the NIPA deflators which uses the quality-adjusted indices for equipment and software (E&S) produced by Cummins and Violante [2002][13]. Unfortunately, there is little availability of quality-adjusted E&S deflators for other economies, and in many cases it is even difficult to find quarterly series for such deflators. Nonetheless, the relative price of equipment, when available, appears to share similar properties to the corresponding series for the United States. For instance, Figure 3 presents the business cycle component of the relative price and the real share of equipment investment obtained from National Accounts for Australia, Canada, Italy, and the United States[14]. There is a clear negative relationships between the two series in the United States, as previously documented in Greenwood, Hercowitz and Krusell [2000] and Fisher [2006]. This pattern holds in the other economies as well, with correlations of -0.36 in Australia, -0.16 in Canada, and -0.38 in Italy.

Motivated by this observation, I calibrate the statistical properties of neutral and investment-specific technology shocks to reproduce the evidence provided by Fisher for the United States. In particular, I target two statistics in this exercise. First, the relative variance of the two domestic technology shocks is set so that the IST shock explains about 50 percent of the variance of output and the TFP shock 25 percent of it. Hence, these shocks together account for 75 percent of the overall variation of output. Notably, Justiniano *et al.* [2008] find very similar results by estimating a structural DSGE model that includes several shocks and frictions. Second, the correlation between innovations of the two technological shocks is set so that the model gener-

[13] The classical reference on this point is Gordon [1989], who first showed the empirical relevance of taking into account quality adjustments for durable equipment. Cummins and Violante [2002] extend Gordon's work by producing quality-adjusted price indexes for 24 categories of E&S from 1947 to 2000. On a related point, Gort et al. [1999] argue that investment in structures is also subject to significant tecnhological improvement not captured by the standard accounting procedures.

[14] The real share of investment is the quantity of equipment in units of capital relative to gross domestic product in consumption units. The cyclical component is obtained by applying a band-pass filter that excludes frequencies higher than 18 months and lower than eight years.

ates countercyclical relative price of investment within each country, consistent with the evidence provided in Figure 3. As for the remaining parameters, the calibration assumes that both neutral and investment-specific shocks are persistent with some moderate spillover across countries, as in the original BKK article.

5 Findings

This section introduces the main findings of the paper. Sections 5.1 presents the quantitative performance of the model and Section 5.2 explores the core economic mechanism by means of impulse response analysis. Section 5.3 and 5.4 derive implications from the theory with respect to the response of international prices to technology shocks and the Barro-King [1984] critique of investment shocks respectively.

5.1 Model Simulations

Table 3 reports HP-filtered statistics for the data, the benchmark economy, and variations of the benchmark economy. The United States represents the home country, while the foreign country is constructed by aggregating series for Canada, EU-15 and Japan. These countries altogether account for more than half of U.S. trade over the sample considered. The appendix provides details about the data sources and the construction of the foreign aggregate. In all tables, net exports refer to the real net trade in goods and services relative to GDP.

[Please insert Table 3 here]

The first column presents the properties of the data. Since I use the quality-adjusted series for the relative price of investment constructed by Fisher [2006], the sample is restricted to the period 1983-2000[15]. Nevertheless, the shorter sample does not affect the standard business cycle features

[15] In his analysis, Fisher [2006] splits the sample in 1983 to account for the abrupt increase in the average decline of the investment price. See also Justiniano and Primiceri [2008] on the same issue.

reported in the literature. In terms of volatility, consumption is less volatile than output (with a ratio of standard deviations of 0.7) whereas investment is almost three times more volatile than output. Thus, overall domestic absorption is more volatile than output, a central observation for understanding movements in international prices and quantities. Turning to inputs of production, labor - measured as total hours of work - is less volatile than output while capacity utilization is more volatile than output. The measure of capacity utilization is constructed by the Board of Governors and is published in the release G.17. As for the trade variables, the volatility of net exports for the United States is about one-third the volatility of output. This value is in the lower range of the distribution presented in Table 1, but remains consistent with sizable fluctuations in trade flows over the business cycle. Finally, international relative prices are more volatile than output, with the real exchange rate more volatile than the terms of trade.

In terms of correlations, all domestic variables are strongly procyclical. Further, consumption, hours worked and investment comove over the business cycle, yet another stylized feature of the data. This last observation is often difficult to reproduce in multi-sector models with supply shocks, as these shocks induce reallocation of resources to the most efficient technology.

In the data, net exports are negatively correlated with output (-0.43).[16] This statistic indicates that countries borrow from international capital markets in good times, different from the implications of standard consumption smoothing theory. As originally documented by Backus and Smith [1993], the correlation between the real exchange rate and relative consumption is negative (-0.23). Similarly, the correlation between the terms of trade and relative output is negative (-0.17). Hence, international relative prices appreciate when domestic consumption and output are higher than abroad.

The second column in Table 3 - labelled "Benchmark Economy" - presents the main quantitative findings of the paper. In terms of volatility (relative to output), the model reproduces the standard deviations of consumption, investment, and domestic absorption. Hours worked are

[16] See, for instance, the original BKK articles, Heathcote and Perri [2002], Raffo [2008], and Engel and Wang [2008].

somewhat less volatile than in the data, but more so than in a typical international real business cycle model. Capacity utilization is also somewhat less volatile than in the data, although in this case the data might overstate the volatility of utilization as it is constructed using information only from the manufacturing, mining and utilities sectors. The model also generates procyclical consumption, hours worked, and investment as well as comevement among these variables. Thus, the usual domestic business cycle properties are unaffected by the introduction of IST shocks, variable capacity utilization and GHH preferences.

The benchmark economy reproduces remarkably well the main features of international quantities and prices. First, the model can reproduce simultaneously the high volatility of trade flows and international relative prices. The volatility of trade flows increases by a factor of four relative to the standard BKK model (see Table 1), and it is even slightly larger than in the U.S. data (0.37 vs 0.28), although the value for the United States is in the lowest range among OECD countries. Notably, the model reproduces about 90 percent of the empirical volatility of the terms of trade. Relative to a standard BKK model, the terms of trade in the benchmark economy are almost three times more volatile (see again Table 1). Therefore, the model can account for *Fact 2*. The main failure in this respect is the lower volatility of the real exchange rate relative to the terms of trade (and, as a consequence, relative to the data). This result is not surprising: absent deviations from the law of one price, the consumption real exchange rate is a linear transformation of the terms of trade. Recent work by Atkeson and Burstein [2008] shows that the producer–price based real exchange rate empirically is also more volatile than the terms of trade, suggesting that the practice of pricing-to-market is widespread among exporters. These authors incorporate imperfect competition with variable markups and trade cost into a model of international trade to generate pricing-to-market and large deviations from relative purchasing power parity. Embedding a richer market structure as in Atkeson and Burstein [2008] into the benchmark economy should not affect the main macroeconomic implications of the mechanism proposed here, but I leave this project to future research.

Turning to the cross-correlations, the model generates negative correlations between the real exchange rate and relative consumption as well as between the terms of trade and relative output. Hence, the model can also account for *Fact 1*. Remarkably, the Backus-Smith correlation characterizes the efficient allocation chosen by a social planner facing IST shocks and non-separable preferences. This last observation suggests that the Backus-Smith correlation is not necessarily evidence in favor of the role of incomplete markets in the transmission of shocks across countries, as often advocated in the literature.

[Please insert Table 4 here]

Are the model's implications for the relative price of investment reasonable *vis-à-vis* the data? Table 4 addresses this issue as follows. First, the table presents the moments targeted in the calibration of the shock process. Then, it documents empirical properties of Fisher's relative price of investment in terms of volatility and correlations, and compares them with the corresponding moments implied by the model. Given that the latter moments are not used in the calibration, they provide an additional test to the mechanism proposed by the theory.

