S-Curve Redux: On the International Transmission of Technology Shocks*

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This version: September 2006

First draft: July 2005

Abstract

Using vector autoregressions on U.S. time series, we find that technology shocks induce an 'S'-shaped cross-correlation function for the trade balance and the terms of trade. In calibrating a standard business cycle model to match this S-curve under complete and incomplete financial markets, we find two distinct sets of parameter values. In the incomplete markets economy the elasticity of substitution between foreign and domestic goods is relatively low and investment adjustment is costly. This induces a transmission mechanism markedly different from the complete markets economy; notably, terms of trade movements amplify relative wealth effects of technology shocks - in line with time series evidence.

Keywords: S-curve, Technology shocks, Terms of trade, Trade balance, International financial markets, Elasticity of substitution, Investment adjustment costs

JEL-Codes: F32, F40, E32

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*A previous version of the paper was circulated under the title 'The role of the terms of trade and the trade balance in the transmission of technology (and monetary) shocks'. We thank Giancarlo Corsetti, Keith Küster, Philip Jung, Morten Ravn and seminar participants at the EUI, the Open Macroeconomics & Development Meeting in Aix-en-Provence and the 2^{nd} German Workshop in Macroeconomics for helpful discussions. The usual disclaimer applies.

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1 Introduction

Throughout the last 15 years international business cycle models have been used to analyze the international transmission of technology shocks. Irrespectively of specific assumptions on the structure of international asset markets and on firm's price setting behavior, these models generally provide a very similar account of how technology shocks impact the economy and are propagated over time and across countries. The *standard transmission mechanism* can be summarized as follows: in response to a country specific positive technology shock, domestic output expands and its relative price falls (i.e. the domestic terms of trade depreciate). At the same time, a surge of investment induces a trade deficit which turns into a surplus once the domestic capital stock has been built up.

The empirical success of models based on this transmission mechanism has been mixed. In a seminal contribution Backus, Kehoe, and Kydland (1994), hereafter BKK, show that the frictionless variant of the model delivers the S-curve, i.e. an S-shaped cross-correlation function for the trade balance and the terms of trade, which is 'one of the striking features of the data' (BKK, p. 94). However, BKK also note two important differences between theory and data. First, in the model the cross-country correlation of consumption is much higher than that of output, while in the data the reverse is true. Second, the volatility of relative prices in the model fails to match those of the data. Subsequent research has documented these anomalies extensively and made various suggestions for their resolution.[1]

In the present paper, we take a different perspective to assess the baseline international business cycle model. Instead of focusing on various unconditional second moments of the data and the ability of different versions of the model to replicate them, we focus on the transmission mechanism *per se*. We do so, because the ability of the model to match unconditional second moments of the data provides only indirect evidence in favor of a particular transmission mechanism. Such moments can serve as a necessary, but not as a sufficient evaluation criterion. This point is forcefully illustrated by Galí (1999) in a closed economy context.

However, a more direct assessment of the transmission mechanism requires additional assumptions in order to extract the appropriate evidence from the raw time series. Specifically, in section 2, we estimate a structural vector autoregressive (VAR) model on U.S. data and identify technology shocks by assuming that only these shocks affect labor productivity in the long-run. On the basis of the estimated VAR model we compute two statistics. First, we compute the cross-correlation function for the trade balance and the terms of trade conditional on the identified time series of technology shocks. We find that this *conditional* cross-correlation function is also S-shaped and quite similar

[1] Examples for further evidence on anomalies include Backus, Kehoe, and Kydland (1995), Baxter (1995), Ravn (1997), Ambler, Cardia, and Zimmermann (2004); for partially successful resolutions see Stockman and Tesar (1995), Chari, Kehoe, and McGrattan (2002), Heathcote and Perri (2002), Kehoe and Perri (2002) and, more recently, Corsetti, Dedola, and Leduc (2006a).

to the unconditional cross-correlation function. This finding reinforces the notion that productivity shocks are a key determinant of the joint dynamics of the trade balance and the terms of trade at business cycle frequency. It also suggests that any theoretical model of the international transmission of technology shocks should deliver this S-curve. As a second statistic we compute the impulse response functions on the basis of the estimated VAR model. We find that a positive technology shock induces a hump-shaped increase in output and investment and a hump-shaped decline in the trade balance. At the same time the relative price of domestic goods increases, i.e. we find a positive technology shock to induce an *appreciation* of the terms of trade and the real exchange rate.

In section 3 we outline a standard international business cycle model which we intent to confront with the VAR evidence. The model is a variant of the model originally proposed by BKK, where in addition to complete financial markets, we also consider the possibility that only non-contingent bonds are traded across countries. Moreover, we allow for investment adjustment costs. To calibrate the model we use the first statistic computed on the basis of the estimated VAR model: by matching the conditional S-curve we pin down parameter values for the elasticity of substitution between domestic and foreign goods, investment adjustment costs and the persistence of technology shock differentials. We consider both asset market structures. If financial markets are complete, we find parameter values close to the baseline calibration of BKK. If financial markets are incomplete we find two distinct sets of parameter values, each of which allows the model to match the conditional S-curve almost equally well. The first set of parameter values is a local optimum and the parameter values are close to those found under complete markets. In contrast, the global optimum under incomplete financial markets is characterized by a relatively low elasticity of substitution and investment adjustment costs.

We assess the transmission mechanism implied by all three specifications of the model in section 4. Regarding impulse response functions, we find that only the incomplete marktes/low elasticity economy induces a hump-shaped decline of the trade balance and appreciation of the terms of trade. Under the two other specifications, in contrast, the model predicts a depreciation of the terms of trade and a sharp decline of the trade balance. In addition, we consider VAR-independent evidence to assess the relative performance of the three economies. In a first experiment, we use the output differential in the U.S. relative to a sample representing the 'rest of the world' to back out the underlying process of relative technology shock. We then compute in-sample predictions for the trade balance and the real exchange rate. Finally, we compute those second moments which usually receive a lot of attention in the literature. Overall, the evidence is in favor of the incomplete markets/low elasticity economy. Its quantitative performance, however, is not fully satisfactory.

Our analysis thus provides evidence against the standard transmission mechanism of technology shocks common to most international business cycle models. An exception is Corsetti, Dedola, and Leduc (2004); in fact, our incomplete markets/low elasticity economy is characterized by a transmission mechanism suggested by those authors as an alternative to the standard transmission mechanism.[2] Specifically, Corsetti et al. (2004) show that if home bias is pervasive, the elasticity of substitution between domestic and foreign goods is low and financial markets are incomplete, technology shocks tend to appreciate the real exchange rate and the terms of trade. As a result, terms of trade movements amplify the effects of technology shocks on the distribution of wealth across different countries. Under these circumstances, the welfare consequences of country-specific technology shocks are thus quite different relative to models based on the standard transmission mechanism. This provides the motivation for the following investigation and for further research outlined in the conclusion (section 5).

2 Time Series Evidence for the United States

In this section we use U.S. time series to establish evidence on the international transmission of technology shocks. First, we compute the unconditional cross-correlation function for the trade balance and the terms of trade - revisiting a key finding of BKK. Next, we estimate a VAR model and compute the cross-correlation function *conditional* on technology shocks. Finally, we compute the impulse response functions to a technology shock.

Our analysis relies on U.S. data which are described in more detail in appendix A.1. It turns out that the terms of trade, a key variable in our analysis, displays large swings during the 1970s. Therefore we rely on post-1980 data only. Specifically, as both Kim and Nelson (1999) and McConnell and Perez-Quiros (2000) report independent evidence in favor of a structural break in the first quarter of 1984, we consider data for 1984:1-2005:4.

2.1 An unconditional S-curve

Before turning to our VAR model, we follow BKK and compute the unconditional cross-correlation function for the trade balance and the terms of trade. The terms of trade, p_t, are defined as the relative price of imports to exports, calculated on the basis of implicit price deflators. The trade balance, nx_t, is measured as the ratio of nominal net exports to nominal GDP. In order to separate short-run fluctuations from long-run movements in both time series we employ the HP-filter using a smoothing parameter of 1600.

The dashed line in figure 1 displays the cross-correlation function for the terms of trade (t) and the

[2] In contrast to the present paper, Corsetti et al. (2004) do not investigate the crosscorrelation function for the trade balance and the terms of trade. Instead, they focus on the consumption-real exchange rate anomaly identified by Backus and Smith (1993).

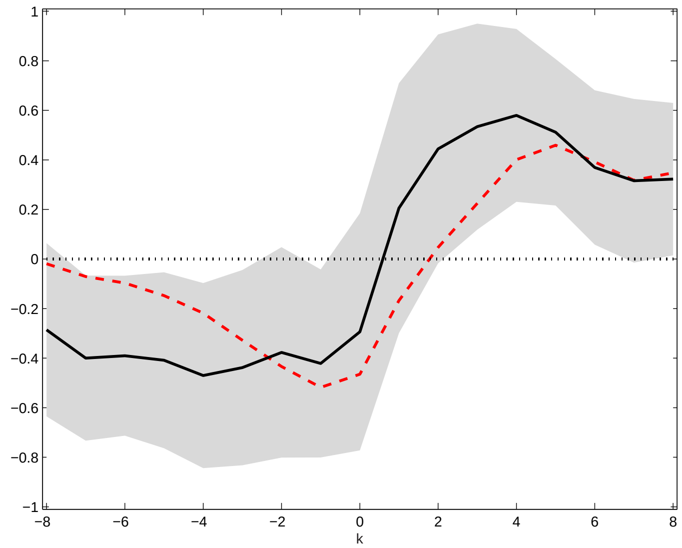

Figure 1: CROSS-CORRELATION FUNCTION FOR THE TRADE BALANCE (T+K) AND THE TERMS OF TRADE (T). DASHED LINE: UNCONDITIONAL CROSS-CORRELATION (AFTER APPLICATION OF HP-FILTER TO RAW DATA). STRAIGHT LINE: CORRELATION CONDITIONAL ON TECHNOLOGY SHOCKS IDENTIFIED IN VAR. SHADED AREAS INDICATE BOOTSTRAPPED 90 PERCENT CONFIDENCE INTERVALS. SAMPLE IS 1984:1-2005:4.

trade balance (t+k) for k ranging from -8 to 8 quarters, i.e. for leads and lags up to two years. As noted by BKK, the shape of the cross-correlation function resembles an horizontal 'S'. Note that in our sample, the S-shape of the cross-correlation function is more pronounced and resembles more closely what BKK report for the non-U.S. countries in their sample. The function is negative at $k = 0$ and crosses the axis to the right of this point: the correlation between p_t and nx_{t+k} becomes increasingly positive for $k > 0$ such that future trade balances are positively associated with current terms of trade.

