On the International Transmission of Technology Shocks

Zeno Enders[a,*] Gernot J. Müller[a]

[a] *University of Bonn, Adenauerallee 24-42, 53113 Bonn, Germany*

March 20, 2009

Abstract

Using vector autoregressions on U.S. time series and an aggregate of industrialized countries, we find that technology shocks appreciate the terms of trade and lower the trade balance; they induce an 'S'-shaped cross-correlation function for both variables (the S-curve). In calibrating a prototypical international business cycle model 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 the evidence.

Keywords: Technology shocks, Terms of trade, Trade balance, Financial markets

JEL-Codes: F41, E32

1 Introduction

Throughout the last 15 years international business cycle models have been used to analyze the international transmission of technology shocks. Irrespective 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. This *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. Under this transmission mechanism, foreign residents will generally reap some of the benefits of domestic technology shocks even in the absence of explicit risk-sharing, because the depreciation of the terms of trade increases the relative value of foreign output.

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

*Corresponding author. University of Bonn, Adenauerallee 24-42, 53113 Bonn, Germany. *Tel.:* +49-228-737976; *fax:* +49-228-736884. *E-mail address:* zeno.enders@uni-bonn.de

markets variant of the model fails to replicate several key properties of the data, notably 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. The S-curve is 'one of the striking features of the data' (BKK, p. 93), and turns out to be robust both across countries and sample periods. As a stylized fact characterizing international business cycles, it will also play a key role in the assessment of the international transmission mechanism provided by the present paper.

We estimate a VAR model on quarterly time series data covering the post-Bretton Woods period for the U.S. and an aggregate of industrialized countries. As in Galí (1999), we identify technology shocks by assuming that only these shocks affect U.S. labor productivity in the long-run. We generate counterfactual time series that would have been obtained, if technology shocks had been the sole source of fluctuations. On the basis of these time series we compute several statistics, notably the cross-correlation function for the trade balance and the terms of trade. We find it to be S-shaped as well, but more pronounced relative to its unconditional counterpart. Regarding impulse response functions, we find that a positive technology shock induces a hump-shaped increase in output, investment and consumption in the U.S. relative to the other countries and a lasting, hump-shaped decline of the U.S. trade balance. In decomposing the consumption response, we find a strong and significant increase in U.S. consumption and a persistent, albeit insignificant, decline in foreign consumption. 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 U.S. terms of trade and its real effective exchange rate.

We confront a prototypical business cycle model, i.e. a variant of the model originally proposed by BKK, with the evidence. In addition to complete financial markets, we also consider the possibility that only non-contingent bonds are traded across countries (incomplete financial markets), and allow for investment adjustment costs. While we maintain the assumption that prices are flexible in order to focus on the role of *relative* prices in the baseline case, we also perform sensitivity analysis suggesting that the quantitative importance of price rigidities is limited for the phenomena under study. We calibrate the model targeting conditional rather than unconditional moments, because according to an emerging consensus technology shocks are unlikely to be the only source of business cycle fluctuations.[2] Specifically, we use conditional volatilities of key variables as well as the conditional S-curve

[1] Subsequent research has documented this failure as well as other 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 (2008).

[2] See Galí (1999), Altig, Christiano, Eichenbaum and Lindé (2005), henceforth ACEL, 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). Moreover, results from a business cycle variance decomposition discussed below suggest that while technology shocks are an important source of business cycle fluctuations, other shocks are likely to play a significant role as well.

to pin down parameter values for the elasticity of substitution between domestic and foreign goods, investment adjustment costs and the persistence of technology differentials. We consider both asset market structures. If financial markets are complete, we find a fairly high elasticity of substitution, while technology differentials are moderately persistent and investment costs are absent. If financial markets are incomplete, we obtain a low elasticity of substitution and a very persistent process for technology. In this case we document evidence for investment adjustment costs.

Our assessment of the model starts with the observation that the S-curve is fairly well matched under both model specifications. We thus turn 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: under the complete markets calibration the model predicts a depreciation of the terms of trade and a sharp fall of the trade balance on impact—in line with the standard transmission mechanism. In contrast, under the incomplete markets calibration, the model 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. Similarly, we find that only under the incomplete markets calibration the model predicts a fall in foreign consumption as suggested by the VAR evidence.