The top portion of Table 4 reports the statistics targeted in the calibration of the shock process, namely the variance decomposition of GDP and the correlation between the investment price and GDP reported in Fisher [2006]. In the benchmark economy, (domestic) IST shocks explain almost half of the variance of GDP whereas TFP shocks account for only a quarter of it. In addition, the relative price of investment is negatively correlated with GDP, which is consistent with the idea that shocks to the supply of investment are important over the business cycle.

The bottom portion compares other empirical moments of the investment price series with the corresponding moments implied by the model. In the data, the investment price series is almost as volatile as GDP, is quite persistent (with a first-order autocorrelation of 0.85), and is positively correlated with trade variables (net exports and the real exchange rate). The model reproduces these features quite well. The volatility of the investment price is slightly above its empirical counterpart, but remains below the volatility of output. The investment price is also quite persistent and positively correlated with trade variables.

In sum, three quantitative implications emerge from this exercise. First, when IST shocks explain a large fraction of the variation of output, international relative prices and trade flows are about as volatile as in the data. Second, the real exchange rates and the terms of trade appreciate when domestic consumption and output increase more than foreign consumption and output. Third, the introduction of IST shocks does not affect the standard features of business cycles in terms of volatility, cyclicality, and comovement of domestic variables.

5.2 Inspecting the Mechanism: Impulse Response Analysis

This section illustrates the transmission mechanism of IST shocks in the benchmark economy by means of impulse response analysis[17]. The main insight of the paper is that investment-specific technology shocks introduce a source of fluctuations in domestic absorption that does not directly affect the aggregate production function. Therefore, IST shocks resemble a typical demand shock, similar to the preference shocks considered in Stockman and Tesar [1995] or Heathcote and Perri [2009]. Differently from these papers, however, the data provide more discipline in modelling IST shocks and the structural interpretation of IST shocks appears less controversial.

[Please insert Figure 4 here]

As shown in the first row of Figure 4, a positive IST shock generates an investment boom associated with an expansion in consumption, leading to a large increase in domestic absorption. In turn, this increase in domestic absorption has three implications for the supply-side of the economy, which can be easily read from the resource constraint of the economy (recall that an IST shock corresponds to a change in the price of investment relative to consumption):

$$C_t + e^{-v_t} I_t = G_a e^{z_t} \left(u_t K_t\right)^{\theta} N_t^{1-\theta} - NX_t \tag{18}$$

[17]For simplicity, I do not discuss the case of a TFP shock as the features introduced in the model do not affect qualitatively the response of the main economic variables to this shock.

First, domestic production expands bacause of higher capital services, achieved through increases in utilization rates. The consequent shift in the marginal product of labor schedule encourages workers to postpone leisure, thus leading to a strong response of aggregate hours worked (middle panels in Figure 4). Second, production efficiency requires moving resources from the foreign country into the domestic country, since producing investment goods in the home country is now more productive. Therefore, an IST shock is associated with a trade deficit (first panel in the last row of Figure 4). Finally, provided that final goods are intensive in domestically-produced intermediates, the increase in domestic absorption makes domestic output more expensive and the relative value of intermediate goods in terms of final goods increases (G_a). Thus, the terms of trade appreciate when domestic production expands, as in the data.

As discussed before, the planner chooses an allocation characterized by a negative relationship between the real exchange rate and relative consumption. Hence, the Backus-Smith correlation in this environment is a requirement of production efficiency. The mechanics of this result can be understood by analyzing the log-linear expression of the real exchange rate:

$$\begin{aligned} \widehat{RER}_t &= \widehat{U}_{C_{2,t}} - \widehat{U}_{C_{1,t}} \\ &= \gamma \left[(\alpha_C \widehat{c}_{1,t} - \alpha_N \widehat{n}_{1,t}) - (\alpha_C \widehat{c}_{2,t} - \alpha_N \widehat{n}_{2,t}) \right] \end{aligned} \tag{19}$$

Efficiency requires that the marginal utility of consumption is equalized across agents in the two countries. After a positive IST shock, the stronger response of hours worked relative to consumption (Figure 4) determines an *increase* in the marginal utility of consumption in the home country. This is so because, as the IST shock triggers a sharp increase in the marginal product of capital, the opportunity cost associated with an extra unit of current consumption is very high. Under standard preferences, the consumer would indeed postpone consumption and leisure. Under GHH preferences, consumption increases, but less than labor input. As for foreign marginal utility, the wealth effects associated with this shock induce a stronger increase in consumption than in hours worked, leading to a decline in the marginal utility of consumption.

This mechanism relies on two essential features of the utility function, namely the non-separability between consumption and leisure, and the absence of wealth effects on labor supply. The role of the first element is straightforward, as under the separable utility function the real exchange rate is perfectly correlated with the ratio of consumption. Section 6.1 below explores in more detail the role of short-run wealth effects on labor supply.

5.3 On the Transmission of Productivity Shocks and International Prices

A large and growing literature investigates the (conditional) response of international prices to structural shocks generating business cycles. In the Mundell-Fleming-Dornbusch (MFD) tradition, an increase in money supply results in a rise in output and a real depreciation of the currency. Similarly, a positive supply shock increases output together with a depreciation of international prices. Demand shocks increase output together with an appreciation of international prices. Starting from these theoretical findings, Clarida and Galì [1994] estimate VARs - identified with long-run restrictions - that include the bilateral real exchange rate of the United States with Germany, Japan, Canada, and the United Kingdom as a variable. They find that demand and monetary shocks account for most of the fluctuations of the real exchange rate and that the impulse responses obtained from the data provide support for the MFD transmission mechanism. Interestingly, they define demand shocks as "*capturing shocks to home absorption relative to foreign absorption*."

More recently, Corsetti, Dedola and Leduc [2007, 2008] find that shocks to productivity are associated with expansions of output, appreciation of international prices, and deterioration of the trade balance. Their empirical strategy relies on structural VARs as well, identified with either long-run restrictions or sign restrictions. Since their theoretical framework is the standard international real business cycle model à la BKK, they interpret these findings as evidence in favor of incomplete markets triggering large changes in relative wealth across countries. In this environment, changes in relative prices amplify wealth disparities. Similarly, Enders and Muller [2009] estimate bivariate VARs and find evidence that in the United States the terms of trade appreciate following a positive productivity shocks.

This paper provides two main insights on the relationship between structural shocks and international relative prices. First, it shows that the conditional response of international relative prices to technology shocks depends critically on the *type* of technology shocks considered. IST and TFP shocks are associated respectively with an appreciation and a depreciation of international relative prices. Second, it provides an explanation for the appreciation of international prices during periods of economic expansion that does not rely on large changes in relative wealth across countries, is driven by what looks like a demand shock, and yet originates from an improvement in the technical efficiency of producing of investment goods.

Figure 5 presents the impulse response of the terms of trade and output to a TFP shock (dotted line) and a IST shock (solid line). Given the strong link between output and hours worked implied by GHH preferences, the impulse responses of output are very similar to the impulse responses of labor productivity. For convenience, I plot only the former.

[Please insert Figure 5 here]

As shown in Figure 5, TFP shocks are associated with a depreciation of the terms of trade whereas IST shocks induce an appreciation of the terms of trade. Both technology shocks generate an expansion in economic activity (and an increase in labor productivity). Hence, the transmission mechanism of the two technology shocks through international prices is very different. The log-linear expression for the terms of trade provides the intuition for this finding:

$$\widehat{TOT}_{1t} = \psi \left[\varphi \ \left(\widehat{y}_{1t} - \widehat{G}_{1t} \right) + \left(\widehat{y}_{1t} - \widehat{y}_{2t} \right) \right] \tag{20}$$

where both $\varphi = \frac{1-2im}{im}$ and $\psi = \frac{1}{2\sigma(1-im)}$ are positive coefficients and, under standard parameter values, $\varphi > 1$. Notably, this derivation depends only on the production structure of the economy, while the form of the utility function is irrelevant.