BKK rationalize the S-curve by appealing to a specific transmission mechanism of technology shocks which, partly as a result of their work, may be considered the standard transmission mechanism.[3] After a one-time positive shock to technology domestic output increases and therefore its relative price falls (p_t increases). Investment increases strongly and induces a fall in net exports (nx_t falls). After the surge in investment dissipates, the trade balance moves into a surplus. The contemporaneous correlation of both variables is therefore negative, while p_t and nx_{t+k} are positively correlated for $k > 0$. To assess this interpretation of the S-curve, we establish the cross-correlation function for the trade balance and the terms of trade *conditional* on technology shocks.

[3]The cross-correlation pattern is also consistent with the notion of a J-curve, whereby a depreciation of the terms of trade (i.e. a rise in p_t) - through sluggish expenditure switching effects - leads to an increase in net exports only with a delay. This consideration provides the starting point for the analysis of BKK.

2.2 A conditional S-curve

To obtain a cross-correlation function conditional on technology shocks we first estimate a VAR model. To identify technology shocks we follow Galí (1999) and others and assume that these shocks are the only shocks which affect the long-run level of average labor productivity. Our implementation follows Christiano, Eichenbaum, and Vigfusson (2003) and is discussed in more detail in appendix B.1.

Our VAR model contains the change in the log of labor productivity (output/hour), the log of per capita hours worked, the log of the terms of trade and net exports (scaled by GDP). In addition to these four variables we also consider the real exchange rate and investment. To economize on the degrees of freedom, we re-estimate the VAR model by replacing, in turn, the terms of trade with the real exchange rate and the trade balance with investment. We include a constant and four lags of each endogenous variable in the VAR model.

Given the estimated model and the identified technology shocks, we compute counterfactual time series that would have been the result had technology shocks been the only source of business cycle fluctuations. We then calculate the cross-correlation function for the trade balance and the terms of trade after HP-filtering the simulated series. Figure 1 displays the result. The straight line gives the point estimate, while the shaded area displays 90 percent confidence intervals computed by bootstrap based on 1000 replications. The conditional cross-correlation function displays a pattern which is similar to the the unconditional cross-correlation function (dashed line); in fact, it also resembles an horizontal 'S'.

A business cycle variance decomposition provides further evidence on the role of technology shocks for the joint dynamics of the trade balance and the terms of trade at business cycle frequency. Again, we rely on the counterfactual series that would have been the result if only technology shocks had occurred. As in Altig, Christiano, Eichenbaum, and Lindé (2005), we compute the variance of these series relative to the variance of the series that result from all shocks occurring. Table 1 displays the results. The numbers give the fraction of the variance that can be attributed to technology shocks (90 percent standard errors computed by bootstrap based on 1000 replications are given in parentheses).

Of course, the importance of technology shocks in accounting for business cycle fluctuations has been a topic of considerable debate in macroeconomics since the early 1980s and is clearly beyond the scope of this paper. Here we are only interested in the importance of technology shocks in accounting for the business cycle fluctuations of the terms of trade and the trade balance: we find that technology shocks account for 57 and 35 percent of fluctuations of the terms of trade and the trade balance, respectively. These numbers are high, in particular, if compared to the contribution of technology shocks to the fluctuation of the other variables included in the VAR. Technology shocks thus appear

Table 1: BUSINESS CYCLE VARIANCE DECOMPOSITION

Output	Hours	p	nx	REER	Investment
0.26 (0.24)	0.09 (0.22)	0.57 (0.20)	0.35 (0.15)	0.11 (0.13)	0.34 (0.25)

Notes: Fraction of variance accounted for by technology shocks after application of HP filter (standard errors in parentheses).

to be an important source of the short-run fluctuations of the trade balance and the terms of trade.[4] Overall, we interpret our findings as evidence in favor of the notion that technology shocks are the key force behind the unconditional S-curve. BKK originally put forward this notion on the basis of a calibrated business cycle model. Here, we have supplemented their analysis by showing that i) the cross-correlation function for the trade balance and the terms of trade also resembles an horizonal 'S' conditional on technology shocks identified in the VAR model and that ii) technology shocks are a major source of business cycle fluctuations of the trade balance and the terms of trade.

2.3 The transmission of technology shocks

In order to gain further insights into *how* technology shocks impact on the trade balance and the terms of trade we compute the impulse response functions of the estimated VAR model. Below, we treat these responses as an empirical characterization of the actual transmission mechanism. Figure 2 displays the responses to an exogenous, one percent increase in labor productivity. All variables are measured in percentage deviations from trend, except for the trade balance which is measured in percentage points of GDP. The shaded area displays 90 percent confidence intervals, computed by bootstrapping based on 1000 replications.

The panels in the first row give the responses of output and hours: both increase in response to a positive shock to technology.[5] The second row gives the responses for the terms of trade and the trade balance. The terms of trade fall (appreciate) significantly on impact, i.e. the price of U.S. imports falls relative to the price of U.S. exports. The trade balance displays a hump-shaped decline which becomes significant after about one year. We find these responses to be robust with respect to variations of the sample period and to inclusions of additional variables in the VAR model. They will therefore play a key role in our assessment of the transmission mechanism implied by various

[4]We also estimated a larger VAR model and identified monetary policy and fiscal shocks in addition to technology shocks. We found that, relative to the policy shocks, technology shocks can account for a substantially larger fraction of the variability of the trade balance and the terms of trade.

[5]The response of hours has been the topic of a considerable debate. Some authors, notably Galí (1999), have argued that hours are difference stationary only. If the change in hours instead of the level is used in VAR models, hours tend fall in response to a technology shock. In appendix B.2 we consider this specification finding a similar result. However, the responses of the other variables are hardly affected by this modification.

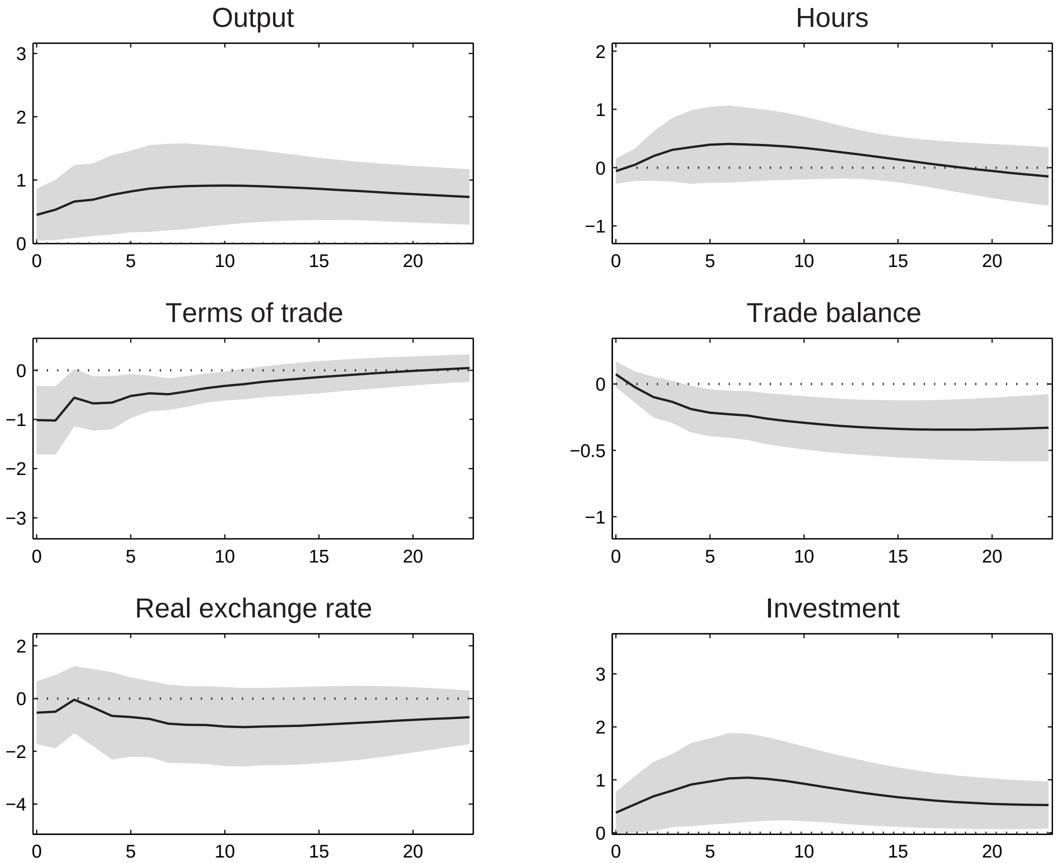

Figure 2: Transmission of a technology shock. The shock is an exogenous, one percent increase labor productivity. Sample: U.S. data 1984:1-2005:4. Shaded areas indicate bootstrapped 90 percent confidence intervals. Horizontal axes: quarters. Vertical axes: percent, except for trade balance (percentage points of output).

specifications of the standard two country business cycle model.

In the last row we display the responses of the real exchange rate and investment. As the real exchange rate also appreciates (albeit not significantly), pricing behavior is unlikely to play a key role in accounting for the appreciation of the terms of trade, see Obstfeld and Rogoff (2000). As investment displays a hump-shaped increase, we will allow for investment adjustment costs in our theoretical model below.

