EUI WORKING PAPERS

ECO No. 2006/36

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

ZENO ENDERS
AND GERNOT J. MUELLER

European University Institute

Department of Economics

EUROPEAN UNIVERSITY INSTITUTE
DEPARTMENT OF ECONOMICS

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

ZENO ENDERS AND GERNOT J. MUELLER

EUI Working Paper **ECO** No. 2006/36

ISSN 1725-6704

Printed in Italy
European University Institute
Badia Fiesolana
I – 50016 San Domenico di Fiesole (FI)
Italy

http://www.eui.eu/
http://cadmus.eui.eu/

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

Zeno Enders†
European University Institute
Ente Luigi Einaudi

Gernot J. Müller‡
Goethe University Frankfurt

November 7, 2006

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 (S-curve). In calibrating a prototypical international business cycle model to match the S-curve under complete and incomplete financial markets, we find two distinct sets of parameter values. While both model specifications deliver the S-curve, the underlying transmission mechanism of technology shocks is fundamentally different. Most importantly, only in the incomplete markets economy the terms of trade appreciate and thus amplify the relative wealth effects of technology shocks - as suggested by time series evidence.

Keywords: S-curve, Technology shocks, Terms of trade, Trade balance, Incomplete markets
JEL-Codes: F41, E32, F32

*We thank Giancarlo Corsetti, Luca Dedola, Philip Jung, Dirk Krüger, Keith Küster, Elvira Prades, Morten Ravn and seminar participants at the ECB, German Economic Association Meeting in Bayreuth, EUI, Open Macroeconomics & Development Meeting in Aix-en-Provence, 2^{nd} German Workshop in Macroeconomics, and ASSET 2006 for very helpful comments on earlier drafts. Zeno Enders thanks the European Investment Bank for financial support. The usual disclaimer applies.

†Mailing address: Ente Luigi Einaudi, Via Due Macelli, 73, 00187 Rome, Italy; Tel.:+39-06-47924768, Fax: +39-06-47924872; E-mail: zeno.enders@eui.eu

‡Mailing address: Mertonstrasse 17, 60054 Frankfurt, Germany; Tel.: +49(0)69-79825282, Fax: +49 (0)69-79825272; E-mail: gernot.mueller@wiwi.uni-frankfurt.de

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, complete markets variant of the model fails to replicate several key properties of the data, notably it fails to replicate the volatility of relative prices.[1] At the same time BKK emphasize that - conditional on technology shocks - 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'.[2] The S-curve is a robust feature of the data and qualifies as a stylized fact characterizing international business cycles.

In the present paper we rigorously assess the transmission mechanism of technology shocks implied by a prototypical international business cycle model - both under complete and incomplete financial markets. Given that the S-curve is one of the (few) dimensions where the prediction of the model squares well with the evidence, we focus on this statistic to pin down key parameters of the model. However, in contrast to earlier work, we compute the cross-correlation function for the trade balance and the terms of trade using counterfactual time-series obtained from purging the raw time series of the contributions of non-technology shocks. In other words, we compute a cross-correlation function conditional on technology shocks. In our view, it is important to focus on the conditional cross-correlation function given an emerging consensus according to which technology shocks are unlikely to be the only source of business cycle fluctuations.[3] In fact, while one-shock models that

[1]Subsequent research has documented this failure as well as further anomalies and made various suggestions for their resolution. 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).

[2]See BKK, page 94. If government shocks are considered in addition to technology shocks, the shape of the cross-correlation function barely changes. If government spending shocks were the sole impulse to the theoretical economy, the cross-correlation function would be tent-shaped.

[3]See Galí (1999), Altig, Christiano, Eichenbaum and Lindé (2005) or Chari, Kehoe and McGrattan (2005). While these papers disagree in various respects, they all suggest that the contribution of technology shocks to business cycle fluctuations is substantially lower than 70 percent as argued, for instance, in Kydland and Prescott (1991).

correctly describe the effects of technology shocks may fail to predict the unconditional S-curve, it is a necessary condition to deliver the *conditional* cross-correlation function.

Of course, additional assumptions are required to obtain the counterfactual time-series. Specifically, in section 2 we estimate a structural vector autoregression (VAR) model on U.S. time series data and identify technology shocks by assuming that only these shocks affect labor productivity in the long-run. The aim of the VAR analysis is twofold. First, we compute counterfactual time series that would have been obtained, had technology shocks been the sole source of fluctuations. These time series, in turn, are used to calculate the conditional cross-correlation function for the trade balance and the terms of trade. We find it to be S-shaped as well, but shifted to left relative to its unconditional counterpart. This implies that, while the unconditional contemporaneous correlation of the trade balance and the terms of trade is negative, it is positive conditional on technology shocks. We use the conditional S-curve to calibrate our quantitative business cycle model where technology shocks are the only source of fluctuations.

Second, we use the VAR model to compute impulse response functions. 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. We treat these responses as an empirical characterization of the actual transmission mechanism and use them to assess the transmission mechanism implied by the prototypical business cycle model. In other words, the empirical impulse responses will serve as a sufficient condition for a successful theoretical account of the international transmission of technology shocks.

The model, a variant of the model originally proposed by BKK, is outlined in section 3. In addition to complete financial markets, we also consider the possibility that only non-contingent bonds are traded across countries (incomplete financial markets). Moreover, we allow for investment adjustment costs and focus on exogenous differences in the level of technology across countries. We use the cross-correlation function conditional on technology shocks to calibrate the model: by matching the S-curve we pin down parameter values for the elasticity of substitution between domestic and foreign goods, investment adjustment costs and the persistence of relative technology. As we match the cross-correlation function for 8 leads and lags, we impose 14 overidentifying restrictions. We consider both asset market structures. If financial markets are complete, we find a relatively high elasticity of substitution, while relative technology is moderately persistent. Investment costs are absent. If financial markets are incomplete, we find a low elasticity of substitution and relative technology is very persistent. There is also evidence for mild investment adjustment costs under incomplete financial markets.

Our assessment of the model starts with the observation that the S-curve is fairly well matched under both model specifications. We thus turn in section 4 to the underlying transmission mechanism and compare the impulse responses of the theoretical economies with those obtained from the VAR model. Here we observe a striking difference across both specifications: the model calibrated under complete financial markets predicts the terms of trade to depreciate and the trade balance to fall sharply on impact - in line with the standard transmission mechanism. In contrast, the model calibrated under incomplete financial markets implies a transmission mechanism which turns the responses of the terms of trade and the trade balance upside down: it predicts an appreciation of the terms of trade and a hump-shaped decline in the trade balance - in line with the VAR evidence. This fundamental difference in the transmission process, however, is not the result of different asset markets *per se*. In fact, for standard calibrations of the prototypical business cycle model, the transmission mechanism hardly differs across the two asset market structures.

Hence, our analysis 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), henceforth CDL; 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.[4] Specifically, CDL 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 countries. Under these circumstances, the welfare implications of country-specific technology shocks are 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).

[4]In contrast to the present paper, CDL do not investigate the cross-correlation function for the trade balance and the terms of trade. Instead, they focus on the relative consumption-real exchange rate anomaly identified by Backus and Smith (1993).

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 as well as the contribution of technology shocks to the volatility of trade variables. 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. Regarding our two key variables, we compute the terms of trade, p_t, as the log of the price index of non-commodity imports of goods and services divided by the price index of non-commodity exports of goods and services. The trade balance, nx_t, is measured as the ratio of nominal net exports to nominal GDP.[5] As macroeconomic volatility and, in particular, those of the terms of trade has been much higher in the 1970s relative to the post-1980 period, we limit our sample to data covering the period 1980:1-2005:4.

2.1 The 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. 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 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 for our time series, 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.[6] 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 balance realizations are positively associated with current terms of trade.