Changes in the terms of trade reflect two offsetting forces. The term $(\widehat{y}_1 - \widehat{y}_2)$ says that changes in relative production across countries alter directly the relative scarcity of goods in the international markets. After an increase in domestic output, foreign output becomes more expensive and the terms of trade depreciate. Under this mechanism, the terms of trade provide insurance against country-specific shocks, as movements in relative prices offset movements in relative outputs. This result was first noted by Cole and Obstfeld [1991] in an endowment economy, and subsequently confirmed quantitatively by Heathcote and Perri [2002] in a two-country model with production à la BKK.

The term $\left(\widehat{y}_1 - \widehat{G}_1\right)$ reflects primarily shifts in domestic absorption relative to domestic output. Investment-specific technology shocks trigger an expansion in domestic absorption relative to foreign absorption, which raises both domestic output and domestic prices. Hence, the terms of trade appreciate and the trade balance deteriorates.

This discussion provides interesting empirical implications for the international transmission of productivity shocks and the sources of business cycle fluctuations. A negative correlation between the terms of trade and output is often considered *prima facie* evidence that domestic factors other than shocks to total factor productivity are an important determinant of international prices, as in Clarida and Galì [1994]. My analysis supports this view, but provides a different interpretation about the sources of fluctuations in absorption, since in my model they originate from investment-specific technology shocks. In addition, and differently from the approach taken by Corsetti *et al.* [2008] or Enders and Muller [2007], the appreciation in international prices generated by the model is consistent with an efficient allocation of resources, and does not depend on the presence of incomplete asset markets. In other words, international prices in this environment do not amplify the wealth effects associated with productivity shocks, and risk is fully shared across countries.

Finally, despite its widespread use, this analysis questions the use of VARs identified through long-run restrictions to recover the impulse response functions of international prices to technology shocks. As extensively discussed in Fisher [2006], when technology shocks other than

TFP are considered, this methodology is robust to the extent that the responses to the different technology shocks are sufficiently similar.[18] Figure 5, and the theoretical mechanism discussed so far, suggest that this condition is likely to be violated, as the sign of the impulse responses of international prices depends on the type of technology shock considered. Hence, not including the relative price of investment in VARs might lead to a mistaken inference in terms of the conditional response of international prices to shocks.

5.4 On the Barro-King [1984] Critique

The benchmark economy presented in this paper preserves the typical features of domestic business cycles, including the comovement of consumption with hours worked and investment. This result is less trivial than it might appear, since models where investment shocks provide significant contribution to business cycle fluctuations often generate weak or even negative comovement.[19]

Barro and King [1984] originally observed that in a simple neoclassical framework, shifts to aggregate investment raise output and the interest rate, but lower consumption, which contrasts with the typical pattern of business cycles. The intuition for this argument relies on an intertemporal substitution mechanism, which can be inferred from the resource constraint:

$$C_t + e^{-v_t} I_t = Y_t(K_t, L_t)$$

After a positive investment shock (a decline in e^{-v_t}), agents increase labor efforts to expand production and allocate more resources to capital accumulation. At the same time, however, today's consumption is very expensive and agents increase saving through investment. Thus, this mechanism generates negative comovement of consumption with hours worked and investment.

In principle, this issue could disappear if we allow borrowing from international capital mar-

[18] The reader is invited to consult Fisher [2006, page 420], for a formal statistical definition of these conditions.

[19] This point is a consequence of the two-sector interpretation of the model. Provided that only technology shocks generate business cycles, reallocation of resources across sectors implies negative comovement.

kets, as foreign trade loosens the domestic resource constraint:

$$C_t + e^{-v_t} I_t + NX_t = Y_t(K_t, L_t)$$

After a positive investment shock, agents can now increase imports, thus reducing the need to sacrifice consumption.

I next investigate quantitatively this point. Figure 6 presents the impulse response of consumption and leisure to a IST shock in a neoclassical economy closed to foreign trade and in the benchmark economy presented in the paper. I also plot the response of these variables in the standard BKK model, in order to assess the impact on comovement of relaxing the resource constraint through foreign trade. For the closed economy experiment and the BKK experiment, capital adjustment costs are calibrated to target the volatility of investment relative to output, the shock process is the same as in the benchmark economy, preferences are isoelastic, and capacity utilization is fixed.[20].

[Please insert Figure 6 here]

The RBC impulse response confirms the findings of Barro and King [1984]. After a positive IST shock, labor efforts increase, consumption drops, and the economy expands production in order to accumulate capital. Consumption moves in opposite direction relative to hours worked and investment. In the BKK model, the response of consumption remains weakly negative, suggesting that foreign trade provides only limited support to domestic consumption. In the eyes of the planner, shocks specific to the production of investment goods encourage a reallocation of resources to the most efficient location. Hence, as for TFP shocks, investment shocks stimulate imports of goods mainly to finance investment booms.

The transmission mechanism adopted in the benchmark economy has two distinctive features. First, variable capacity utilization implies that investment shocks have a larger short-run impact

[20] For the closed economy case, I set the persistence parameter equal to the largest eigenvalue implied by the open economy process.

on output. After an investment shock, the increase in capital utilization shifts the schedule of the marginal product of labor, triggering an increase in the real wage and hours of work. Nevertheless, this mechanism alone would not be sufficient to generate comovement as increasing the income effect of shocks provides incentives to enjoy both consumption *and* leisure. With GHH preferences, there is an additional intratemporal effect that creates substitution away from leisure towards consumption, as labor supply responds only to substitution effects. Benhabib *et al.* [1991] show that under a few parametric assumptions ($\nu = 1$ and $\gamma = 1$), GHH preferences represent a limiting case for a two-sector model that incorporates home and market productions, perfect substitutability between technologies and standard isoelastic preferences.[21] Hence, leisure in the benchmark economy is to be interpreted as the sum of hours spent in home production and leisure activities. After a shock to market technologies, the response of leisure activities is no different from the isoelastic utility case, while consumers reduce considerably home work and home consumption in favor of market work and market consumption. As a consequence, market work and market consumption are strongly positively correlated whereas home and market activities are negatively correlated.[22]

The ability of the model to reproduce the comovement among domestic variables bears additional implications for the cyclical properties of the trade balance. As mentioned above, net exports are countercyclical in the data, indicating that countries borrow from abroad at times of expansion in economic activity. This observation implies that absorption is more volatile than output. In fact, starting from the identity

$$DA = Y - NX$$

[21] Raffo [2008] finds that the parametric assumptions for GHH preferences commonly adopted in the literature ($\nu = 1.64$ and $\gamma = 2$) are equivalent, quantitatively, to a lower elasticity of substitution between home and market technlogies. Benhabib *et al.* [1991] show also that the standard case of isoelastic preferences corresponds to a unit elasticity of substitution between home and market technologies.

[22] There is large amount of evidence on the negative correlation between home and market activites. For instance, services that are substitutes for home production are strongly procyclical, such as restaurants, child-care, and cleaning services. Time-surveys provide a similar picture in terms of the allocation of time over the business-cycle or the life-cycle. See Benhabib *et al.* [1991] and Raffo [2008].

and, computing the variance of both sides of the equality, yields

$$Var(DA) = Var(Y) + Var(NX) - 2Cov(NX, Y) \tag{21}$$

Expression (21) shows that countercyclical net exports are an indication that domestic absorption fluctuates more than output over the business cycle. However, by the same logic, the volatility of absorption depends on the comovement between consumption and investment

$$Var(DA) = Var(C) + Var(I) + 2Cov(C, I)$$

Therefore, provided that models can generate the volatility of consumption and investment observed in the data, the comovement between these variables is intimately related to the cyclicality of net exports through the volatility of absorption. Table 5 presents simulations for the three economies analyzed above.