Before accounting for this evidence using a standard two country business cycle model, we note that our identification scheme is meant to capture technology shocks by assuming that only these shocks affect U.S. labor productivity in the long-run.[6] These shocks are likely to consist of both a country-

[6]Corsetti, Dedola, and Leduc (2006b) make an alternative identification assumption in a differently specified VAR model. Specifically, they consider relative variables and assume that technology shocks are the only shocks which have a long-run effect on *relative* labor productivity. Their results are broadly in line with ours, notably regarding the behavior of

specific (idiosyncratic) and a global (common) component. However, to the extent that terms of trade and the trade balance respond to technology shocks, we are likely to pick up the idiosyncratic component, because the global component will have a similar effect on all countries and therefore little impact on the terms of trade and the trade balance.[7] The conditional S-curve can therefore be interpreted as resulting from the country-specific component of technology shocks, i.e. exogenous changes in the level of U.S. technology *relative* to its trading partners.

3 The Model

In this section we analyze the international transmission of technology shocks in a standard two country business cycle model. The model is a variant of the model originally proposed by BKK. In the next subsection, we closely follow the exposition of Heathcote and Perri (2002) in outlining the model. We then discuss our strategy to solve the model numerically around a deterministic steady state while assuming that technology shocks have permanent effects on labor productivity. In a third subsection, we calibrate the model by matching the S-curve conditional on technology shocks.

3.1 Setup

The world economy consists of two countries each of which produces a distinct good and is populated by a unit measure of identical households. Regarding internationally traded assets, we distinguish the possibility of complete financial markets from an economy where only non-contingent bonds are traded across countries.[8] In the following, s^t denotes the history of events before and including time t, consisting of all events $s_\tau \in S$, $\tau \leq t$, where S is the set of possible events. The probability of history s^t at time 0 is given by $\pi(s^t)$.

international relative prices.

[7]Glick and Rogoff (1995) test a small open economy version of the international business cycle model by comparing the effect of country-specific relative to global productivity innovations on the current account. They find no effect of global productivity innovations on the current account. Similarly, Gregory and Head (1999) estimate a dynamic factor model to identify common and country-specific factors driving productivity, investment and the current account. A key finding is that common factors account for almost none of the variation in current accounts. Finally, Normandin and Fosso (2006) decompose technology into a country-specific and a global component using a (one-good) international business cycle model. They find no role for global technology shocks in accounting for current account movements.

[8]While BKK consider only complete financial markets, Heathcote and Perri (2002) also investigate a third case: financial autarky. In fact, they find that the model performs relatively well under this assumption. However, by definition trade is always balanced in this case and thus not suited for our analysis. Note that we depart from the model in Heathcote and Perri (2002) by i) introducing an endogenous discount factor under incomplete financial markets to ensure the stationarity of bond holdings; ii) introducing investment adjustment costs to account for the hump-shaped investment response observed in the data; and iii) assuming that technology is labor augmenting as we allow for a non-stationary process of technology.

Households allocate consumption expenditures on final goods, $c_i(s^t)$, and supply labor, $n_i(s^t)$, to intermediate good firms. The representative household in country i maximizes

$$\sum_{t=0}^{\infty}\sum_{s^t}\pi(s^t)\beta(\{c_i(s^\tau)\}_{\tau=0}^{\tau=t-1},\{n_i(s^\tau)\}_{\tau=0}^{\tau=t-1})U(c_i(s^t),n_i(s^t)), \tag{1}$$

subject to a budget constraint which depends on the structure of international asset markets. As further detailed below, the discount factor β may depend on the sequence of consumption and labor. Instantaneous utility is non-separable in consumption and leisure, $1-n_i(s^t)$:

$$U(c_i(s^t),n_i(s^t)) = \frac{1}{1-\gamma}[c_i(s^t)^{\mu}(1-n_i(s^t))^{1-\mu}]^{1-\gamma}. \tag{2}$$

The representative household in each country households owns the capital stock, $k_i(s^t)$, and rents it to intermediate good firms. Capital and labor are internationally immobile. As in Christiano, Eichenbaum, and Evans (2005), we assume that it is costly to adjust the level of investment, $x_i(s^t)$. Specifically, the law of motion for capital is given by

$$k_i(s^{t+1}) = (1-\delta)k_i(s^t) + F(x_i(s^t),x_i(s^{t-1})), \text{ with } F = [1-G(x_i(s^t)/x_i(s^{t-1}))]x_i(s^t). \tag{3}$$

Restricting $G(1) = G'(1) = 0$ ensures that the steady state level of capital is independent of investment adjustment costs captured by the parameter $\chi = G''(1) > 0$.

Intermediate good firms specialize in the production of a single intermediate good, $y_i(s^t)$. It is produced by combining capital and labor according to a standard Cobb-Douglas production function:

$$y_i(s^t) = k_i(s^t)^{\theta}[z_i(s^t)n_i(s^t)]^{1-\theta}, \tag{4}$$

where $z_i(s^t)$ denotes technology which follows an exogenous process discussed below. Letting $w_i(s^t)$ and $r_i(s^t)$ denote the wage rate and the rental rate of capital in terms of the local intermediate good, the problem of intermediate good firms is given by

$$\begin{aligned}&\max_{n_i(s^t),k_i(s^t)} y_i(s^t) - w_i(s^t)n_i(s^t) - r_i(s^t)k_i(s^t),\\ &\text{subject to} \quad k_i(s^t), n_i(s^t) \geq 0.\end{aligned} \tag{5}$$

Intermediate goods are sold on to final good producers in both countries and the law of one price is assumed to hold throughout.

Final good firms assemble intermediate goods produced both domestically and abroad. Let $a_i(s^t)$ and $b_i(s^t)$ denote the uses of the two intermediate goods in country i, originally produced in country

1 and 2, respectively. Then final goods are produced on the basis of the following constant returns to scale technology

$$F_i(a_i(s^t), b_i(s^t)) = \begin{cases} \left[\omega^{1/\sigma} a_i(s^t)^{(\sigma-1)/\sigma} + (1-\omega)^{1/\sigma} b_i(s^t)^{(\sigma-1)/\sigma}\right]^{\sigma/(\sigma-1)}, & \text{for } i=1 \\ \left[(1-\omega)^{1/\sigma} a_i(s^t)^{(\sigma-1)/\sigma} + \omega^{1/\sigma} b_i(s^t)^{(\sigma-1)/\sigma}\right]^{\sigma/(\sigma-1)}, & \text{for } i=2 \end{cases} \quad (6)$$

where σ measures the elasticity of substitution between foreign and domestic goods and $\omega > 0.5$ measures the extent to which the composition of final goods is biased towards domestically produced goods. Final good firms solve the following problem

$$\begin{aligned} &\max_{a_i(s^t), b_i(s^t)} F_i(s^t) - q_i^a(s^t) a_i(s^t) - q_i^b(s^t) b_i(s^t), \\ &\text{subject to} \quad a_i(s^t), b_i(s^t) \geq 0, \end{aligned} \quad (7)$$

where q_i^a and q_i^b denotes the price of intermediate goods a and b in terms of final goods i, respectively. The budget constraint of the representative household depends on the asset market structure. We consider both incomplete and complete international financial markets.

Incomplete financial markets

In this case only a non-contingent bond is traded across countries. It pays one unit of the intermediate good a in period $t+1$ in each state of the world. Letting $B_i(s^t)$ and $Q(s^t)$ denote the quantity and the price of this bond bought by the representative household in country i at the end of period t, then the budget constraint of household 1 reads as follows

$$c_1(s^t) + x_1(s^t) + q_1^a(s^t) Q(s^t) B_1(s^t) = q_1^a(s^t)[w_1(s^t) n_1(s^t) + r_1(s^t) k_1(s^t)] + q_1^a(s^t) B_1(s^{t-1}). \quad (8)$$

The budget constraint for the representative household in country 2 is analogously defined in terms of final good 2.

To ensure stationarity of bond holdings, we follow Mendoza (1991) by assuming that the time discount factor depends on the sequence of consumption and leisure. Specifically, we assume

$$\beta(\{c_i(s^\tau)\}_{\tau=0}^{\tau=t-1}, \{n_i(s^\tau)\}_{\tau=0}^{\tau=t-1}) = \exp\left[\sum_{\tau=0}^{t-1} -\nu(c_i(s^\tau), n_i(s^\tau))\right], \quad (9)$$

where

$$\nu(c_i(s^\tau), n_i(s^\tau)) = \ln(1 + \psi[c_i(s^t)^\mu (1 - n_i(s^t))^{1-\mu}]), \quad (10)$$

with $\psi > 0$ set to determine the discount factor in steady state.

Complete markets

Alternatively, we consider the case in which a complete set of state-contingent securities is traded on international financial markets. Letting $B_i(s^t, s_{t+1})$ denote the quantity of bonds bought by household i in period t that pay one unit of the intermediate good a in $t+1$ if the state of the economy is s_{t+1}, then the budget constraint for the household in country i reads as

$$\begin{aligned} & c_1(s^t) + x_1(s^t) + q_1^a(s^t) \sum_{s_{t+1}} Q(s^t, s_{t+1}) B(s^t, s_{t+1}) \\ & = q_1^a(s^t)[w_1(s^t) n_1(s^t) + r_1(s^t) k_1(s^t)] + q_1^a(s^t) B(s^{t-1}, s_t). \end{aligned} \tag{11}$$

The budget constraint for the representative household in country 2 is analogously defined in terms of final good 2. For convenience, we assume that the time discount factor is constant in this case, i.e. $\beta(\{c_i(s^\tau)\}_{\tau=0}^{\tau=t-1}, \{n_i(s^\tau)\}_{\tau=0}^{\tau=t-1}) = \beta^t$.