BKK rationalize the S-curve by appealing to a specific transmission mechanism of technology shocks that, partly as a result of their work, may be considered the standard transmission mechanism.[7] After a one-time positive shock to technology domestic output increases and its relative price falls (p_t

[5] We use price indices for non-commodity imports and exports in order to limit the impact of oil price fluctuations on the terms of trade. We follow BKK and consider net exports in current prices and thus allow valuation effects to play an important role in the dynamics of the trade balance. Note that this is quite distinct from analyzing the dynamics of the trade balance in constant prices, see Raffo (2006).

[6] Differences with respect to BKK are mostly due to considering a different sample period; only very small changes result from considering price indices for non-commodity imports and exports to compute the terms of trade.

[7] 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.

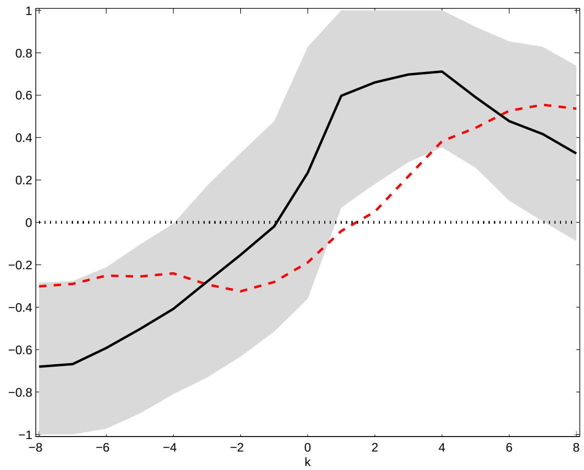

Figure 1: CROSS-CORRELATION FUNCTION FOR THE TRADE BALANCE (T+K) AND THE TERMS OF TRADE (T); SAMPLE: U.S. DATA 1980:1-2005:4; DASHED LINE: UNCONDITIONAL, COMPUTED AFTER APPLYING HP-FILTER TO RAW TIME SERIES; SOLID LINE: CONDITIONAL, COMPUTED AFTER APPLYING HP-FILTER TO COUNTERFACTUAL TIME SERIES OBTAINED FROM THE VAR MODEL; SHADED AREA: BOOTSTRAPPED 90 PERCENT CONFIDENCE INTERVALS

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 $k > 1$.

2.2 The conditional S-curve

To obtain a cross-correlation function conditional on technology shocks we estimate a structural VAR model. In order 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. The 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 log of the real effective exchange rate, rx_t, and the trade balance with the log of investment over GDP. We include a constant and four lags of each endogenous variable.

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 solid 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’. However, relative to its unconditional counterpart, the conditional cross-correlation function shifts to the left, i.e. while the unconditional contemporaneous correlation is negative, the conditional contemporaneous correlation is positive. This suggests that actual business cycle fluctuations of the trade balance and the terms of trade are to some extent driven by non-technology shocks. Hence, in order to understand the transmission of technology shocks it seems important to focus on those fluctuations of the data that can be attributed to technology shocks.

2.3 Business cycle variance decomposition

To assess quantitatively the contribution of technology shocks to fluctuations of the trade balance and the terms of trade, we perform a business cycle variance decomposition following Altig et al. (2005). Again, we rely on the counterfactual series that would have been the result if only technology shocks had occurred. We then 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 (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

Table 1: BUSINESS CYCLE VARIANCE DECOMPOSITION

Output	Hours	p	nx	rx	Investment
0.33 (0.23)	0.21 (0.22)	0.46 (0.23)	0.29 (0.15)	0.55 (0.21)	0.22 (0.18)

Notes: Fraction of variance accounted for by technology shocks HP filtered series used (standard errors in parentheses).

importance of technology shocks in accounting for the shape of the S-curve: we find that technology shocks account for 46 and 29 percent of fluctuations of the terms of trade and the trade balance, respectively. These numbers are relatively 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 to be an important source of the short-run fluctuations of the trade balance and the terms of trade.[8]

[8] We also estimated a larger VAR model and identified monetary and fiscal policy shocks in addition to technology shocks. Technology shocks always accounted for the bulk of the business cycle fluctuations of the trade balance and the

2.4 Impulse response functions

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 will treat these responses as an empirical characterization of the actual transmission mechanism. Figure 2 displays the responses to a positive, one percent increase in technology. All variables are measured in

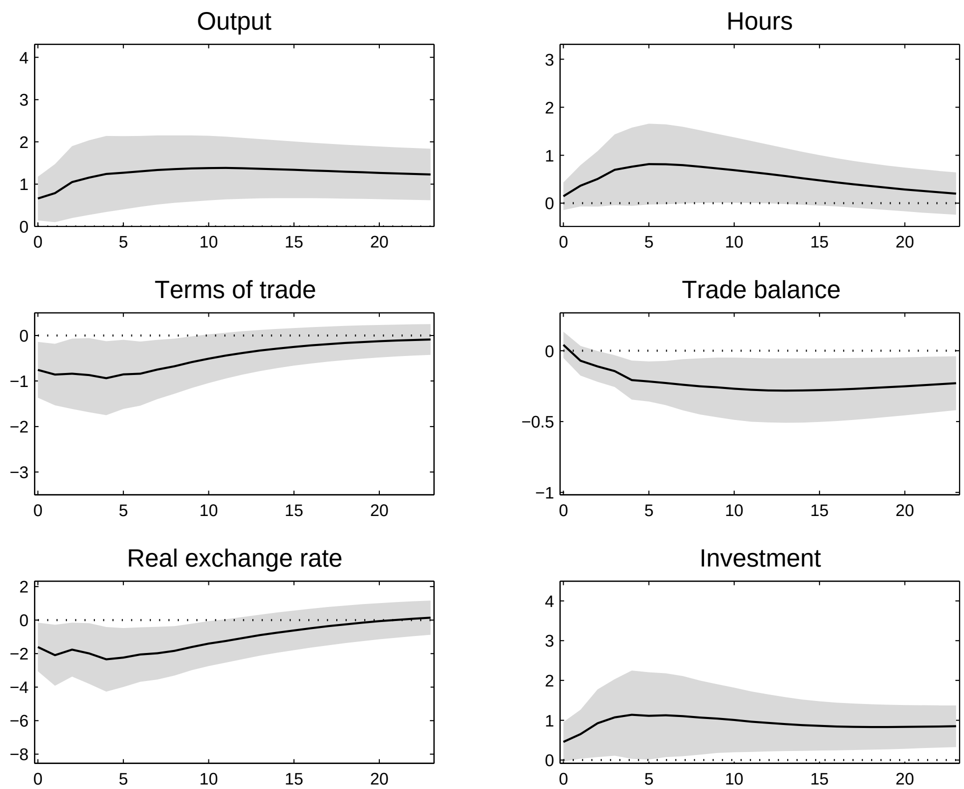

Figure 2: TRANSMISSION OF A ONE PERCENT INCREASE IN TECHNOLOGY; SAMPLE: U.S. DATA 1980:1-2005:4; SHADED AREAS INDICATE BOOTSTRAPPED 90 PERCENT CONFIDENCE INTERVALS; HORIZONTAL AXES: QUARTERS; VERTICAL AXES: PERCENT, EXCEPT FOR TRADE BALANCE (PERCENTAGE POINTS OF OUTPUT)

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 bootstrap 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.[9] The second row gives the responses for the terms of trade and the trade

terms of trade.

[9] The response of hours to technology shocks has been the topic of a considerable debate. Some authors, notably Galí (1999), have argued that hours are difference stationary only. If first differences of hours instead of levels are used in the VAR model, hours tend fall in response to a technology shock. In appendix B.2 we consider this specification, finding a

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 and significant decline. 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 different 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, 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 turning to the international 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.[10] These shocks are likely to consist of both a country-specific (idiosyncratic) and a global (common) component. However, to the extent that the 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 affect all countries similarly and is therefore unlikely to have a substantial effect on the terms of trade and the trade balance.[11] 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.