[Please insert Table 5 here]

The top panel presents the volatility of consumption, investment and absorption relative to output. All models generate reasonable volatilities for these variables, yet they have very different implications for absorption. For the closed economy case, absorption shares the same properties of output, by construction. In the open economy models, however, the volatility of absorption is much higher than output only in the benchmark economy. The middle panel presents the correlation of consumption with labor and investment and the correlation of net exports with output. As anticipated in the impulse response analysis, investment shocks in closed economies generate negative comovement between consumption and investment, which is counterfactual. In a two-country model à la BKK, this issue is somewhat alleviated but it not fully resolved. Remarkably, in both experiments investment shocks account for a very small fraction of the variation of output (bottom panel), and yet no comovement is preserved. Turning to the correlation of net exports with output, this statistic is positive in the BKK model with IST shocks and negative in the benchmark economy, confirming quantitatively our previous intuition. In sum, the inability of models with investment shocks to generate comovement between consumption and investment affects the cyclical properties of the trade balance, a stylized feature of international business cycles.

6 Features of the Model: A Discussion

This section presents a discussion of the features of the benchmark economy that are not commonly adopted in two-country models à la BKK. First, I investigate the role of GHH preferences by comparing simulations against three alternative utility functions, namely the isoelastic utility function adopted in BKK, the utility function proposed in Jaimovich and Rebelo [2009] and a utility function with external habit in consumption. Next, I investigate the role of variable capacity utilization. Finally, I present some discussion on the quantitative impact of the trade elasticity.

6.1 Utility Function

The absence of wealth effects on labor supply embedded in GHH preferences might appear an unappealing feature of the model, as it implies a large value for the labor supply elasticity. A large amount of literature provides estimates for this parameter, but disagreement on the appropriate value that should be used for macro models remains. Although our previous discussion regarding the home production interpretation of GHH preferences mitigates these concerns, it is still of interest to investigate the quantitative importance of the absence of wealth effects on labor supply for my findings. For this puropose, the first three variations of the benchmark economy presented in Table 3 summarize the results obtained by adopting alternative utility functions.

Following BKK, the literature usually assumes that utility is non-separable in consumption and leisure, and isoelastic:

$$U(C,N) = \frac{\left[C^{\mu}(1-N)^{\mu}\right]^{1-\gamma}}{1-\gamma} \tag{22}$$

The share parameter μ is equal to 0.34, so that in steady state agents allocate 30 percent of their time endowment to market activities. The curvature parameter γ is set to 2.0 as in the benchmark case. Notably, when $\gamma = 1$ this utility function corresponds to a case of unit elasticity of substitution between home and market activities.

This economy performs remarkably well in terms of business cycle statistics. Overall, the model reproduces the usual empirical regularities in terms of domestic volatilities and correlations, and net exports are weakly countercyclical. International relative prices and net exports display volatilities much closer to the data than in a standard BKK model (see Table 1). In addition, the correlation between the terms of trade and relative output is close to zero, confirming the role played by investment shocks in shifting relative absorption across countries. However, the model performs poorly with respect to the Backus-Smith puzzle and, to a lesser extent, the comovement of consumption with labor and investment. The first failure can be explained by noting the low volatility of hours relative to output (0.41): the response of labor to shocks is muted, and the risk-sharing condition is primarily determined by relative movements in consumption. In terms of comovement, the Barro-King critique discussed earlier applies, but comovement among consumption, hours and investment is only weak, not negative. The possibility of varying capital services through the capacity utilization rate is quantitatively an important factor for generating positive correlations (see Table 5 for comparison).

The experiment with BKK preferences emphasizes the importance of the wealth effects on labor supply for the Backus-Smith condition. How large do these wealth effects need to be? I next consider the utility function proposed by Jaimovich and Rebelo [2009]:

$$U(C_t, N_t) = \frac{[C_t - \psi N_t^{\nu} X_t]^{1-\gamma}}{1-\gamma} \tag{23}$$

where

$$X_t = C_t^{\eta} X_{t-1}^{1-\eta} \tag{24}$$

The parameter η is such that $0 \leq \eta \leq 1$. These preferences nest as limiting cases two classes of preferences commonly used in the business cycle literature. When $\eta = 0$, (23) reduces to the GHH utility function adopted in the benchmark economy and the wealth effects on labor supply are zero. When $\eta = 1$, on the other hand, (23) reduces to the class of preferences discussed in

King, Plosser and Rebelo (1988), for which wealth effects on labor supply tend to be negative (i.e. the wealth effect induced by an increase in the wage rate implies an increase in consumption and leisure).

The simulation reported in Table 3 assumes that $\eta = 0.10$.[23] Despite the very weak short-run wealth effects associated with this low value of η, the risk-sharing condition implies a correlation between the real exchange rate and the ratio of consumption across countries close to zero. Therefore, weak wealth effects on labor supply are quantitatively important to generate the Backus-Smith correlation. When $\eta = 0.10$ the model can still account for the volatility of international prices and trade flows, and for the negative correlation between the terms of trade and relative output. Finally, the performance of the model in terms of comovement is also unaffected.[24]

Last, I consider the case of external habit persistence in consumption, which is commonly used in the empirical macroeconomic literature. The utility function takes the form:

$$U(C_t, N_t) = \frac{(C_t - dC_{t-1})^{1-\gamma}}{1-\gamma} + \frac{(1-\psi N_t)^{1-\gamma}}{1-\gamma} \tag{25}$$

with $0 < d < 1$. The simulation assumes that $d = 0.8$ and $\gamma = 1$. Similarly to the case with BKK preferences, this model performs quite well with respect to usual business cycle properties as well as the volatility of international prices and quantities. The correlation between the terms of trade and relative output is positive, but very low. Once again, the main failure of the model consists in its inability to reproduce the Backus-Smith regularity and strong comovement among omestic variables. From the log-linear expression for the real exchange rate under external habit:

$$\widehat{RER} = A\left[(\widehat{c}_{1,t} - \widehat{c}_{2,t}) - d(\widehat{c}_{1,t-1} - \widehat{c}_{2,t-1})\right] \tag{26}$$

where $A = \frac{\gamma}{1-d}$ and d is the habit persistence parameter.[25] The habit persistence parameter has

[23] Jaimovic and Rebelo [2009] report that when $\eta = 0.10$ and no news shocks are considered, their two-sector model generate sectoral comovement.

[24] Simulations results (not shown) suggest that this is still the case even for specifications in which wealth effects on labor supply are sizable: when $\eta = 0.5$, the correlations of consumption with investment and labor are 0.56 and 0.58 respectively.

[25] The utility function is now separable in leisure, and labor does not enter the expression of the real exchange rate.

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 to increase the risk-aversion parameter. Nevertheless, no value of d could generate a negative correlation between real exchange rate and relative consumption.

In terms of comovement, the model with habit persistence performs similarly to the case with BKK preferences, although the correlation between consumption and hours is still slightly negative. Variable capacity utilization remains a quantitatively important feature for these results.

Lastly, it remains to verify what implications these alternative prefecence specifications carry for the relative price of investment (Table 4). In all cases, the relative price of investment turns out to be more volatile than in the data. Its volatility is about twice as large as in the data for Jaimovic-Rebelo preferences and is more than three times larger in the habit case. All three models perform like the benchmark economy in terms of autocorrelation of the relative price of investment and cross-correlation with trade variables.

In sum, these experiments suggest that a general equilibrium model that incorporates TFP and IST shocks together with variable capacity utilization can account for the volatility of international quantities and prices (*Fact 2*) and generate weak correlations between the terms of trade and relative output. However, these findings require a considerably larger volatility of the relative price of investment than observed in the data. The functional form of the utility function appears to be quantitatively important for the Backus-Smith correlation, as wealth effects on labor supply limit the response of hours to shocks.

6.2 Variable Capacity Utilization

Variable capacity utilization represents the second feature introduced in the benchmark economy as it allows to endogenously vary capital services through an intensive margin. I next explore quantitatively the importance of this feature.

The "Fixed Capacity" experiment in Table 3 reports simulation for the benchmark economy with constant capacity utilization. The shock process is calibrated as in Section 4, and the correlation between innovations is set to reproduce a negative correlation between the relative price of investment and output. However, under no reasonable parameterization for the relative volatility of TFP and IST innovations the model was able to reproduce the variance decomposition targeted in the benchmark economy. Hence, I decided to leave this parameter unchanged.