Equilibrium is a set of prices for all s^t and all $t \geq 0$ such that when intermediate and final good firms, as well as households take these prices as given, households solve (1) subject to the capital accumulation equation (3) and to either constraint (8) or (11); firms solve their static problems (5) and (7) subject to the production functions (4) and (6); furthermore all markets clear, i.e. for intermediate goods we have

$$a_1(s^t) + a_2(s^t) = y_1(s^t), \tag{12}$$

$$b_1(s^t) + b_2(s^t) = y_2(s^t); \tag{13}$$

while for final goods we have

$$c_i(s^t) + x_i(s^t) = F_i(s^t), \qquad i = 1, 2;$$

and - under incomplete financial markets - we have

$$B_1(s^t) + B_2(s^t) = 0,$$

while - under complete financial markets - we have

$$B_1(s^t, s_{t+1}) + B_2(s^t, s_{t+1}) = 0, \;\; \forall \;\; s_{t+1} \in S.$$

Additional variables of interest are the terms of trade, $p(s^t)$, and the trade balance, $nx(s^t)$. The former are defined as the price of imports relative to the price of exports. Thus

$$p(s^t) = q_1^b(s^t)/q_1^a(s^t)$$

denotes the terms of trade for country 1. Its trade balance is defined as the ratio of net exports to output

$$nx(s^t) = \frac{a_2(s^t) - p(s^t) b_1(s^t)}{y(s^t)}.$$

3.2 Model solution

We linearize the model around a symmetric steady state and consider the deviations of a variable from its steady state value. More precisely, we focus on relative variables, i.e. the deviation from steady state of a variable in the home country (country 1) minus the deviation from steady state of the corresponding variable in the foreign country (country 2). Note that the terms of trade and net exports in one country are just the negative of the value of the variable in the other country. We assume that domestic and foreign technologies, written in deviations from the steady-stat using 'hats', i.e. $\hat{z}_1(s^t)$ and $\hat{z}_2(s^t)$, follow the joint process

$$\begin{bmatrix} \hat{z}_1(s^t) \\ \hat{z}_2(s^t) \end{bmatrix} = \begin{bmatrix} \rho_1 & \rho_2 \\ \rho_2 & \rho_1 \end{bmatrix} \begin{bmatrix} \hat{z}_1(s^{t-1}) \\ \hat{z}_2(s^{t-1}) \end{bmatrix} + \begin{bmatrix} \varepsilon_1(s^t) \\ \varepsilon_2(s^t) \end{bmatrix}, \tag{14}$$
$$\text{with} \quad \begin{bmatrix} \varepsilon_1(s^t) \\ \varepsilon_2(s^t) \end{bmatrix} \sim N\left(\begin{bmatrix} 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \sigma^2_{\varepsilon_1} & \sigma_{\varepsilon_1\varepsilon_2} \\ \sigma_{\varepsilon_1\varepsilon_2} & \sigma^2_{\varepsilon_2} \end{bmatrix} \right).$$

Note that, as in the calibrated models of BKK and Heathcote and Perri (2002), technology spillovers are assumed to be symmetric. In addition, to be consistent with our identification strategy used in the VAR model, we assume that $\rho_1 + \rho_2 = 1$ such that innovations to technology have permanent effects on the level of technology. In addition, we assume that $\rho_1 > \rho_2 > 0$. As a result there is a cointegration relation between $\hat{z}_1(s^t)$ and $\hat{z}_2(s^t)$, with cointegrating vector $[\ 1 \quad -1\ ]$. This allows us to focus on relative technology $\tilde{z}(s^t) = \hat{z}_1(s^t) - \hat{z}_2(s^t)$, which is stationary and follows the AR(1) process

$$\tilde{z}(s^t) = \rho \tilde{z}(s^{t-1}) + \varepsilon(s^t), \quad \varepsilon(s^t) \sim N(0, \sigma^2_{\varepsilon_1} + \sigma^2_{\varepsilon_2} - 2\sigma_{\varepsilon_1\varepsilon_2}) \tag{15}$$

with $\rho = \rho_1 - \rho_2$. As stressed in Kollmann (1998), in the standard two country business cycle model only relative technology matters for the dynamics of relative variables as well as for dynamics of the terms of trade and trade balance. Given that we are primarily interested in the joint dynamics of these two variables, we focus on the parameter ρ, i.e. on the persistence of relative technology, without having to take a stand on the relative size of ρ_1 to ρ_2. We thus rely on the process (15) in calibrating the model. However, in section 4 we also rely on (14) in order to compute statistics of country-specific variables.

3.3 Calibration

The model outlined in the previous subsection is meant to provide a structural interpretation of the time series evidence established in section 2. A subset of the results of the VAR analysis will therefore play a key role in calibrating the model. In a first step, we use the conditional S-curve to calibrate the model. Simple experimentation shows that the shape of the cross-correlation function for the trade balance and the terms of trade implied by the model is governed by the values of three parameters:

the elasticity of substitution between domestic and foreign goods, σ, investment adjustment costs, χ, and the persistence of the process of relative technology, ρ.

Our calibration strategy is thus to pin down values for these model parameters in order to match the conditional S-curve obtained from the VAR model. This strategy is particularly suitable, given that values for all three parameters are not identified by first moments of the data and are at the focus of the debate on the international transmission process.[9] Other parameters have little bearing on the cross-correlation function for the trade balance and the terms of trade and are less controversial in the literature. We therefore simply follow BKK's choice of parameter values.

More formally, our calibration strategy can be stated as follows. Let m_d denote a 17×1 vector containing the empirical cross-correlation function and $m(\lambda)$ the corresponding cross-correlation function obtained from a simulation of the model (averages over 20 simulations of 100 observations). As the theoretical moments depend on $\lambda = \{ \sigma \quad \chi \quad \rho \}$, we find values for these parameters by solving the following problem

$$\min_{\lambda} \left(m(\lambda) - m_d\right)' W \left(m(\lambda) - m_d\right), \tag{16}$$

where W is the efficient weighting matrix, i.e. the inverse of the (bootstrapped) variance-covariance matrix of m_d. We solve (16) for both asset market structures - complete and incomplete international financial markets.

Table 2 displays the results. The upper part of the table reports parameter values which are assumed independently of the asset market structure. All values are taken from BKK, except for the import share which we assume to be 0.12, the average in our sample. The lower part of table 2 reports the values for for the elasticity of substitution between domestic and foreign goods, σ, investment adjustment costs, χ, and the persistence of cross-country technology differential, ρ, obtained by solving (16).

The set of parameter values obtained by solving (16) under the assumption that financial markets are complete defines economy A (left column). The elasticity of substitution between intermediate goods, σ, takes a value of 1.51. This is very close to 1.5, the value used in the benchmark economy of BKK. Investment adjustment costs are also absent from economy A so that it is indeed very similar to the benchmark economy of BKK. The value for the persistence of technology differentials is $\rho = 0.86$.

The set of parameter values obtained by solving (16) under the assumption that financial markets are incomplete defines economy C (right column). However, under incomplete financial markets there is a second (local) minimum which we also report in table 2 (economy B, middle column). While the

[9] This is particularly true for σ, see Corsetti et al. (2004). Regarding the process for technology, the traditional approach is to estimate an AR(1) process on Solow residuals for the U.S. and the rest of the world. Our approach allows us to avoid the construction of these series which are likely to be contaminated by measurement error. In section 4.2 below we will consider an alternative approach which allows us to infer the actual process for technology on the basis of observed output differentials.

Table 2: PARAMETER VALUES OF THREE THEORETICAL ECONOMIES

Standard values:			
Discount factor (steady state)	$\beta = 0.99$		
Consumption share	$\mu = 0.34$		
Risk aversion	$\gamma = 2$		
Capital share	$\theta = 0.36$		
Depreciation rate	$\delta = 0.025$		
Import share (steady state)	$1 - \omega = 0.12$		
	Complete markets	Incomplete markets	
Machting S-curve:	A	B	C
Elasticity of substitution between intermediate goods	$\sigma = 1.514$	1.661	0.195
Capital adjustment costs	$\chi = 0.000$	0.000	0.116
Autoregressive coefficient of technology	$\rho = 0.864$	0.884	0.989
Loss function:	3.579	3.240	2.871

Notes: Standard parameter values are taken from Backus et al. (1994). Values for parameters in the second part of table are obtained by solving the objective (16); the last line gives its the value in the optimum. Economy B is a local optimum under incomplete financial markets.

value of the loss function (16) is lower for economy C, economy B is of particular interest, given that the parameter values are very close to those defining economy A. In fact, below we will show that the international transmission of technology shocks in economy A and B is quite similar - despite different asset market structures.

The parameter values defining economy C, in contrast, are rather distinct. The elasticity of substitution between intermediate goods, σ, takes a value of 0.2.[10] Economy C is also characterized by moderate investment adjustment costs of $\chi = 0.11$. Christiano et al. (2005), using the same specification in a different context, report an estimate of approximately 2.5. Finally, note that economy C is also characterized by quite persistent technology differentials.[11]

Finally, in figure 3 we plot the cross-correlation functions for the trade balance and the terms of trade for all three economies. Clearly, all three economies deliver a cross-correlation function quite close to the conditional S-curve obtained from the VAR. Moreover, the theoretical S-curves are well within the 90 percent confidence interval at all horizons. In the light of this evidence, the values reported for

[10]This number is lower than the values often used or found in the literature. Recent estimates in a similar order of magnitude, however, are reported by Lubik and Schorfheide (2006). Note, moreover, that such a low effective elasticity may be the result of a higher elasticity in an economy with a distribution sector as in Corsetti et al. (2004).

[11]We are not aware of any estimates for this parameter and thus simply note that any technology gap opening up in response to idiosyncratic technology shocks is quite persistent in economy C. It is interesting to observe that Kollmann (1998) cannot reject the null hypothesis of no cointegration of the process for U.S. total factor productivity and total factor productivity in the G6 countries estimated on the basis of Solow residuals.