A more formal assessment of our VAR model is provided in appendix B.3, where we use the calibrated business cycle model outlined below to carry out a Monte Carlo experiment. Overall, we find that the VAR performs quite well. In particular, the S-curve obtained from the VAR is almost identical to the true cross-correlation function and the impulse responses have the correct sign.

---

similar result. However, the responses of trade variables are strikingly robust with respect to this modification.

[10] 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 across countries. Interestingly, their results are broadly in line with ours, notably regarding the behavior of international relative prices.

[11] Glick and Rogoff (1995) test a small open economy version of the international business cycle model by comparing the effect of country-specific and global technology shocks on the current account. They find no effect of the global component. 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 variations 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.

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) and then discuss our strategy to solve the model numerically around a deterministic steady state. 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 representative household. Regarding internationally traded assets, we consider the possibility of complete and incomplete financial markets, where only non-contingent bonds are traded across countries.[12] 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 $\pi(s^t)$.

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 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

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

[12] 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, which is 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 non-stationary and labor augmenting.

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. 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 while 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

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

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

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

where q_i^a and q_i^b denote the prices of intermediate goods a and b in terms of the final good F_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. Therefore 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

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

with $\psi>0$ set to determine the discount factor in steady state.[13]

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 of the household 1 reads as

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

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. $\beta(\{c_i(s^\tau)\}_{\tau=0}^{\tau=t-1},\{n_i(s^\tau)\}_{\tau=0}^{\tau=t-1})=\beta^t$.

[13]As discussed in Bodenstein (2006) the assumption of an endogenous discount factor also ensures the uniqueness of the steady state - in contrast to other assumptions which induce stationarity of bond holdings. While Bodenstein warns against excluding a priori the multiplicity of steady states, note that an endogenous discount factor will generally pick the symmetric steady state. Regarding impulse responses functions to technology shocks, Bodenstein also points out the possibility of multiplicities, which are ignored if a linearized version of the model is used. We will rely on such a version of the model in our simulations below. This seems sensible, because we thereby ignore time paths, which induce implausibly large jumps in consumption and output in response to technology shocks.

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 budget 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

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

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

for final goods

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

holds, and - under incomplete financial markets - we have

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

or - under complete financial markets

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

Additional variables of interest are the terms of trade, $p(s^t)$, the trade balance, $nx(s^t)$, and the real exchange rate, $rx(s^t)$. For the terms of trade and the real exchange rate in country 1, we have

$$p(s^t) = q_1^b(s^t)/q_1^a(s^t) \quad \text{and} \quad rx(s^t) = q_1^a(s^t)/q_2^a(s^t),$$

respectively. 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 logs using 'hats', follow the joint process

$$\begin{bmatrix} \hat{z}_1(s^t) \\ \hat{z}_2(s^t) \end{bmatrix} = \begin{bmatrix} \rho_1 & \rho_2 \\ \rho_2 & \rho_1 \end{bmatrix} \begin{bmatrix} \hat{z}_1(s^{t-1}) \\ \hat{z}_2(s^{t-1}) \end{bmatrix} + \begin{bmatrix} \varepsilon_1(s^t) \\ \varepsilon_2(s^t) \end{bmatrix}, \tag{14}$$

$$\text{with} \qquad \begin{bmatrix} \varepsilon_1(s^t) \\ \varepsilon_2(s^t) \end{bmatrix} \sim N\left(\begin{bmatrix} 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \sigma_{\varepsilon_1}^2 & \sigma_{\varepsilon_1\varepsilon_2} \\ \sigma_{\varepsilon_1\varepsilon_2} & \sigma_{\varepsilon_2}^2 \end{bmatrix} \right).$$

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 the 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 the 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.

3.3 Calibration

The model outlined in the previous subsections 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, given that its unconditional counterpart is one of the dimensions where the prediction of the model has been shown to square well with the evidence. 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 mostly 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 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.[14] 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

[14] This is particularly true for σ, see CDL. 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.

containing the empirical cross-correlation function for 8 lags and leads and let $m(\lambda)$ denote the corresponding cross-correlation function obtained from a simulation of the model (averages over 20 simulations of 104 observations, corresponding to the number of observations used in the VAR). 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. In a recent contribution Canova and Sala (2005) stress identification issues that may arise in the calibration and estimation of richly specified DSGE models. While the present model is relatively parsimonious, we nevertheless assess whether the structural parameters σ, ρ and χ are jointly identified by our criterion function (16). Figure A 7 in appendix C.1 shows that our criterion function is well suited to pin down the parameters of interest.

Table 2: PARAMETER VALUES OF 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)	$1 - \omega = 0.12$	
	Financial markets	
	Complete	Incomplete
Matching the S-curve:	(Economy A)	(Economy B)
Elasticity of substitution between intermediate goods	$\sigma = 2.182$	0.250
Investment adjustment costs	$\chi = 0.000$	0.025
Autoregressive coefficient of technology	$\rho = 0.871$	0.987
Loss function:	8.911	6.116

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 value in the optimum.

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 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 about 2.2. This is relatively close to 1.5, the value used in the benchmark economy of BKK. Investment adjustment costs are also absent from economy A and the value for the persistence of technology differentials is $\rho = 0.87$.

The set of parameter values obtained by solving (16) under the assumption that financial markets are incomplete defines economy B (right column). In this case, the elasticity of substitution between

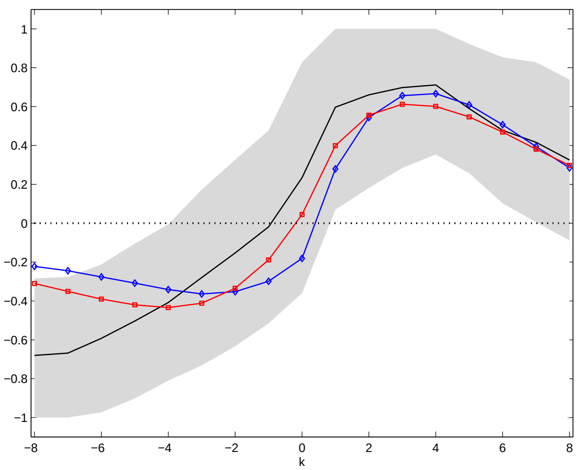

Figure 3: CONDITIONAL CROSS-CORRELATION FUNCTION FOR THE TRADE BALANCE AND THE TERMS OF TRADE; SOLID LINE: COMPUTED AFTER APPLYING HP-FILTER TO COUNTERFACTUAL TIME SERIES OBTAINED FROM THE VAR MODEL; SHADED AREA: BOOTSTRAPPED 90 PERCENT CONFIDENCE INTERVALS; MODEL SIMULATIONS: ◇ ECONOMY A, □ ECONOMY B

intermediate goods, σ, takes a value of 0.25.[15] Economy B is also characterized by very mild investment adjustment costs as $\chi = 0.025$. Christiano et al. (2005), using the same specification in a different context, report an estimate of approximately 2.5. Finally, note that economy B is also characterized by very persistent technology differentials.[16] Regarding the calibration of the model under incomplete financial markets, it is interesting to observe that there is also a local minimum which is characterized by parameter values close to those defining economy A.[17]

[15]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). Other recent papers which suggest a relatively low elasticity of substitution between intermediate goods include Kollmann (2006) and de Walque, Smets and Wouters (2005). 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 CDL.

[16]It is interesting to observe that Kollmann (1998) cannot reject the null hypothesis of no cointegration for the process of U.S. total factor productivity and total factor productivity in the G6 countries estimated on the basis of Solow residuals.