This economy performs well in terms of the usual business cycle statistics and the cyclical correlation of net exports with output. The volatilities of net exports and the terms of trade (*Fact 2*) are also well reproduced by the model. The correlation between the terms of trade and relative output is negative, and the Backus-Smith correlation is slightly negative. Hence, this specification brings the model close to account for *Fact 1* as well. Consumption is positively correlated with hours worked and investment, as in the data. Notably, IST shocks account for only 4 percent of the variation of output in this experiment, whereas TFP shocks account for 80 percent of business cycle fluctuations.

This last observation confirms that variable capacity utilization essentially allows demand-like shocks to stimulate output. The first order conditions that characterize the optimal choice of capacity utilization and of hours worked are:

$$e^{-v_{1t}}\left(\kappa u_{1t}^{\omega-1}K_{1t}\right)=\frac{\partial G_{1t}(A_{1t},B_{1t})}{\partial B_{1t}}\theta e^{z_{1t}}{u_{1t}}^{\theta-1}K_{1t}^{\theta}N_{1t}^{1-\theta} \tag{27}$$

$$\psi\upsilon N_{1t}^{\upsilon-1}=\frac{\partial G_{1t}(A_{1t},B_{1t})}{\partial B_{1t}}(1-\theta)e^{z_{1t}}u_{1t}^{\theta}K_{1t}^{\theta}N_{1t}^{-\theta} \tag{28}$$

Equation (27) states that the marginal cost of increasing capacity utilization has to equal its marginal benefit in terms of production. The marginal cost depends on two components. Changes in the price of investment $(e^{-v_{1t}})$ induce firms to invest more to replace installed capital. The term $\left(\kappa u_{1t}^{\omega-1}K_{1t}\right)$ represents the cost of increasing depreciation from current levels. Equation (28) is the intratemporal condition equating the marginal rate of substitution between consumption and leisure to the marginal product of labor under GHH preferences.

With constant capacity utilization ($u_t = u_{ss}$), IST shocks change the incentives to invest only through the price effect. Shifts in the MPL are small, and output increases only because of changes in labor input. As implied by the variance decomposition of output (Table 4), the elasticity of output to these shocks is very small and business cycle fluctuations are mostly driven by productivity shocks. Conversely, the volatility of prices increases, as market clearing requires larger responses in prices.

When capacity utilization can vary, the planner increases the short-run response of output to IST shocks using capital more intensively. The additional reduction in the marginal cost of depreciation translates into a larger shift of the MPL schedule,inducing a larger increase in hours worked.

Therefore, variable capacity utilization represents the main transmission mechanism of IST shocks to output. Absent this channel, the model still performs reasonnably well in terms of reproducing *Fact 1* and *Fact 2*, although it requires a larger volatility of the relative price of investment compared to the data (Table 4). The issue of domestic comovement does not arise, since TFP shocks dominate business cycle fluctuations.

6.3 Trade Elasticity

There is a lot of uncertainty about the appropriate value for the trade elasticity for business cycle studies. In their original work, BKK set this parameter equal to 1.5, referring to J. Whalley [1985]. More recently, Hooper et al. [2000] report estimates for G7 countries in a range between 0.1 and 2. Heathcote and Perri [2002] estimate a value of 0.9 for this elasticity. CDL [2008] use a model à la BKK that includes a distribution sector which lowers the implied trade elasticity. When they estimate via GMM methods the trade elasticity, they find a value below 0.5.

In contrast to the business cycle literature, general equilibrium trade models adopt large trade elasticities. Yi [2003] shows that, with an elasticity of about 12, these models match the large growth in international trade flows after a trade liberalization. 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 trade elasticity close to 1.

Based on this discussion, Table 4 presents simulations in which the trade elasticity is equal to 1.5, the value considered in the original BKK work. The usual business cycle properties, including comovement, are preserved. In terms of relative standard deviations, the volatility of trade flows increases but international prices are less volatile than output. In the data, however, international prices are typically more volatile than output. Expression (20) provides once again guidance in understanding this result: a larger trade elasticity is associated with a lower response of the terms of trade to changes in relative supply and demand of intermediate goods. If intermediate goods are more substitutes, changes in productivity will have higher impact on quantities than prices.[26] Hence, low trade elasticity appears an important feature to account for *Fact 2*.

Turning to the cross-correlations, the correlation between the terms of trade and relative output remains negative and the correlation between real exchange rate and consumption is close to zero. Thus, the model can still account reasonably well for *Fact 1*. This last finding provides support for the mechanism presented, especially in light of the fact that (i) TFP shocks in this experiment account for a large fraction of the variation of output, and (ii) the volatility of the relative price of investment is only slightly higher than in the data.

Overall, this analysis confirms that the trade elasticity remains a key parameter to account for the volatility of international prices, as previously documented in the literature (see, for example, Heathcote and Perri [2002] and CDL [2008]). The performance of the model improves dramatically when the trade elasticity is lower than one. The model can still account for the correlation between international prices and relative consumption and output, without requiring unrealistically high volatility in the relative price of investment.

7 Conclusions

International relative prices appreciate when domestic consumption and output increase more than abroad. In addition, the terms of trade and trade flows are quite volatile. These two central

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

features of international data bear implications for risk-sharing, the transmission of shocks across countries, and the sources of business cycle fluctuations.

This paper finds that a two-country model that incorporates neutral as well as investment-specific technology shocks, variable capacity utilization and weak wealth effects on labor supply can account for the aforementioned features of the data. IST shocks introduce a source of fluctuations in domestic absorption that does not change aggregate production possibilities, like a taste shock. Output expands, domestic prices increase, the terms of trade appreciate and the trade balance deteriorates.

The mechanism proposed in this paper is close to Stockman and Tesar [1995], since an additional source of variations in absorption (IST shocks) is used to generate realistic dynamics in international relative prices. However, IST shocks appear less controversial than taste shocks, as both theory and data provide more discipline in embedding these shocks into the model. For instance, Chari *et al.* [2009] argue that shocks to total factor productivity, investment-specific technology and monetary policy are arguably structural shocks on which there has been convergence in macroeconomics. Cummins and Violante [2002] and Fisher [2006] document the long-run and cyclical properties of the real price of investment, often used as a proxy for investment-specific technology shocks.

The findings of the paper point towards at least two interesting research avenues. First, I show that the response of international prices to technology shocks depends on the *type* of technology shocks considered, since their transmission mechanism is very different. Further empirical work on this issue appears a natural development. Second, IST shocks have potentially interesting implications for the cyclical properties of stock prices in open economies[27]. Boldrin, Christiano and Fisher [2001] build a model that incorporates these shocks together with habit persistence and constraints to the reallocation of factors across sectors which is able to account for several asset prices features of the United States. Their work, however, does not consider international trade. Coeurdacier, Kollmann, and Martin show that in a two-country model with IST shocks

[27] I thank Nan Li for raising this comment in her discussion.

can provide valuable insights on the lack of international diversification observed in the typical investor portfolio. I leave the investigation of these issues to future research.

8 Appendix A. Linearization

Given that the Armington aggregator is homogenous of degree one, its log-linearized version is[28]

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

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

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

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

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

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

9 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

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

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. Volatility: Net Exports and Terms of Trade

	Standard Deviation§	
	Net Exports	Terms of Trade
Australia	0.62	2.76
Belgium	0.86	1.24
Canada	0.58	1.32
Denmark	0.81	0.95
Finland	0.62	1.09
France	0.49	2.04
Germany	0.20	2.39
Italy	0.96	3.10
Japan	0.39	4.02
the Netherlands	0.62	0.93
New Zealand	0.78	1.64
Portugal	0.77	1.84
Spain	0.79	3.54
Sweden	0.58	1.27
United Kingdom	0.47	1.35
United States	0.25	1.72
Median	0.62	1.68
BKK [1994]		
- Benchmark	0.08	0.53
- High Elasticity	0.14	0.19

§ Standard deviations relative to the standard deviation of GDP. Statistics refer to HP-filtered quarterly data for the period 1980Q1-2007Q4.