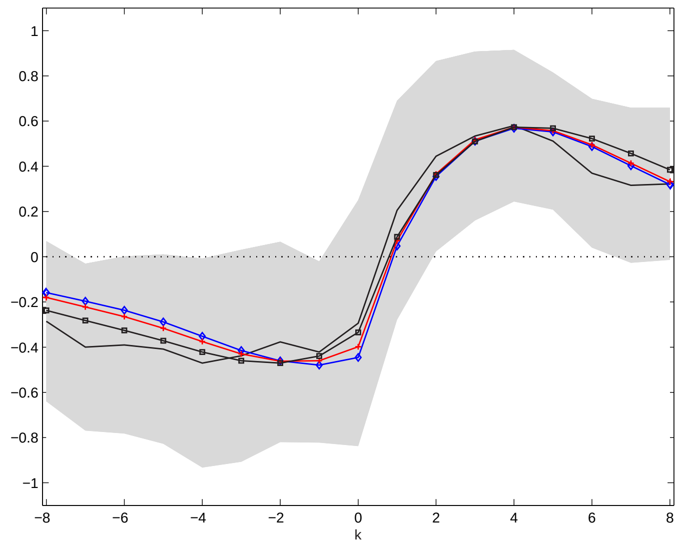

Figure 3: CROSS-CORRELATION FUNCTION FOR THE TRADE BALANCE AND THE TERMS OF TRADE. SOLID LINE: CROSS-CORRELATION FUNCTION COMPUTED ON THE BASIS OF THE VAR MODEL AND IDENTIFIED TECHNOLOGY SHOCKS; SHADED AREA INDICATES BOOTSTRAPPED 90 PERCENT CONFIDENCE INTERVALS; MODEL SIMULATIONS: ◇ ECONOMY A, + ECONOMY B, □ ECONOMY C.

the loss function in the last row of table 2 should be interpreted with some caution.[12]

4 Properties of theoretical economies

As a result of our calibration strategy, all three model specifications, i.e. all three economies deliver the S-curve. In the following we assess their relative performance regarding three different dimensions. First, we study in detail the international transmission of technology shocks in the theoretical economies and compare it with the transmission mechanism apparent from the data. Second, we compare in-sample predictions of the model with actual times series for the real exchange rate and net exports. Finally, we compare a set of second moments computed for the theoretical economies to those characterizing international data.

[12]However, the fact that economies B and C do almost equally well in minimizing the criterion function (16) can be related to a recent finding by de Walque, Smets, and Wouters (2005). These authors estimate a two-country DSGE model with *incomplete international financial markets* using Bayesian techniques. They also find two economically distinct optima depending on the starting value of the intratemporal elasticity of substitution between domestic and foreign goods. Statistically, their ‘low elasticity’ model (our economy C) also slightly dominates their ‘high elasticity’ model (our economy B) in terms of the marginal likelihood.

4.1 The transmission of technology shocks

We now turn to the transmission of a technology shock, originating in country 1. Specifically, given the joint process for domestic and foreign technologies (14), we consider the propagation of $\varepsilon_1(s^t)$ through the domestic economy and the variables characterizing foreign trade.[13] To compare the transmission process of the theoretical economy to the data, we focus on the responses of those variables included in the VAR. Eventually, we are interested in the ability of the theoretical economies to account for the evidence on the transmission process obtained from the VAR model and displayed in figure 2.

Figure 4 displays the responses to a one percent increase in domestic technology. The upper left panels shows the response of domestic output, which increases by about 0.8 percent on impact in all three economies. Hours also increase in all three economies in line with the VAR evidence (level specification). Both the response of output and hours are quantitatively similar to the responses obtained from the VAR model. Economy C, as a result of mild investment adjustment costs, also predicts mild humps in the responses of output and hours - in line with the VAR evidence. The responses of the terms of trade and the trade balance are displayed in the second row. Here one observes a striking difference between economies A and B, on the one hand, and economy C, on the other hand. In economy A and B the terms of trade depreciate, i.e. the price of imports increases relative to the price of exports. Only in economy C, the terms of trade appreciate - in line with the VAR evidence.

Before discussing the role of the terms of trade in the international transmission of technology shocks in more detail, we note that the response of the trade balance is also markedly different in economies A and B on the one hand and economy C on the other hand. The trade balance displays a hump-shaped decline in economy C - a pattern very much in line with the response obtained from the VAR model, see figure 2. In contrast, in economies A and B the trade balance falls sharply on impact and moves into surplus after about five quarters. Similarly, economy C, in contrast to economy A and B, delivers the right prediction for the sign of the response of the real exchange rate and predicts a hump-shaped response in investment.

A key result of our analysis is thus that while all three economies deliver the S-curve (figure 3) the underlying transmission process is quite distinct (figure 4). In fact, as far as the terms of trade and the trade balance are concerned, the transmission mechanism in economy C turns the transmission process of economies A and B upside down. This is not the result of different asset market structures *per se*: economy A and B are characterized by an almost identical transmission mechanism and yet they are characterized by different asset market structures.

[13] Recall that in calibrating the model we rely on relative variables only. Now we are also interested in the value of domestic variables *per se*. Therefore we have to specify the parameters governing (14). From the assumption $\rho_1 + \rho_2 = 1$ (see section 3.2) and the value obtained for the persistence of relative technology $\rho = \rho_1 - \rho_2$ in the calibration of the model (see table 2), we obtain $\rho_1 = (1 + \rho)/2$ and $\rho_2 = 1 - \rho_1$.

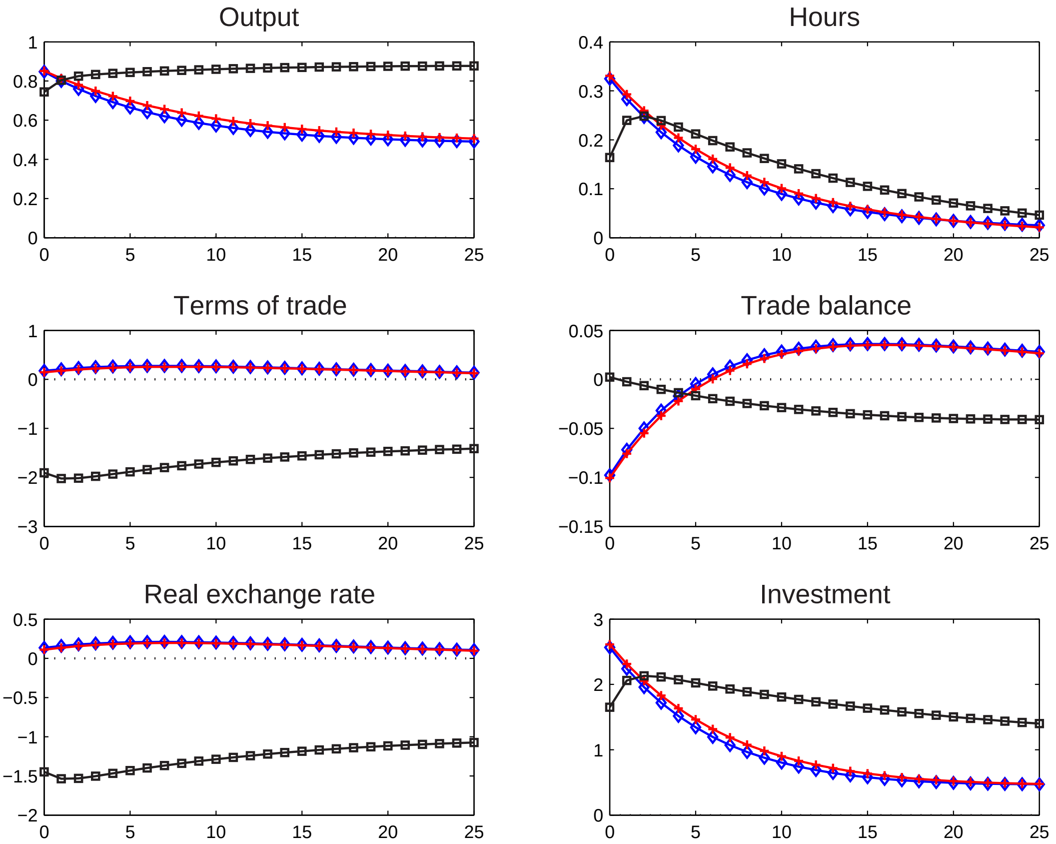

Figure 4: TRANSMISSION OF TECHNOLOGY SHOCK IN THEORETICAL ECONOMIES SHOCK IS ONE PERCENT INCREASE IN TECHNOLOGY. VERTICAL AXES: PERCENT EXCEPT FOR TRADE BALANCE WHICH IS MEASURED IN PERCENTAGE POINTS OF OUTPUT. HORIZONTAL AXES: QUARTERS. ◇ ECONOMY A, + ECONOMY B, □ ECONOMY C.

Earlier literature, e.g. Baxter and Crucini (1995), has established that moving from complete to incomplete financial markets does not necessarily affect the equilibrium allocations very much. It has also been noted that under incomplete markets terms of trade movements play a key role in supporting an equilibrium allocation close to the complete markets allocation. Specifically, Cole and Obstfeld (1991) show that terms of trade movements provide complete insurance against country specific risk in the absence of complete financial markets if the elasticity of substitution between domestic and foreign goods is equal to one. To see how this works, consider economy B, where the home country faces temporarily favorable technology shock. As a result, its output expands relative to foreign. At the same time the terms of trade depreciate, i.e. the price of domestically produced goods falls relative to foreign intermediate goods. This change in relative prices implies a wealth transfer from home to foreign, partially off-setting the technology shock. Depending on the degree of substitutability between home and foreign goods, terms of trade movements provide implicit risk-sharing which otherwise could be implemented through trade in state-contingent securities if international financial markets were complete. As a result, the equilibrium allocations induced by a country-specific technology shock is quite similar in economy A and B despite different asset market structures.