[17]More generally, the economy defined by this local minimum has properties similar to economy A - in line with earlier results reported in the literature, e.g. Baxter and Crucini (1995). However, the global optimum defines an economy

In figure 3 we plot the cross-correlation function for the trade balance and the terms of trade. Both economies deliver a cross-correlation function quite close to the conditional S-curve obtained from the VAR. Moreover, the theoretical S-curves are generally well within the 90 percent confidence interval. This is noteworthy, given that we match 8 leads and lags as well as the contemporaneous moment of the cross-correlation function when pinning down 3 structural parameters. In other words, we impose 14 overidentifying restrictions. On the other hand it is also interesting to note that the contemporaneous correlation is positive only in economy B.[18]

4 The international transmission of technology shocks

Given the calibrated model, we now turn to the transmission of a technology shock in order to assess the ability of economies A and B to account for the time series evidence as represented by the impulse response functions displayed in figure 2. Given the joint process for domestic and foreign technologies (14), we consider a one percent, permanent increase in the level of domestic technology.[19] To compare the transmission process of the theoretical economy to the data, we focus on the responses of those variables included in the VAR.

Figure 4 displays the results. The upper left panel shows the response of domestic output, which increases by about 0.8 percent on impact in both economies. Hours also increase 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 B, as a result of mild investment adjustment costs, also predicts small 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. In economy A the terms of trade depreciate, i.e. the price of imports increases relative to the price of exports. In economy B, in contrast, 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 both economies. It displays a hump-shaped decline in economy B - a pattern much in line with the response obtained from the VAR model. In contrast, in economy A the trade balance falls sharply on impact and moves into surplus after about four quarters. Similarly, only economy B delivers the

---

(economy B) which is characterized by a particularly low elasticity of substitution and this - as we show below - will fundamentally alter the international transmission mechanism of technology shocks.

[18]Relative to the cross-correlation function reported by BKK, the S-curve which characterizes economy A is shifted to the left. The analysis in BKK shows that such a shift is likely to result from an increase in the elasticity of substitution between intermediate goods. BKK's benchmark case is defined by a value of 1.5.

[19]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 $\rho_2 = 1 - \rho_1$.

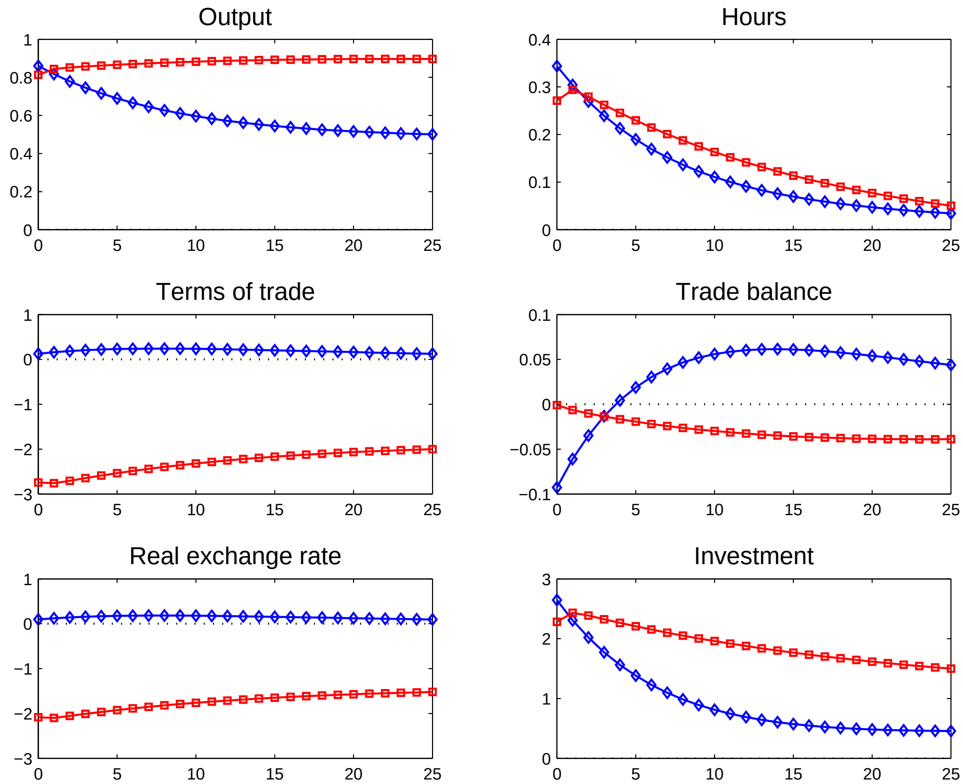

Figure 4: TRANSMISSION OF A ONE PERCENT INCREASE IN TECHNOLOGY; HORIZONTAL AXES: QUARTERS; VERTICAL AXES: PERCENT, EXCEPT FOR TRADE BALANCE (PERCENTAGE POINTS OF OUTPUT); ◇ ECONOMY A, □ ECONOMY B

correct prediction for the sign of the response of the real exchange rate and predicts a (mildly) hump-shaped response for investment.

A key result of our analysis is thus that while both 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 B turns the transmission process of economy A upside down.

This is not the result of different asset market structures *per se*. Earlier literature, e.g. Baxter and Crucini (1995), has established that - all else equal - moving from complete to incomplete financial markets does hardly affect the equilibrium allocation. The reason for this result is that terms of trade movements can provide implicit risk sharing under incomplete markets and thus support an equilibrium allocation close to the complete markets allocation. To see how this works, consider the standard transmission mechanism in an economy with incomplete financial markets, where the home country faces a favorable technology shock. As a result, 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 counteracting the wealth effect of the technology shock. Under incomplete markets, this transmission mechanism, however, depends on the elasticity of substitution between intermediate goods.[20]

In fact, in the low elasticity/incomplete markets economy B, the transmission of technology shocks is quite distinct from what the standard transmission mechanism suggests. Notably, the terms of trade appreciate and thus *amplify* the relative wealth effect induced by the technology shock. CDL analyze the possibility of such a 'negative' international transmission of technology shocks.[21] They find that the domestic 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 leads the price of domestically produced goods to rise relative to the price of foreign goods. The rise in the price of domestic goods, in turn, supports the initial rise in domestic absorption as it transfers wealth from foreign to domestic residents. Apparently, economy B is characterized by the transmission mechanism suggested by CDL.

To sum up, in assessing the performance of economies A and B, we find that only economy B 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 B 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.[22]

[20]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.

[21]The transmission is 'negative', because the foreign country loses in terms of purchasing power if the domestic economy is experiencing an increase in technology.

[22]To see this more formally, we computed the standard deviations of the variables included in the VAR relative to output: for the U.S. time series, for the counterfactual time series conditional on technology shocks, and for economies A and B. Table A 1 in appendix C.2 shows the results. It illustrates that economy A clearly fails in delivering the volatility of relative prices which characterizes the data, while economy B fails to deliver the volatility of the trade balance. This trade-off is related to the elasticity of substitution between intermediate goods, as noted by Backus et al. (1994, 1995).

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 under complete and incomplete financial markets with evidence from U.S. time series for 1980-2005.

We have estimated a VAR model and identified technology shocks assuming that these are the only shocks affecting labor productivity in the long run. In a next step, we have computed counterfactual time series assuming that technology shocks had been the sole source of business cycle fluctuations. We calculated the cross-correlation function for the trade balance and the terms of trade on the basis of these counterfactual time series (conditional S-curve). Relative to its unconditional counterpart, the conditional S-curve shifts to the left, i.e. while the unconditional contemporaneous correlation is negative, the conditional contemporaneous correlation is positive. A second result from our VAR analysis is given by the responses to a positive technology shock: it appreciates the terms of trade and induces a hump-shaped decline in the trade balance.