Table 2. Benchmark Parameters

Preferences	$\beta = 0.99$	$\gamma = 2.0$	$\nu = 1.64$
Production	$\theta = 0.36$	$\kappa = 0.0525$	$\omega = 1.404$
Trade	$\sigma = 0.5$	$im = 0.15$	
Shock Process			

$$\Omega = \begin{bmatrix} 0.906 & 0.088 & 0.00 & 0.00 \\ 0.088 & 0.906 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.906 & 0.088 \\ 0.00 & 0.00 & 0.088 & 0.906 \end{bmatrix}$$

$$\Sigma = 10^{-3} * \begin{bmatrix} 0.012 & 0.003 & -0.016 & 0.000 \\ 0.003 & 0.012 & 0.000 & -0.016 \\ -0.016 & 0.000 & 0.073 & 0.019 \\ 0.000 & -0.016 & 0.019 & 0.073 \end{bmatrix}$$

Table 3. Business Cycles Statistics

Statistic	Data[†]	Benchmark Economy	BKK Utility	JR Utility	Habit Utility	Fixed Capacity	High Trade Elasticity
			Variations of the Benchmark Economy				
Standard deviations[‡]							
Consumption	0.72	0.67	0.69	0.60	0.67	0.74	0.73
Investment	2.88	2.84	2.89	2.85	2.86	2.86	2.84
Domestic absorption	1.13	1.14	1.06	1.11	1.04	1.17	1.15
Hours worked	0.88	0.61	0.41	0.56	0.68	0.61	0.61
Capacity utilization	1.82	1.18	1.73	1.28	2.23	-	1.16
Net exports	0.28	0.37	0.19	0.32	0.19	0.39	0.47
Terms of trade	1.49	1.30	1.09	1.25	1.36	1.61	0.84
Real exchange rate	3.56	0.91	0.76	0.90	0.96	1.13	0.59
Cross-correlations							
Between GDP and							
Consumption	0.78	0.94	0.82	0.93	0.80	0.94	0.96
Investment	0.93	0.90	0.86	0.92	0.88	0.87	0.79
Hours worked	0.86	1.00	0.73	0.94	0.10	1.00	1.00
Capacity utilization	0.82	0.79	0.75	0.78	0.42	-	0.79
Net exports	-0.43	-0.55	-0.26	-0.45	-0.17	-0.57	-0.25
Between Consumption and							
Investment	0.76	0.72	0.45	0.75	0.43	0.66	0.65
Hours worked	0.58	0.94	0.20	0.90	-0.08	0.94	0.96
Between terms of trade and relative GDP	-0.17	-0.68	0.12	-0.53	0.12	-0.44	-0.21
Between real exchange rate and relative consumption	-0.23	-0.41	0.98	-0.04	0.64	-0.05	0.09

[†] Statistics are based on logged and HP-filtered U.S. quarterly data for the period 1983Q1-2000Q4.
[‡] Standard deviations of the variables are divided by the standard deviation of GDP.

Table 4. Relative Price of Investment for the Models

Statistic	Data†	Benchmark Economy	BKK Utility	JR Utility	Habit Utility	Fixed Capacity	High Trade Elasticity
			Variations of the Benchmark Economy				
Statistics targeted in the benchmark calibration							
Contribution to business cycles							
TFP	0.27	0.22	0.22	0.25	0.24	0.80	0.37
IST	0.53	0.47	0.59	0.47	0.59	0.04	0.43
Cross-correlations							
Between Investment Price and GDP	-0.52	-0.42	-0.46	-0.40	-0.51	-0.41	-0.29
Statistics implied by the model							
Standard deviations‡							
Investment Price	0.80	0.94	1.83	1.37	2.60	1.42	1.04
Autocorrelation							
Investment Price	0.85	0.70	0.69	0.70	0.69	0.70	0.70
Cross-correlations							
Between Investment Price and							
Net exports	0.18	0.55	0.58	0.58	0.50	0.56	0.59
Real exchange rate	0.26	0.57	0.33	0.52	0.22	0.50	0.53

† Statistics for the relative price of investment are calculated using quality-adjusted investment price series as constructed by Fisher [2006]. Statistics for the other variables are based on logged and HP-filtered U.S. quarterly data for the period 1983Q1-2000Q4.
‡ Standard deviation of the investment price series divided by the standard deviation of GDP.

Table 5. On the Barro-King [1984] Critique

Experiment:

- Same shock process as in the benchmark economy
- Adjustment cost to capital

Statistic	U.S. Data	RBC Model	BKK Model	Benchmark Economy
Standard deviation[‡]				
Consumption	0.72	0.69	0.67	0.67
Investment	2.88	2.89	2.86	2.84
Domestic absorption	1.13	1.00	1.04	1.14
Cross-correlations				
Between consumption and				
Investment	0.78	-0.12	-0.03	0.72
Hours worked	0.86	-0.45	-0.23	0.94
Between GDP and Net Exports	-0.43	-	0.23	-0.55
Contribution to business cycles				
TFP	0.27	0.86	0.80	0.22
IST	0.53	0.13	0.07	0.47

[‡] Standard deviation of series divided by the standard deviation of GDP.