The transmission of technology shocks, however, is quite distinct in the incomplete markets economy C. Notably, the terms of trade appreciate. Thereby the change in relative prices *amplifies* the relative wealth effect induced by the technology shock. Corsetti et al. (2004) analyze the possibility of such a 'negative' international transmission of technology shocks. Specifically, they find that the terms of trade appreciate in response to a positive technology shock if i) financial markets are incomplete, ii) home bias is substantial and iii) the elasticity of substitution between domestic and foreign goods is low. To see how these features induce a terms of trade appreciation, consider an increase in domestic technology. Ceteris paribus, this increases domestic wealth relative to foreign if financial markets are incomplete. As a result domestic absorption increases relative to foreign. If, in addition, home bias is pervasive and substitution elasticities are low, this induces a more than proportional increase in the demand for domestically produced goods. In equilibrium this induces the price of domestically produced goods to rise relative to the price of foreign goods. Apparently, the economy C is characterized by the transmission mechanism suggested by Corsetti et al. (2004).[14]

In assessing the relative performance of the economies A, B and C, we find that economy C stands out as the only economy which correctly predicts a terms of trade appreciation and a hump-shaped decline of the trade balance. As a caveat it should be noted that the quantitative performance of economy C is not fully satisfactory. While the terms of trade respond too much relative to the VAR evidence, the trade balance responds too little to the technology shock. Furthermore, our model assessment is based on VAR results which are subject to the usual critique regarding identification and auxiliary assumptions, see Cooley and Dwyer (1998). We therefore turn to an alternative, non-VAR criterion to assess the relative performance of economies A and C. For simplicity, we will neglect economy B as it delivers an allocation close to the allocation of economy A.

4.2 In-sample predictions

In this subsection we use economy A and C to generate an in-sample prediction for the real exchange rate and the trade balance. We use a measure for output in the U.S. relative to the rest of the world to obtain an estimate for the underlying process of relative technology for both economies. This allows us to compute the implied time series of all other variables of interest.[15] To construct the output

[14] In contrast to the present paper, Corsetti et al. (2004) focus on the finding of Backus and Smith (1993) whereby the correlation between relative consumption and the real exchange rate is low or even negative for most OECD countries - in contrast to what is predicted by models based on the standard transmission mechanism.

[15] Jung (2005) suggests this approach in a closed economy context. Note also that output growth differentials are often evoked as a possible rationale for the U.S. trade deficit, see, for instance, Engel and Rogers (2006) or Backus, Henriksen, Lambert, and Telmer (2006).

differential we take the log-difference of U.S. GDP and GDP in a 'rest of the world' sample (ROW) which includes the Euroarea, U.K., Japan and Canada. In the following analysis we consider the trade balance and the real exchange rate of the U.S. with this particular set of countries.[16]

To infer the underlying innovations in relative technology, we use the Kalman filter, i.e. we calculate linear least squares forecasts of the state vector on the basis of the observed output differential.[17] To estimate the underlying state vector of the model we use the parameter values obtained in section 3.3. An exception is the standard deviation of the innovations to relative technology, which we estimate by maximizing the log-likelihood: we find a value of 0.0094 and 0.0080 for economy A and C, respectively.

Figure 5 displays actual time series and model predictions. The upper right panel displays the output differential, measuring the difference between the deviation of output from trend in the U.S. and the ROW. A value of -0.05 means that the percentage deviation of U.S. output from trend is 0.05 percentage points lower than the percentage deviation of ROW output from trend. In the early part of our sample the U.S. experienced output realizations below trend - relative to the ROW, while the opposite holds the late 1990s. The upper right panel displays the underlying technology differential - which differs somewhat across both theoretical economies but essentially mimics closely the output differential in both cases - a finding familiar from closed economy RBC models, which are generally found to have a weak internal propagation mechanisms, see Cogley and Nason (1995).

The lower left panel displays the change in the real exchange rate. The predicted exchange rate changes are less volatile in both economies than in the data. This is particularly true for the predictions of economy A, which can be hardly distinguished from the zero line. The failure of international business cycle models to account for actual exchange rate volatilities has been noted before and has been considered a major puzzle in international macroeconomics, see Chari et al. (2002). Figure 5 provides yet another illustration in this respect as far as economy A is concerned. Moreover, while economy C also fails to account for the actual changes in the U.S. real exchanges rate, it still dominates the performance of economy A: the correlation of the actual series and the predicted series is -0.13 and 0.09, for economy A and C, respectively.

The lower right panel displays the trade balance. Note that the U.S. trade deficit with our ROW sample is an order of magnitude smaller than the overall U.S. trade deficit. Both economies, however, have difficulties to account for the size of the deficit. While economy C seems to capture the general trend in the deficit, economy A seems to capture better the volatility of the actual time series. The correlation of the actual series and the predicted series is 0.09 and 0.18, for economy A and C, re-

[16] See appendix A.2 for details. We consider the real exchange rate instead of the terms of trade because of data availability for our ROW sample. More precisely, we will focus on the change in the real exchange rate, because the real exchange rate is constructed as an index.

[17] In a related context, Normandin and Fosso (2006) use the Kalman filter in a (one good) international business cycle model to decompose observed technology (Solow residuals) into a country-specific and a global component.

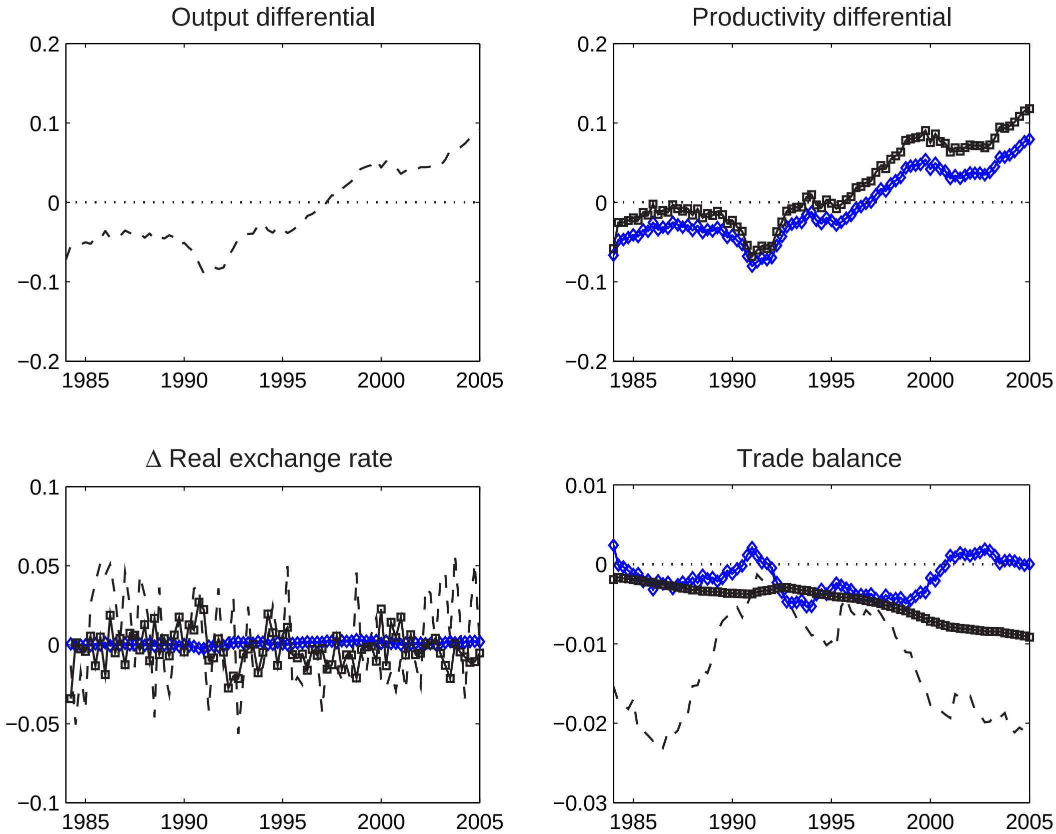

Figure 5: IN SAMPLE PREDICTION OF ECONOMY A AND C. PREDICTION IS BASED ON OBSERVED OUTPUT DIFFERENTIAL IN U.S. VS ROW (EUROAREA, U.K., CANADA AND JAPAN). - - ACTUAL TIME SERIES, ◇ ECONOMY A AND □ ECONOMY C.

spectively.

Regarding the joint dynamics of the real exchange rate and the trade balance it seems worth noting that moving from economy A to economy C increases exchange rate volatility at the expense of lowering the volatility of the trade balance. A similar observation is made by Backus et al. (1995) who analyze the trade off between exchange rate volatility and the volatility of imports.

Overall, the ability of both economies to predict the actual series of the real exchange rate and the trade balance is limited. Clearly, predicting these series is quite an ambitious task given the parsimonious model. While economy C performs slightly better, a richer theoretical structure will be necessary if the predictive success of the model is to be increased.

4.3 Second moments

We now turn to an assessment of our theoretical economies on the basis of second moments. Specifically, we compute some of those second moments of economy A and C which have been the focus of the debate on international business cycles in the last 15 years. We compare these moments with those of international data for the U.S. vis-à-vis the ROW.[18]

We report the moments in table 3. The first panel displays the variability of investment, net exports and the real exchange rate relative to that of output. Both theoretical economies induce a variability of investment close to what characterizes the data. As discussed in BKK, the concavity of technology

Table 3: SECOND MOMENTS

Statistics	U.S. Data	Economy A	Economy C
Standard deviation relative to GDP			
Investment	3.13	3.05	2.58
Trade balance	0.25	0.15	0.02
Real exchange rate	4.39	0.27	2.38
Autocorrelation			
Real exchange rate	0.78	0.81	0.71
Correlations			
Real exchange rate and relative consumption	-0.10	0.93	-0.98
Trade balance and output	-0.24	-0.61	-0.16
Output across countries	0.28	0.03	0.12
Consumption across countries	0.05	0.80	-0.24

Notes: All foreign variables refer to the group of Canada, Japan, the U.K. and the Euro area. Statistics refer to HP-filtered series.

implied by imperfect substitutability of domestic and foreign goods reduces the variability of investment relative to a one good world. Against this background, the effect of investment adjustment costs in economy C appears to be relatively mild. Economy C, however, fails to match the variability of the trade balance. This mirrors the result of section 4.1 and 4.2, which showed that the response of the trade balance to technology shocks is limited in economy C. Economy A, on the other hand, fails to deliver the variability of the real exchange rate.[19] This failure is also known as the price anomaly, see Backus et al. (1994, 1995). Economy C, in contrast, induces a variability of relative prices closer to that of the data. This is a result of the low elasticity of substitution between domestic and foreign goods. Recall, that Backus et al. (1995) also analyze the trade-off between trade and price variability in some detail. Economy A and C seem to be extreme solutions in that respect.