We have then calibrated a prototypical international business cycle model to match the S-curve conditional on technology shocks, both under complete and incomplete financial markets. The complete markets economy A matches the S-curve for parameter values close to those used in the baseline calibration of BKK. The elasticity of substitution between domestic and foreign goods is about 2.2 and investment adjustment costs are absent. Under incomplete financial markets (economy B) the elasticity of substitution is substantially lower and there is evidence for mild investment adjustment costs. Technology differentials appear to be much more persistent in economy B.

To assess the ability of both theoretical economies to account for the transmission of technology shocks apparent from the data, we have computed the impulse responses functions to a one percent increase in technology. It turns out that the transmission process is quite distinct. Economy A predicts a depreciation of the terms of trade and a sharp decline the trade balance (standard transmission mechanism). Economy B, in contrast, predicts the terms of trade to appreciate and a hump-shaped decline in the trade balance. Clearly, from a qualitative point of view, only economy B can account for the time series evidence.

In our view, the main result of our analysis may be summarized as follows: while both theoretical economies deliver the S-curve conditional on technology shocks, the underlying transmission process is fundamentally different. In fact, as far as the terms of trade and the trade balance are concerned, the transmission mechanism in economy B turns the transmission process of economy A upside down. Its predictions are qualitatively in line with time series evidence for the U.S.

We have also stressed that this result is not evidence against the assumption of complete markets *alone*. More generally, it is evidence against the standard transmission mechanism of technology shocks. The standard transmission mechanism, in turn, may be obtained under complete and incomplete financial markets. In fact, the transmission mechanism of technology shocks implied by the prototypical business cycle model is the result of assumptions on the asset market structure *and* parameter values.

We conclude by noting that much is at stake regarding the international transmission mechanism of technology shocks. As stressed by CDL, if the terms of trade appreciate in response to a positive technology shock, terms of trade movements fail to provide implicit insurance against country-specific risks. Instead, they amplify the relative wealth effect of technology shocks.

Against this background, further research into the international transmission of technology shocks is required. 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 by, for instance, considering a non-tradable sector or consumer durables, as in earlier work by Stockman and Tesar (1995) and Burda and Gerlach (1992).

Appendix

A Data

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. Specifically, we compute six time series, displayed in figure A:

- 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 price index of non-commodity imports of goods and services (OECD, Economic Outlook: USAP-MGSX) and exports of non-commodity goods and services (OECD, Economic Outlook: US-APXGSX)
- 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 (Main Economic Indicators)

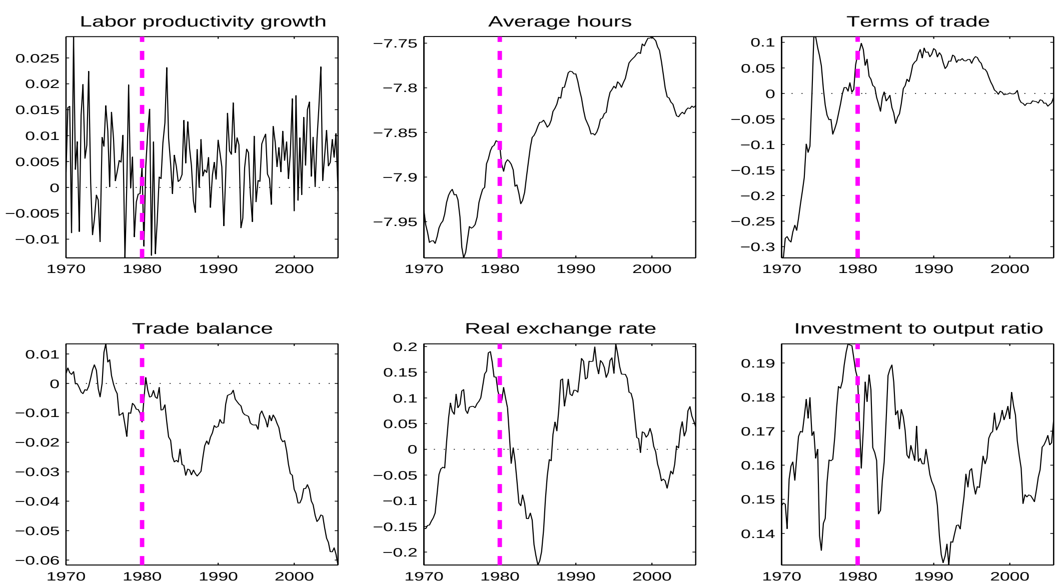

Figure A 1: U.S. TIME SERIES 1970-2005, VERTICAL DASHED LINES INDICATE START OF SAMPLE (DEPENDENT VARIABLE)

B The VAR model

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

$$Y_t = \begin{pmatrix} \Delta \ln \left(\text{GDP}_t/\text{Hours}_t\right) \\ \ln \text{Hours}_t \\ \ln \left(\text{Terms of Trade}_t\right) \\ \text{Net Exports}_t/\text{GDP}_t \end{pmatrix} = \begin{bmatrix} \Delta a_t \\ h_t \\ p_t \\ nx_t \end{bmatrix}. \tag{A 1}$$

The structural VAR model of the economy is given by

$$A(L)Y_t = \varepsilon_t, \tag{A 2}$$

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.

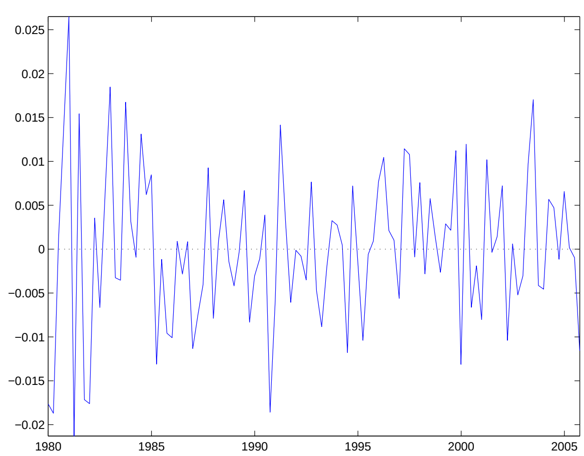

Figure A 2: TECHNOLOGY SHOCKS IDENTIFIED IN U.S. DATA USING BASELINE VAR MODEL

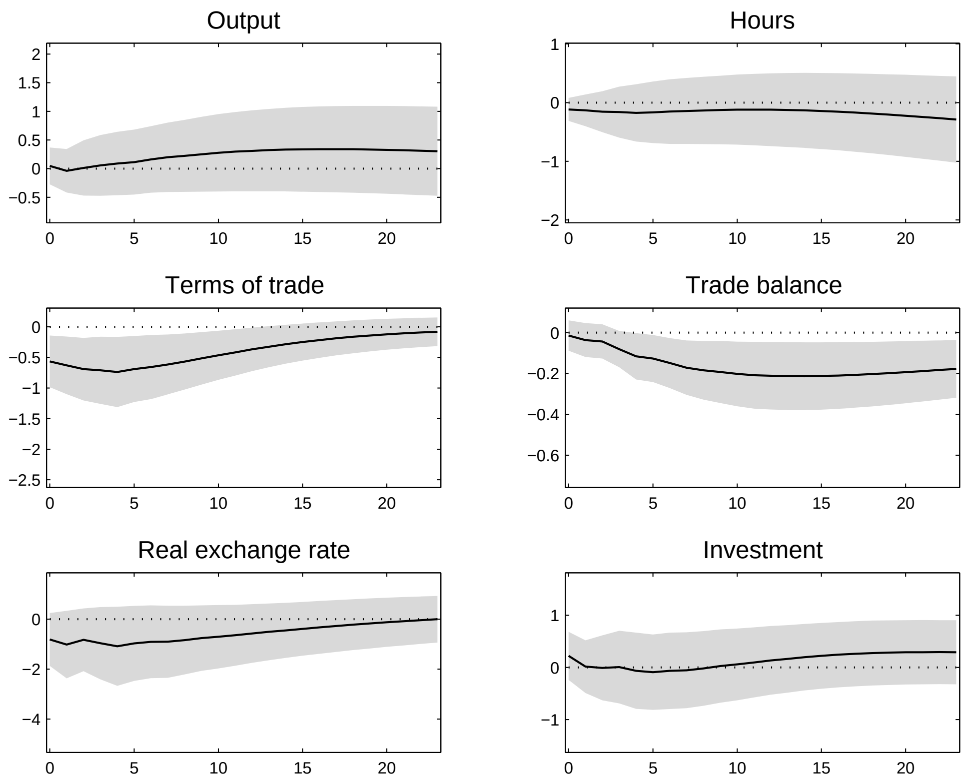

Figure A 3: TRANSMISSION OF ONE PERCENT INCREASE IN TECHNOLOGY, SEE FIGURE 2; HERE: VAR ESTIMATED WITH HOURS IN DIFFERENCES INSTEAD OF LEVELS