Figure 1. U.S. Real Exchange Rate and Relative Consumption

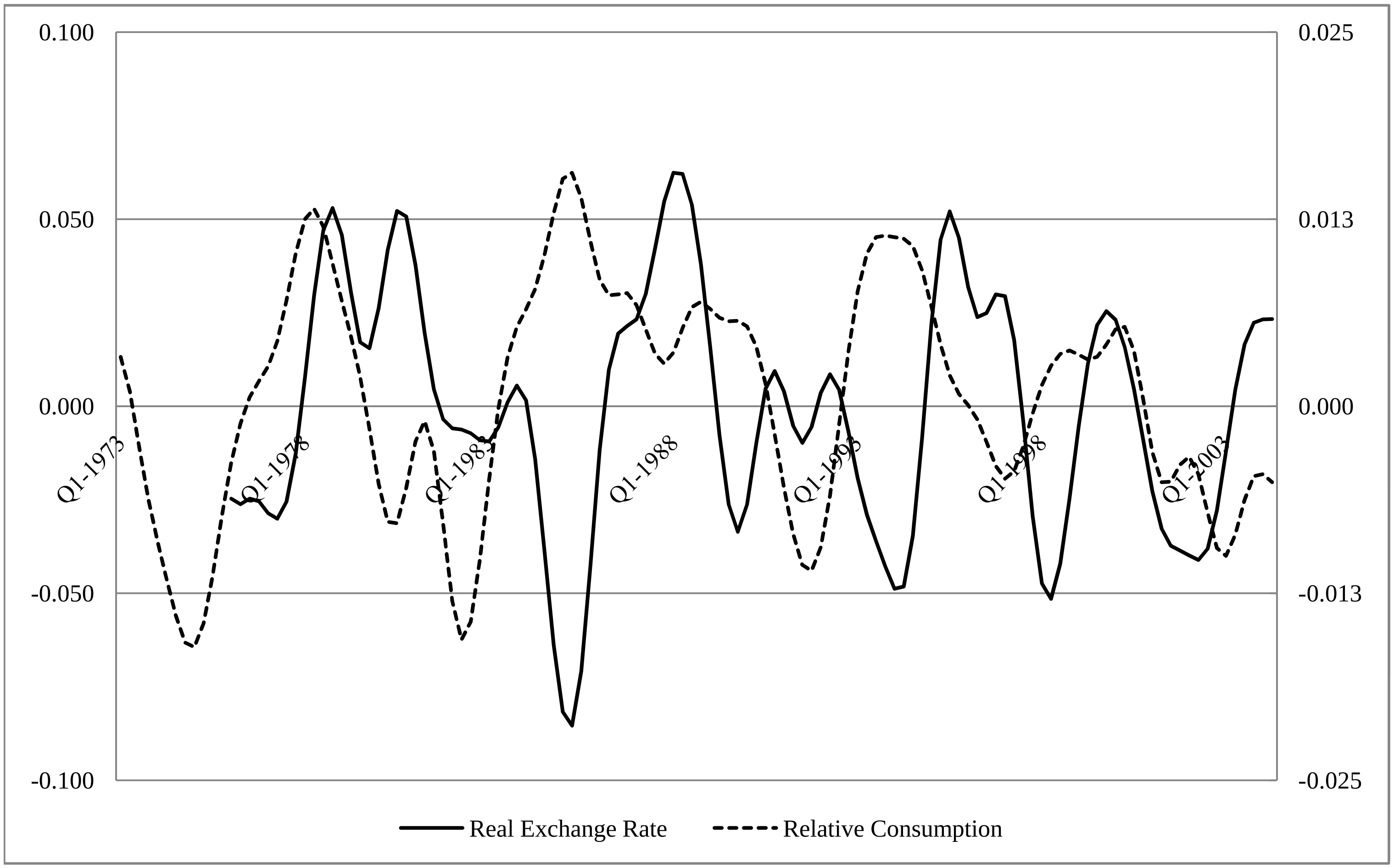

Figure 2. U.S. Terms of Trade and Relative Output

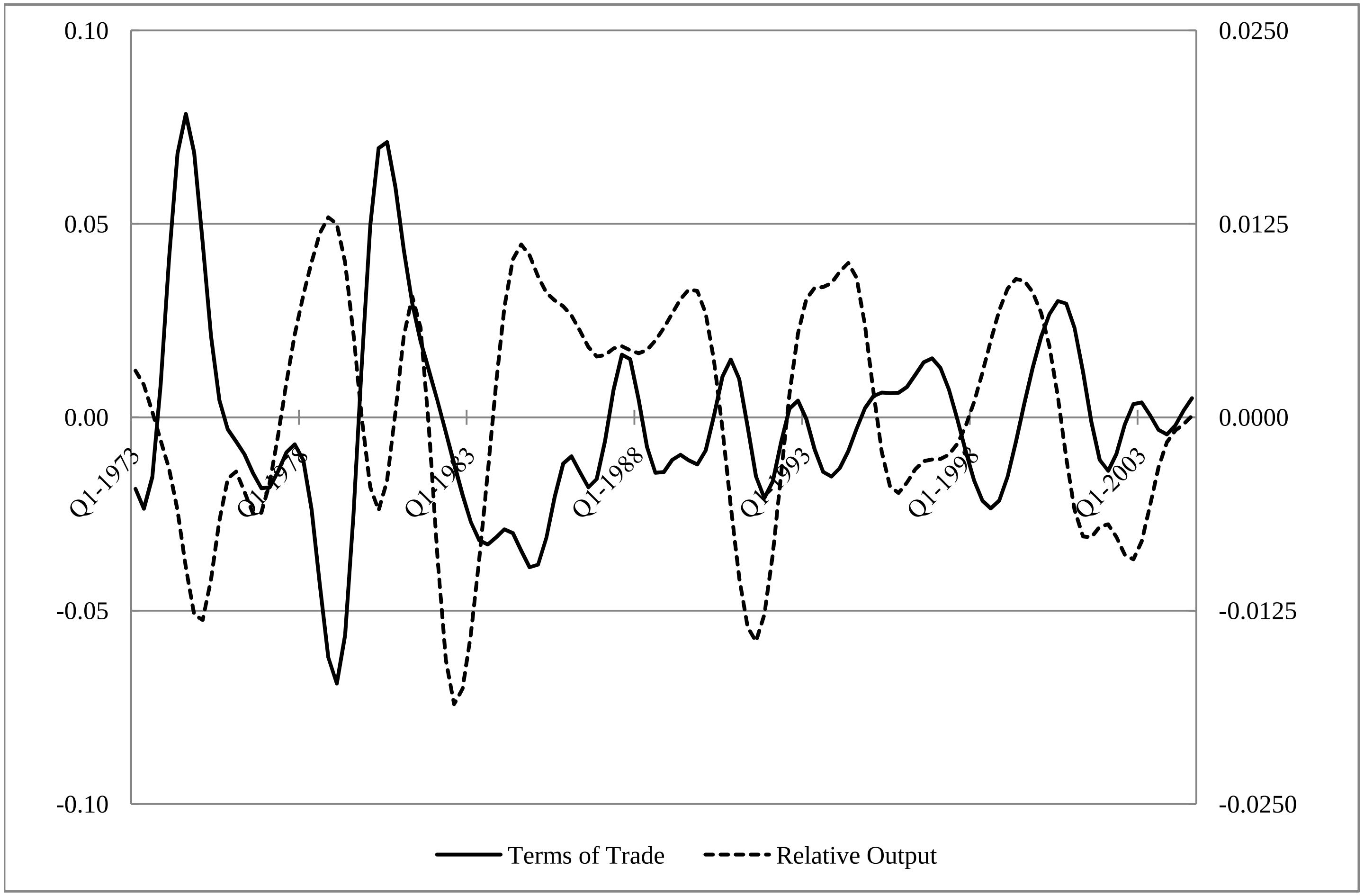

Figure 3. Equipment over the Business Cycle