In the second panel of table 3 we report the autocorrelation of the real exchange rate. It is interesting to note that we do not observe the 'persistence anomaly' for the real exchange rate identified by Chari et al. (2002). As shown by these authors this is likely to be the result of assuming non-separable preferences in consumption and leisure.

[18]In our simulations we follow BKK and set the correlation between $\varepsilon_1(s^t)$ and $\varepsilon_2(s^t)$ to 0.258. We also assume that the innovations in both countries have the same variance. Then, given our estimates for the variance of the innovations to relative technology $\tilde{z}(s^t)$, we can pin down the variance of the innovations to technology in both countries ($\sigma^2_{\varepsilon_1}$ and $\sigma^2_{\varepsilon_2}$).

[19]We are focusing on the real exchange rate of the U.S. with respect to ROW. Considering the U.S. terms of trade (unadjusted for the ROW sample) gives a similar picture.

As Backus and Smith (1993) and Chari et al. (2002) stress the importance of the consumption-real exchange rate anomaly in the standard two country business cycle model, we report this statistic in the first row of the last panel. This anomaly is also observed for economy A which predicts a correlation of the real exchange rate with relative consumption close to one, while the data show a correlation of -0.1. Economy C, in contrast, predicts a correlation close to -1. This is a result of 'negative' transmission and is analyzed in Corsetti et al. (2004) in greater detail.

The last two rows report the cross-country correlation of output and consumption. Backus et al. (1994, 1995) and Ambler et al. (2004), among others, have analyzed the 'quantity anomaly', i.e. that the cross-country correlation of output is higher than that of consumption while the standard two country business cycle model predicts the opposite. Note that this anomaly only emerges for economy A, but not for economy C where the cross-country correlation of consumption is lower than the cross-country correlation of output. Again, this is the result of the 'negative' transmission mechanism by which terms of trade movements amplify relative wealth effects due to technology shocks and thus induce a negative cross-country correlation of consumption.

Overall, the performance to match the second moments of the data is mixed for both economies. We find it noteworthy, however, that economy C does quite well in terms of the relative size of the cross-country correlation of output and consumption.

5 Conclusion

In this paper we have analyzed the international transmission of technology shocks by confronting the transmission mechanism of a standard international business cycle model with time series evidence for the U.S. in the period 1984-2005.

We estimated a VAR model and computed the cross-correlation function for the trade balance and the trade balance induced by the identified technology shocks. This conditional cross-correlation function resembles closely the S-curve which characterizes the unconditional cross-correlation function; one of the striking features of the international business cycle data, according to BKK.

Then, we calibrated a standard international business cycle model to match the S-curve conditional on technology shocks, both under complete and incomplete financial markets. As result we found three economies which deliver the S-curve. The complete markets economy A matches the S-curve for parameter values close to those used in the baseline calibration of BKK, i.e. the elasticity of substitution between domestic and foreign goods is about 1.5 and investment adjustment costs are absent. Under incomplete financial markets two optima emerge. The local optimum (economy B) is characterized by parameter values close to those of economy A. In fact, both economies A and B imply the standard transmission mechanism for technology shocks. The global optimum under incomplete financial markets (economy C), in contrast, is characterized by investment adjustment costs and a relatively low elasticity of substitution between domestic and foreign goods.

We then turned to the impulse responses of the VAR to assess the model. Technology shocks depreciate the terms of trade and induce a strong fall in the trade balance in economy A and B. In economy C, technology shocks appreciate the terms of trade and induce a hump-shaped decline in the trade balance. Thereby, economy C, in contrast to economy A and B, provides a characterization of the transmission of technology shocks which is qualitatively in line with the VAR evidence. In addition, we considered in-sample forecasts and second moments as criteria to assess the relative performance of the three economies.

Overall, there is considerable evidence against the standard transmission mechanism and some evidence in favor of the transmission mechanism implied by economy C. Its defining feature is the appreciation of the terms of trade in response to technology shocks. As stressed by Corsetti et al. (2004), in this case the welfare implications of incomplete financial markets are rather drastic: terms of trade movements fail to deliver implicit risk sharing, but instead tend to amplify the relative wealth effect of technology shocks.

Against this background, we conclude that further research into the international transmission of technology shocks is necessary. Specifically, the role of relative prices in the transmission of technology shocks is of particular interest. It therefore seems worthwhile to allow for richer dynamics in that respect, for instance, by considering a non-tradable sector or consumer durables, as in earlier work by Stockman and Tesar (1995) and Burda and Gerlach (1992).

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Appendix

A Data

A.1 U.S. time series

The data used to calculate the S-curve and estimate the VAR model are obtained from the Bureau of Economic Analysis (National Income and Product Accounts, NIPA), the Bureau of Labor Statistics (BLS) and the OECD Main Economic Indicators Database. The series are displayed in figure A.1. It also describes basis transformations of the original data.

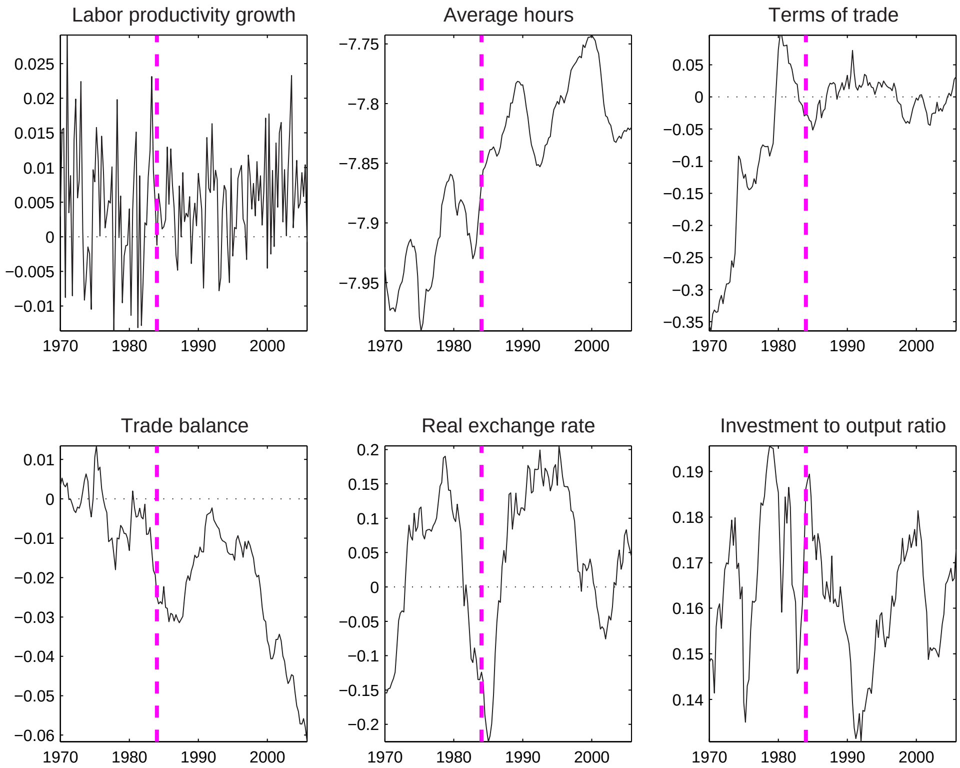

Figure A.1: Labor productivity growth: first difference of log output per hour in the non-farm business sector (BLS: PRS85006093); Average hours: log of hours in non-farm business sector (BLS: PRS85006033) divided by population (NIPA: B230RC0); Terms of trade: log of relative price of imports to exports, calculated on the basis of the implicit price deflators (NIPA: A021RD3 and A020RD3, respectively); Trade balance: nominal net exports (NIPA: A019RC1) divided by nominal GDP (NIPA: A191RC1); Investment to output ratio: gross private domestic investment (NIPA: A006RC1) divided by nominal GDP (NIPA: A191RC1); Real Exchange Rate: log of inverted real effective exchange rate as provided by OECD.

A.2 ROW data and construction of output differential

In section 4.2 and 4.3 we consider statistics computed for international data. Specifically, we consider data for the U.S. relative to a sample representing the 'rest of the world' (ROW). In practice this comprises the Euroarea, U.K., Japan, and Canada. Quarterly data for GDP for the U.S. and the ROW are taken from the OECD Main Economic Indicators and are converted to 2001 constant prices U.S. dollars. The ROW series are aggregated using PPP exchange rates from the IMF. Data for the trade balance of the U.S. with the ROW are obtained from the Bureau of Economic Analysis. The real exchange rate towards the ROW is constructed with nominal exchange rates taken from the Bank of England, and the respective CPI's from national sources.

In section 4.2 we discuss how to infer the underlying process of relative technology, given a time series for the output differential, $\tilde{y}(s^t)$. Specifically, the empirical equivalent to the theoretical output differential can be computed as in log-deviations from a balanced growth path. Letting the superscript 'A' denote actual values and 'T' the underlying trend, then

$$\tilde{y}(s^t) := \hat{y}_1(s^t) - \hat{y}_2(s^t) = \log\left(\frac{y^A_{us}(s^t)}{y^T_{us}(s^t)}\right) - \log\left(\frac{y^A_{row}(s^t)}{y^T_{row}(s^t)}\right)$$

Assuming that at any point in time $y^T_{row}(s^t) = By^T_{us}(s^t)$, we rewrite the output differential as

$$\tilde{y}(s^t) = \log\left(\frac{y^A_{us}(s^t)}{y^A_{row}(s^t)}\right) - \log\left(\frac{y^T_{us}(s^t)}{By^T_{us}(s^t)}\right) = \log\left(\frac{y^A_{us}(s^t)}{y^A_{row}(s^t)}\right) + \log(B)$$

In practice we compute B as the ratio of mean GDP in ROW to mean GDP in the US - which is 1.38.