We want to estimate the coefficients of the structural VAR model (A 2). To ensure identification further assumptions have to be made. To simplify the discussion define $Z_t' = \begin{bmatrix} h_t & p_t & nx_t \end{bmatrix}$. 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 (A 2) in the long-run with $p = 4$ gives

$$\underbrace{\begin{pmatrix} \underset{1\times 1}{\sum_{i=0}^4 \alpha_{i,11}} & \underset{1\times 3}{\sum_{i=0}^4 \alpha_{i,12}} \\ \underset{3\times 1}{\sum_{i=0}^4 \alpha_{i,21}} & \underset{3\times 3}{\sum_{i=0}^4 \alpha_{i,22}} \end{pmatrix}}_{\equiv A(1)} \begin{bmatrix} \underset{1\times 1}{\Delta a_t} \\ \underset{3\times 1}{Z_t} \end{bmatrix} = \begin{bmatrix} \underset{1\times 1}{\varepsilon_t^a} \\ \underset{3\times 1}{\varepsilon_t^Z} \end{bmatrix}.$$

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 $A(1)$:

$$\sum_{i=0}^{4} \alpha_{i,12} = 0. \tag{A 3}$$

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

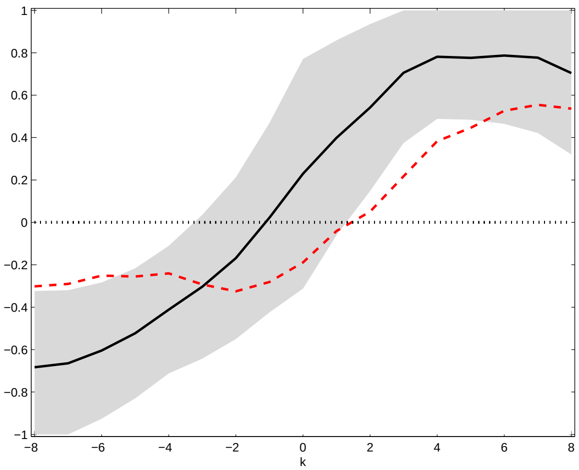

Figure A 4: CROSS-CORRELATION FUNCTION FOR THE TRADE BALANCE (T+K) AND THE TERMS OF TRADE (T), SEE FIGURE 1; HERE: VAR ESTIMATED WITH HOURS IN DIFFERENCES INSTEAD OF LEVELS

in the long run, which is ruled out by assumption. Christiano et al. (2003) provide a more detailed discussion. In practice we impose this restriction on the first equation of (A 2), given by

$$\Delta a_t = -\sum_{i=1}^{4} \alpha_{i,11} L^i \Delta a_t - \sum_{i=0}^{4} \alpha_{i,12} L^i Z_t + \varepsilon_t^a, \qquad \text{(A 4)}$$

which, after imposing (A 3), reads as[23]

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

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-stage 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 these 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 (A 2) and identify technology shocks. Figure A 2 displays the identified technology shocks. In the main text we report several statistics computed on the basis of the estimated VAR model and these shocks.

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

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

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 A 3 displays the impulse response functions, which are different for output, investment and, in particular, for hours relative to the baseline specification. 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 trade balance, the terms of trade, and the real exchange rate are robust with respect to the trend specification of hours in the VAR model. This is also reflected in the counterfactual S-curve displayed in figure A 4.

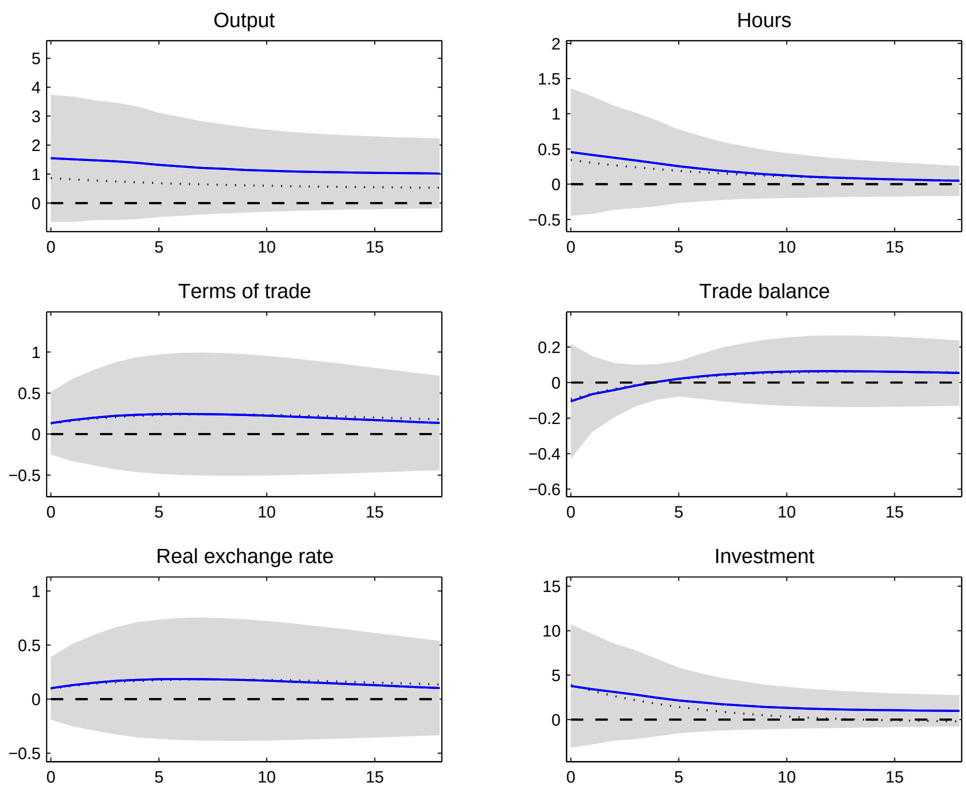

Figure A 5: TRUE (DOTTED LINE) VS. ESTIMATED (STRAIGHT LINE) RESPONSES TO ONE PERCENT INCREASE IN TECHNOLOGY WITH BOOTSTRAPPED 90 PERCENT CONFIDENCE INTERVALS (SHADED AREA)

B.3 VAR Assessment

The use of VAR models to identify technology shocks on the basis of long-run restrictions has been criticized by, among others, Cooley and Dwyer (1998) and Chari et al. (2005). We therefore perform a Monte Carlo experiment similar to Christiano, Eichenbaum and Vigfusson (2006). Note, however, that the scope of our analysis is limited to a specific case: we assess whether the VAR model used in section 2 is able to uncover the true impulse responses and the true cross-correlation function for the trade balance and the terms of trade - using our calibrated business cycle model as the data generating process. Since we estimate the VAR on four time series, while there are only two fundamental shocks in the model, we add measurement error to labor productivity growth and the trade balance to avoid stochastic singularity, as, for instance, in Ireland (2004). We set the standard deviation of the measurement errors to 3%. The standard deviations of the innovations to technology are assumed to be uncorrelated and are taken from the estimates reported in Heathcote and Perri (2002).