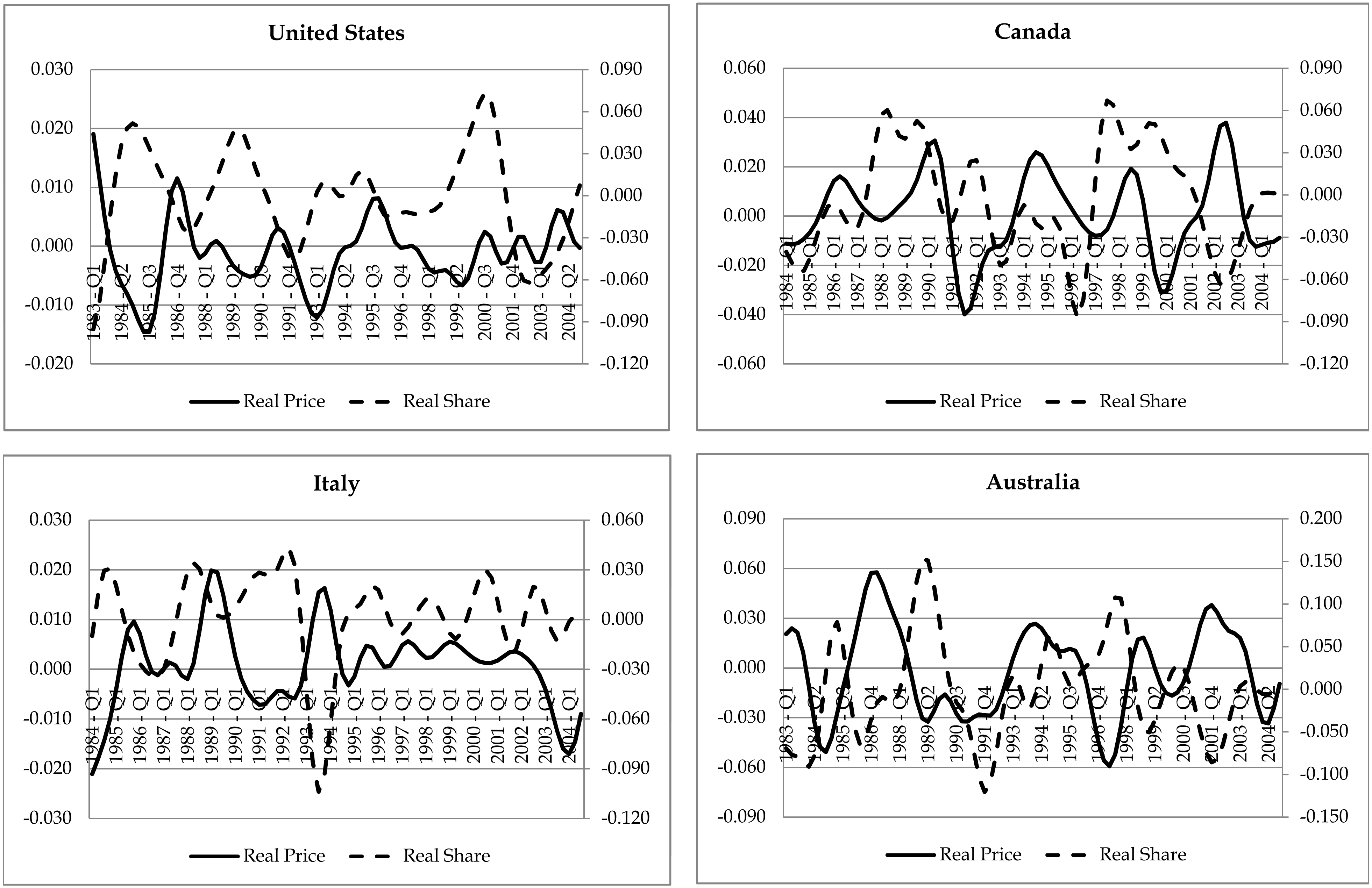

Figure 4. Impulse Response to a IST Shock

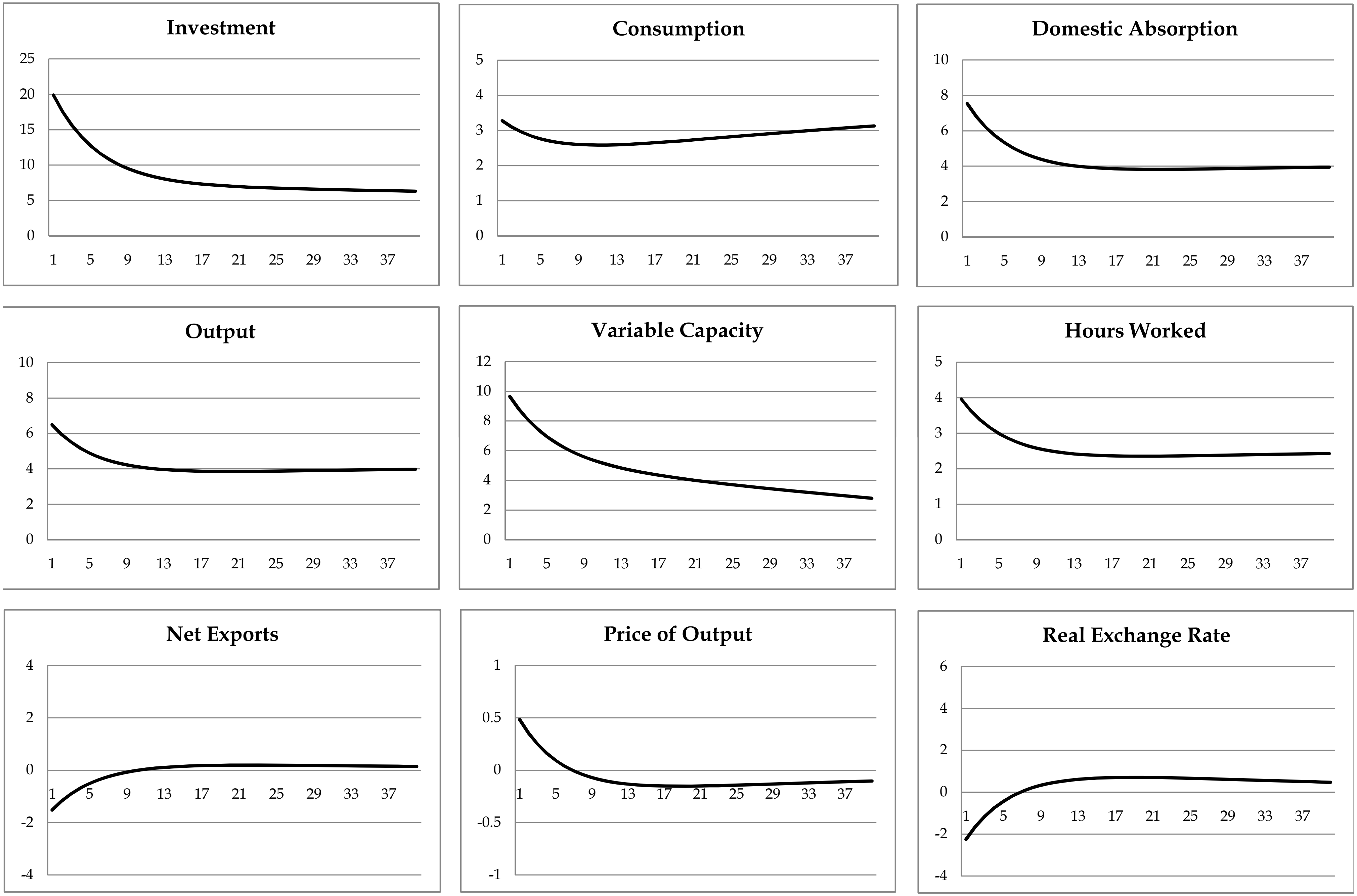

Figure 5. Technology Shocks and Terms of Trade

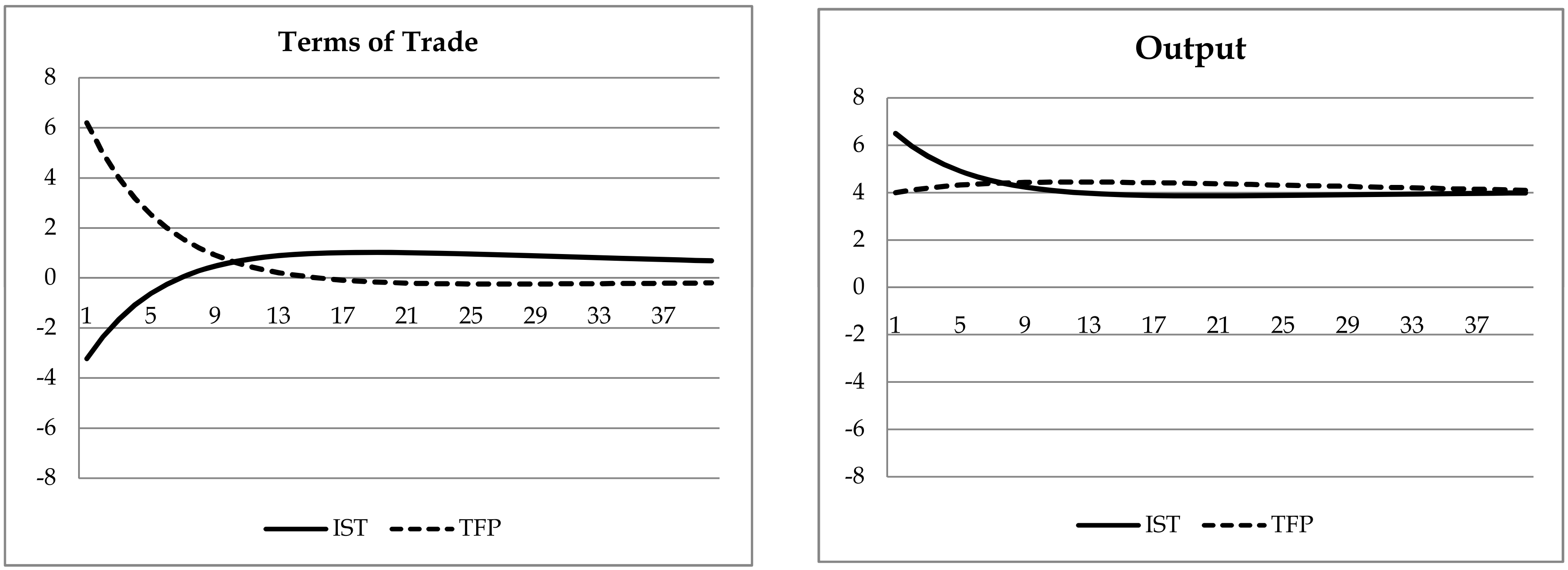

Figure 6. On the Barro-King [1984]: Impulse Responses