B The VAR

B.1 Identification

Our identification strategy is based on Christiano et al. (2003) or Altig et al. (2005). As described in the main text our VAR model contains the following variables

$$Y_t = \begin{pmatrix} \Delta \ln\left(\text{GDP}_t/\text{Hours}_t\right) \\ \ln \text{Hours}_t \\ \ln\left(\text{Terms of Trade}_t\right) \\ \text{Net Exports}_t/\text{GDP}_t \end{pmatrix} = \begin{bmatrix} \Delta a_t \\ h_t \\ p_t \\ nx_t \end{bmatrix} \tag{17}$$

The structural VAR model of the economy is given by

$$A(L)Y_t = \varepsilon_t, \tag{18}$$

where a constant is omitted to simplify the exposition and $A(L)$ denotes a p^{th}-ordered polynomial in the lag operator L. Specifically, we consider four lags, i.e.

$$A(L) = A_0 + A_1 L + A_2 L^2 + A_3 L^3 + A_4 L^4,$$

such that A_0 allows for contemporaneous interaction of the variables contained in Y_t. The fundamental economic shocks are contained in the 4×1 vector ε_t. We assume that these fundamental shocks are mutually uncorrelated such that

$$E\left(\varepsilon_t \varepsilon_t'\right) = D,$$

is a diagonal matrix and the diagonal elements of A_0 are normalized to one.[20] We want to estimate the coefficients of the structural VAR model (18). To ensure identification further assumptions have to be made. To simplify the discussion define $Z_t' = \left[\begin{array}{ccc} h_t & p_t & nx_t \end{array}\right]$. Also define an element in $A_i = \alpha_{i,kl}$, where k denotes the row and l the column of A_i. Note that evaluating (18) in the long-run with $p = 4$ gives

$$\underbrace{\left(\begin{array}{cc} \underset{1\times1}{\sum_{i=0}^{4}\alpha_{i,11}} & \underset{1\times3}{\sum_{i=0}^{4}\alpha_{i,12}} \\ \underset{3\times1}{\sum_{i=0}^{4}\alpha_{i,21}} & \underset{3\times3}{\sum_{i=0}^{4}\alpha_{i,22}} \end{array}\right)}_{\equiv A(1)} \left[\begin{array}{c} \underset{1\times1}{\Delta a_t} \\ \underset{3\times1}{Z_t} \end{array}\right] = \left[\begin{array}{c} \underset{1\times1}{\varepsilon_t^a} \\ \underset{3\times1}{\varepsilon_t^Z} \end{array}\right].$$

Technology shocks are identified through the assumption that only technology shocks have a long run effect on labor productivity. This imposes the following restriction on the long-run multiplier $A\left(1\right)$:

$$\sum_{i=0}^{4} \alpha_{i,12} = 0. \tag{19}$$

To see this, assume to the contrary that this sum was not zero. Then, given that other shocks induce Z_t to be different from zero in the long run, also labor productivity may be affected by these shocks in the long run, which is ruled out by assumption. Christiano et al. (2003) provide a more detailed discussion. In practice we impose these restriction on the first equation of (18), given by

$$\Delta a_t = -\sum_{i=1}^{4} \alpha_{i,11} L^i \Delta a_t - \sum_{i=0}^{4} \alpha_{i,12} L^i Z_t + \varepsilon_t^a, \tag{20}$$

which after imposing (19) reads as[21]

$$\Delta a_t = -\sum_{i=1}^{4} \alpha_{i,11} L^i \Delta a_t - \sum_{i=0}^{3} \alpha_{i,12}' L^i \Delta Z_t + \varepsilon_t^a.$$

[20] Note that in Altig et al. (2005) $D = I$. Here we assume a diagonal matrix as we prefer to normalize the diagonal elements of A_0 to one.

[21] Here we use the fact that $\alpha(L) = \alpha(1) + \alpha'(1-L)$ together with $\alpha(1) = 0$ implies

$$\alpha_{i,1k} = \alpha_{i,1k}' - \alpha_{i-1,1k}'.$$

Note, however, that since $\alpha_{0,21} \neq 0$, this equation cannot be estimated by OLS. Instead, as originally proposed by Shapiro and Watson (1988), we use $Y_{t-1}, \ldots Y_{t-4}$ as instruments in a two-stages least squares regression.

Finally, the structural shocks related to Z_t cannot be identified as the mapping from the reduced form to the structural form is not unique, see the discussion in the technical appendix to Altig et al. (2005). In order to estimate the structural model - leaving ε_t^Z unidentified (we do not give a structural interpretation to the estimated shocks) - we assume that $\alpha_{0,22}$ is lower triangular. Given these restrictions we are in a position to estimate the structural VAR model (18) and identify technology shocks. Figure B.1 displays the identified technology shocks. In the main text we report several statistics computed on the basis of the estimated VAR model and the identified technology innovations.

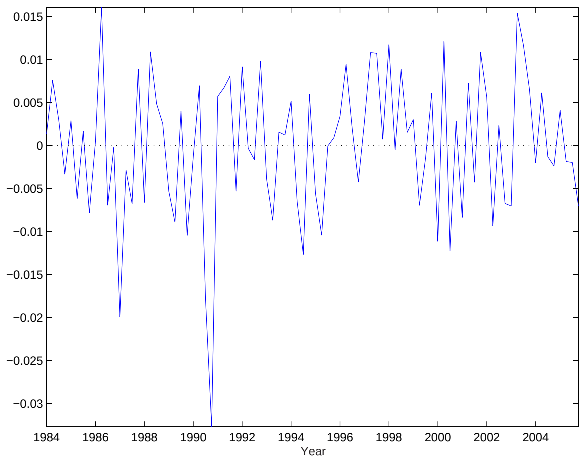

Figure B.1: TECHNOLOGY SHOCKS IDENTIFIED IN U.S. DATA ON THE BASIS OF BASELINE VAR MODEL.

B.2 Sensitivity of results with respect to hours specification

To explore the robustness of the VAR results, we also consider the specification where hours enter the VAR in first differences. Figure B.2 displays the impulse response functions - which are somewhat different for output and, in particular, for hours. This has been the topic of a considerable debate, see, for instance, Galí (1999) and Christiano et al. (2003). However, for the present analysis it is important to note that the responses of the other variables are robust with respect to the way hours are modeled. This is also reflected in the counterfactual S-curve displayed in figure B.3.

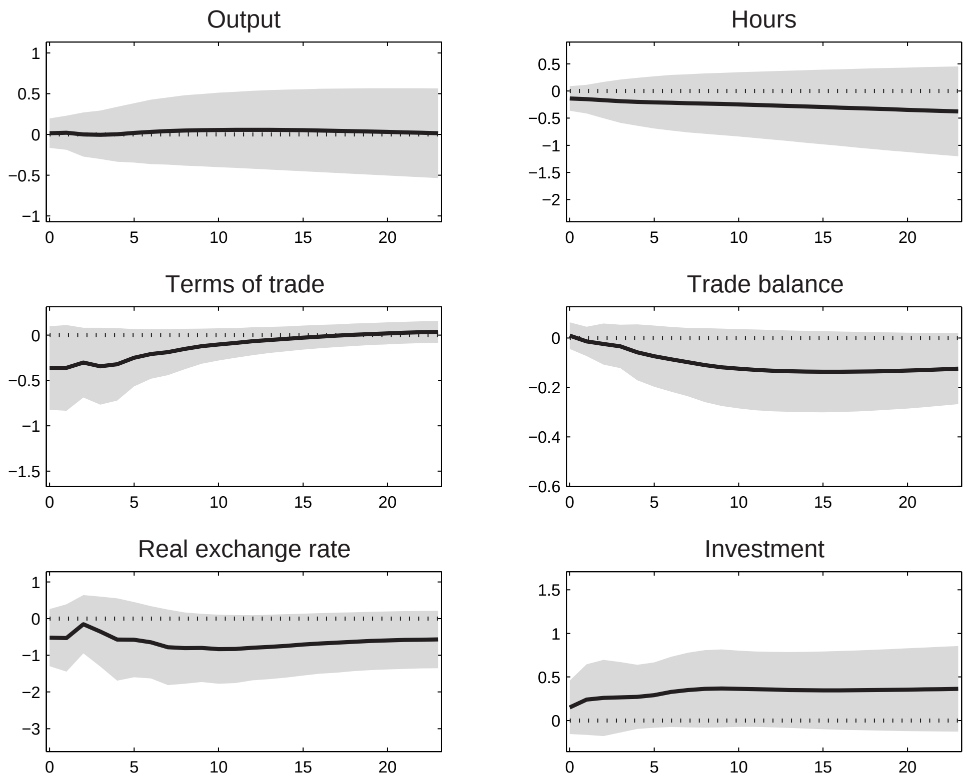

Figure B.2: TRANSMISSION OF PRODUCTIVITY SHOCK IN US DATA, SEE FIGURE 2. VAR IS NOW ESTIMATED WITH HOURS IN FIRST DIFFERENCES INSTEAD OF LEVELS.

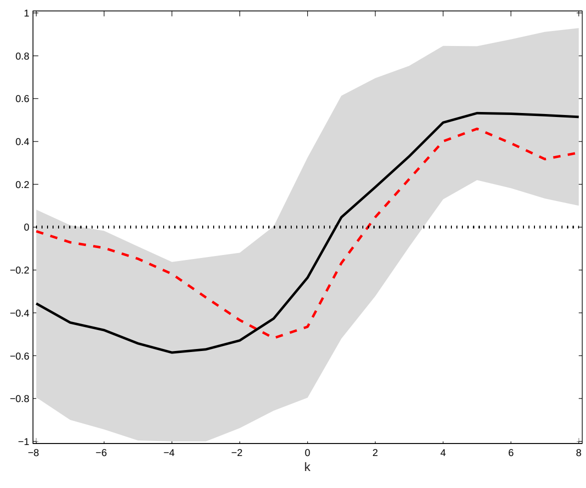

Figure B.3: THE S-CURVE, SEE FIGURE 1. COMPUTATION OF CONDITIONAL S-CURVE IS NOW ON BASIS OF VAR MODEL WITH HOURS IN FIRST DIFFERENCES INSTEAD OF LEVELS.