Another issue is related to the existence of a VAR representation of the DSGE model.

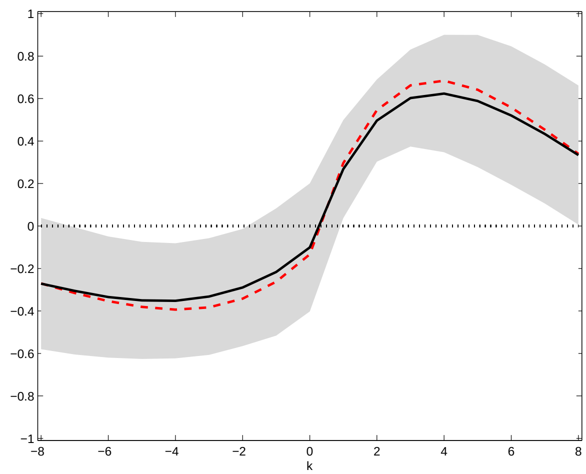

Figure A 6: TRUE (DASHED LINE) VS. ESTIMATED (SOLID LINE) CROSS-CORRELATION FUNCTION WITH BOOTSTRAPPED 90 PERCENT CONFIDENCE INTERVALS (SHADED AREA)

Fernández-Villaverde, Rubio-Ramírez, Sargent and Watson (2006) show that DSGE models only have (infinite-order) VAR representations if certain conditions are satisfied. We find that these conditions hold for our calibration and the VAR model.[24]

We then generate data using the calibrated DSGE model (economy A). Specifically, we simulate the model for 104 periods (corresponding to the number of observations used to estimate the VAR model), estimate the VAR model, and repeat this exercise a 1000 times.

Figure A 5 displays the results. The dotted lines display the true impulse response functions of the model, the solid lines display the mean of the estimated response functions and the shaded areas indicate 90 percent confidence intervals. In our view, the VAR performs quite well. Except for output it is difficult to detect any bias.

[24]The theoretical model can be written using the following representation

$$\begin{aligned} x_{t+1} &= Ax_t + Bw_{t+1} \\ y_{t+1} &= Cx_t + Dw_{t+1}, \end{aligned}$$

where x_t is a $n \times 1$ vector of state variables, y_t is a $k \times 1$ vector of the variables which are observed in the empirical VAR model, and w_t is a $m \times 1$ vector of shocks to the states and the observables. The condition for invertibility then reads as follows: The eigenvalues of $A - BD^{-1}C$ have to be strictly less than one in modulus. We find that the highest eigenvalue for economies A and B is 0.95 and 0.978, respectively, such that both economies have a (infinite-order) VAR representation.

Figure A 6 displays the cross-correlation function for the trade balance and the terms of trade calculated on the basis of the simulated data using the same procedure as in section 2. The shaded areas indicate 90 percent confidence intervals. The dashed line is the S-curve stemming from the simulation of the model with technology shocks only. Again, the VAR performs quite well in detecting the true S-curve.[25]

C Empirical and theoretical moments

C.1 Identification of DSGE model parameters

In a recent contribution, Canova and Sala (2005) take up identification issues that typically arise in the estimation and calibration of richly specified DSGE models. In principle, different combinations of values for the structural model parameters may induce identical values for the criterion function. To assess whether our approach to calibration is prone to identification problems, we compute the value for our criterion function (16) for the relevant range of parameter values. Figure A 7 displays the results for each combination of χ, ρ and σ keeping, in turn, the third parameter constant at the value obtained in the global minimum and for both asset market structures. We find that the objective function is well behaved and reasonably curved in the relevant range of parameter values. In our view, this experiment lends support to our calibration strategy.

C.2 Unconditional and conditional volatilities

In the main text we focus on the cross-correlation function for the trade balance and the terms of trade: in the raw time series, for the counterfactual time series and the theoretical economies. For completeness, we also compute the relative volatilities of the variables included in our VAR model across those dimensions. Table A 1 shows the results.

Table A 1: STANDARD DEVIATIONS RELATIVE TO GDP

	U.S. Data		Theoretical	
Statistics	Unconditional	Conditional	Economy A	Economy B
Investment	4.72	2.38	3.15	3.01
Trade balance	0.29	0.20	0.15	0.02
Terms of Trade	1.16	1.03	0.27	3.91
Real Exchange Rate	2.83	2.81	0.21	2.97
Hours	1.20	0.33	0.42	0.38

Notes: HP-filtered series have been used to calculate the standard deviations; Conditional refers to calculations based on counterfactual time series obtained from the VAR model assuming that only technology shocks had occurred.

[25] The VAR performs similarly if economy B is used as data generating process. In particular, the shape of the cross-correlation function and the signs of the impulse responses are correctly estimated. However, due to highly persistent technology differentials, the VAR estimates for the impulse responses indicate some bias.

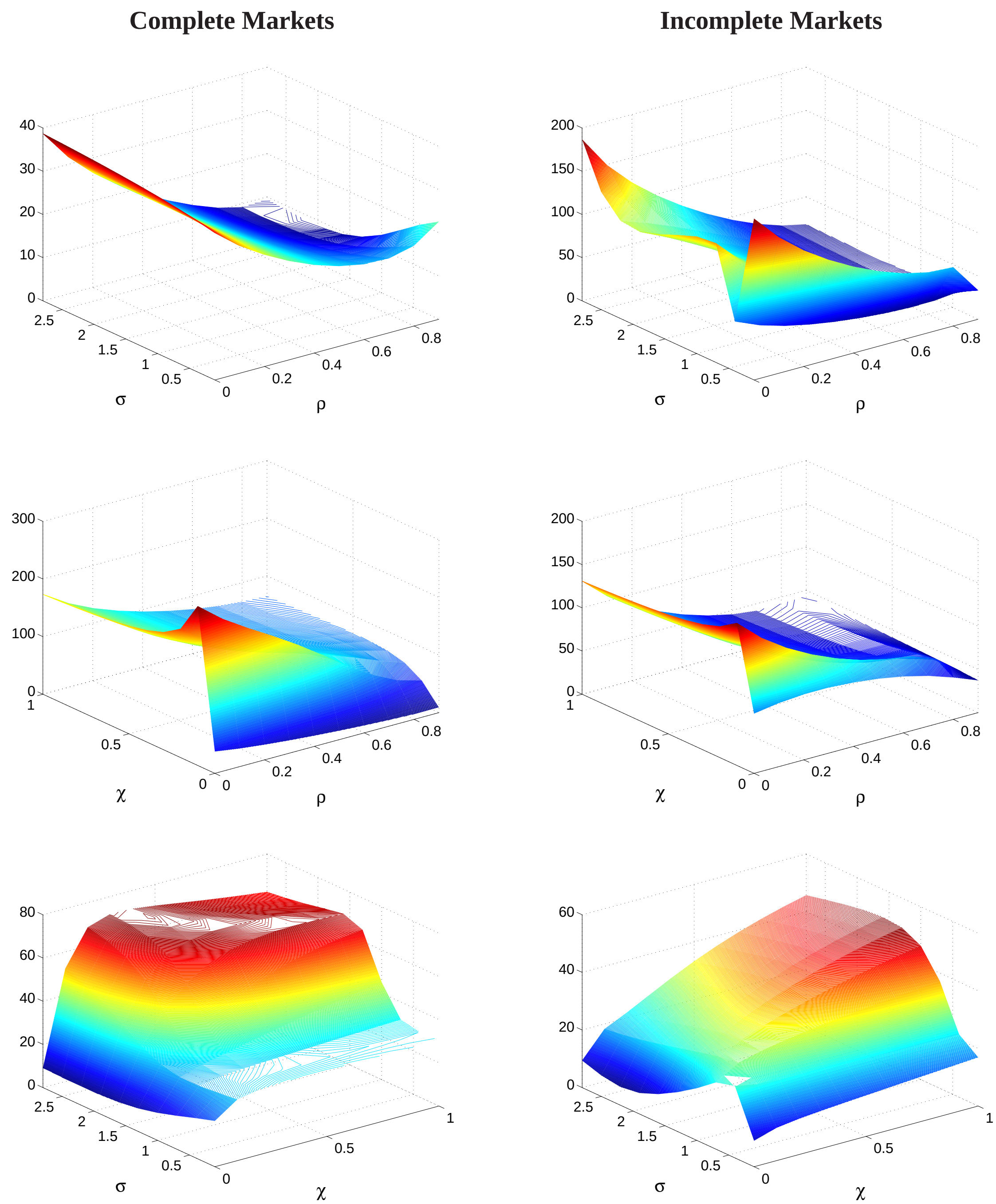

Figure A 7: CRITERION FUNCTION (VERTICAL AXIS) EVALUATED FOR DIFFERENT VALUES OF STRUCTURAL MODEL PARAMETERS (HORIZONTAL AXES)

References

Altig, D., Christiano, L. J., Eichenbaum, M. and Lindé, J.: 2005, Firm specific capital, nominal rigidities and the business cycle, *NBER Working Paper 11034*.

Ambler, S., Cardia, E. and Zimmermann, C.: 2004, International business cycles: What are the facts?, *Journal of Monetary Economics* **51**, 257–276.

Backus, D., Kehoe, P. and Kydland, F.: 1994, Dynamics of the trade balance and the terms of trade: the J-curve?, *American Economic Review* **84**(1), 84–103.

Backus, D., Kehoe, P. and Kydland, F.: 1995, International business cycles: Theory and evidence, *in* T. F. Cooley (ed.), *Frontiers of Business Cycle Research*, Princeton University Press, Princeton, pp. 331–356.

Backus, D. and Smith, G. W.: 1993, Consumption and real exchange rates in dynamic economies with non-traded goods, *Journal of International Economics* **35**, 297–316.

Baxter, M.: 1995, International trade and business cycles, *in* G. M. Grossmann and K. Rogoff (eds), *Handbook of International Ecnomics*, North Holland, Amsterdam, pp. 1801–1864.

Baxter, M. and Crucini, M. J.: 1995, Business cycles and the asset structure of foreign trade, *International Economic Review* **36**(4), 821–854.

Bodenstein, M.: 2006, Closing open economy models. Mimeo.

Burda, M. C. and Gerlach, S.: 1992, Intertemporal prices and the U.S. trade balance, *American Economic Review* **82**(5), 1234–1253.

Canova, F. and Sala, L.: 2005, Back to square one: identification issues in DSGE models, *ECB Working Paper 383*.

Chari, V. V., Kehoe, P. J. and McGrattan, E. R.: 2002, Can sticky price models generate volatile and persistent real exchange rates?, *Review of Economics Studies* **69**, 533–563.

Chari, V. V., Kehoe, P. J. and McGrattan, E. R.: 2005, A critique of structural VARs using business cycle theory, *Federal Reserve Bank of Minneapolis, Staff Report 364*.

Christiano, L. J., Eichenbaum, M. and Evans, C.: 2005, Nominal rigidities and the dynamic effects of a shock to monetary policy, *Journal of Political Economy* **113**(1), 1–45.

Christiano, L. J., Eichenbaum, M. and Vigfusson, R.: 2003, What happens after a technology shock?, *NBER Working Paper 9819*.

Christiano, L. J., Eichenbaum, M. and Vigfusson, R.: 2006, Assessing structural VARs, *in* D. Acemoglu, K. Rogoff and M. Woodford (eds), forthcoming in NBER Macroeconomics Annual 2006, Volume 21, MIT Press, Cambridge MA.

Cole, H. and Obstfeld, M.: 1991, Commodity trade and international risk sharing: How much do financial markets matter, *Journal of Monetary Economics* **28**, 3–24.

Cooley, Thomas, F. and Dwyer, M.: 1998, Business cycle analysis without much theory - a look at structural VARs, *Journal of Econometrics* **83**, 57–88.

Corsetti, G., Dedola, L. and Leduc, S.: 2004, International risk-sharing the transmission of productivity shocks, *ECB Working Paper 308*.

Corsetti, G., Dedola, L. and Leduc, S.: 2006a, DSGE models of high exchange-rate volatility and low pass-through. mimeo.

Corsetti, G., Dedola, L. and Leduc, S.: 2006b, Productivity, external balance and exchange rates: Evidence on the transmission mechanism among G7 countries, *NBER Working Paper 12483*.

de Walque, G., Smets, F. and Wouters, R.: 2005, An estimated two-country DSGE model for the Euro area and the US economy, *mimeo*.

Fernández-Villaverde, J., Rubio-Ramírez, J., Sargent, T. J. and Watson, M. W.: 2006, A, B, C's (and D's) for understanding VARs. mimeo.

Galí, J.: 1999, Technology, employment, and the business cycle: Do technology shocks explain aggregate fluctuations?, *American Economic Review* **89**, 249–271.

Glick, R. and Rogoff, K.: 1995, Global versus country-specific productivity shocks and the current account, *Journal of Monetary Economics* **35**, 159–192.

Gregory, A. W. and Head, A. C.: 1999, Common and country-specific fluctuations in productivity, investment and the current account, *Journal of Monetary Economics* **44**, 423–451.

Heathcote, J. and Perri, F.: 2002, Financial autarky and international business cycles, *Journal of Monetary Economics* **49**, 601–627.

Ireland, P. N.: 2004, A method for taking models to the data, *Journal of Economic Dynamics and Control* **28**, 1205–1226.

Kehoe, P. J. and Perri, F.: 2002, International business cylces with endogenous incomplete markets, *Econometrica* **70**, 709–729.

Kollmann, R.: 1998, US trade balance dynamics: the role of fiscal policy and productiviy shocks and of financial market linkages, *Journal of International Money and Finance* **17**, 637–669.

Kollmann, R.: 2006, International portfolio equilibrium and the current account,. mimeo.

Kydland, F. E. and Prescott, E. C.: 1991, Hours and employment variation in business cycle theory, *Economic Theory* **1**, 63–81.

Lubik, T. and Schorfheide, F.: 2006, A bayesian look at new open economy macroeconomics, *in* M. Gertler and K. Rogoff (eds), *NBER Macroeconomics Annual 2005, Volume 20*, MIT Press, Cambridge MA, pp. 313–366.

Mendoza, E. G.: 1991, Real business cycles in a small open economy, *American Economic Review* **81**, 797–818.

Normandin, M. and Fosso, B. P.: 2006, Global versus country-specific shocks and international business cycles, *Cahiers de recherche 0601*, CIRPEE.

Obstfeld, M. and Rogoff, K.: 2000, New directions for stochastic open economy models, *Journal of International Economics* **20**, 117–153.

Raffo, A.: 2006, Net exports, consumption volatility, and international real business cycle models, *Federal Reserve Bank of Kansas City RWP 06-01*.

Ravn, M. O.: 1997, International business cycles in theory and in practice, *Journal of International Money and Finance* **16**(2), 255–283.

Shapiro, M. and Watson, M.: 1988, Sources of business cycle fluctuations, *in* S. Fischer (ed.), *NBER Macroeconomics Annual*, MA: MIT Press.

Stockman, A. C. and Tesar, L. L.: 1995, Tastes and technology in a two-country model of the business cycle: Explaining international comovements, *American Economic Review* **85**(1), 168–185.