Regarding the role of asset markets in shaping the transmission process, it is important to stress that the difference across calibrations 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 results are not to be taken as evidence in favor of incomplete markets as such, but as support for incomplete markets-*cum*-low-elasticity. Put differently, we provide evidence in favor of a particular transmission mechanism which is quite distinct from the standard transmission mechanism of technology shocks common to most international business cycle models.

Corsetti, Dedola and Leduc (2007), henceforth CDL, were the first to observe such a possible alternative to the standard transmission mechanism.[3] 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 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. To assess this more formally, we compute the dynamic wealth effect of a domestic technology shock, both at home and abroad. We find that under the complete markets calibration, both countries' residents experience a positive wealth effect. Under the incomplete markets calibration, in contrast, foreign residents' wealth is adversely affected by the shock.

[3]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 consumption-real exchange rate anomaly identified by Backus and Smith (1993).

The remainder of the paper is organized as follows. In the next section, we provide time series evidence on the international transmission mechanism of technology shocks. We outline and calibrate the business cycle model under both asset market structures in section 3 and analyze the implied transmission mechanism and its implications in section 4 together with results from sensitivity analysis. In section 5 we offer a brief conclusion. The appendix provides details on the VAR model and several robustness tests.

2 Time Series Evidence

In this section we use quarterly time series data for the U.S. and an aggregate of industrialized countries to establish evidence on the international transmission of technology shocks. Our sample covers the post-Bretton Woods period 1973–2006. Before turning to the estimation of a VAR model, we compute the unconditional cross-correlation function for the trade balance and the terms of trade—revisiting a key finding of BKK. The terms of trade p_t are defined as the import deflator divided by the export deflator of goods and services. The trade balance nx_t is measured as the ratio of nominal net exports to nominal GDP.[4] In order to separate short-run fluctuations from long-run movements in both time series, we employ the HP-filter with a smoothing parameter of 1600.

The dashed line in the left panel of Figure 1 displays the cross-correlation function for the terms of trade (in time t) and the trade balance (in time $t+k$) for k ranging from -8 to 8 quarters, i.e. for leads and lags up to two years. As described by BKK, the shape of the cross-correlation function resembles an horizontal 'S'. The correlation is about zero at $k = 0$ and becomes negative to the left of this point. The correlation between p_t and nx_{t+k} is 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 as the standard transmission mechanism.[5] After a one-time positive shock to technology, domestic output increases and its relative price falls (p_t increases). Investment increases strongly and induces a fall in net exports. After the surge in investment dissipates, the trade balance moves into a surplus. The contemporaneous correlation of both variables is therefore likely to be small or negative, while p_t and nx_{t+k} are positively correlated for $k > 1$.

Figure 1 about here

[4] We follow BKK and consider net exports in current prices thereby allowing 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 (2008). The appendix provides a detailed description of the data.

[5] 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) leads—through sluggish expenditure switching effects—to an increase in net exports only with a delay. This consideration provides the starting point for the analysis of BKK.

2.1 The VAR model

In the following we estimate a VAR model and identify technology shocks using long-run restrictions. The model includes the following variables: the growth rate of U.S. labor productivity (output/hour), the log of U.S. output relative to a measure of output in an aggregate of industrialized countries, which we refer to as the 'rest of the world' (or 'ROW'), the U.S. terms of trade, and the U.S. trade balance scaled by GDP. To economize on the degrees of freedom, we replace relative output, in turn, with relative investment and relative consumption and re-estimate the VAR model each time. Similarly, we replace the terms of trade with the real exchange rate to assess the effect of technology shocks on the latter. Finally, we also consider specifications of our VAR model where we substitute, in turn, U.S. consumption and ROW consumption for relative consumption. The responses of these variables will turn out to be important in order to assess different calibrations of our theoretical model below.

Our identification strategy hinges on the assumption that the endogenous variables are stationary. On the basis of the available data, however, it is not possible to reject stochastic trends in relative output, investment and consumption as well as in the trade balance; we therefore use first differences of these variables in our baseline specification.[6] In all specifications measures for oil price changes, relative inflation and the relative short-term nominal interest rate are included as well. We add these variables in order to control for a possible role of monetary policy and price rigidities in the transmission of technology shocks, suggested by several authors (see, e.g., Galí 1999 in a closed economy context).[7] We also include a constant and four lags of each of the seven variables.

In order to identify technology shocks we follow Galí (1999) and others by assuming that these are the only shocks which affect the level of U.S. labor productivity in the long run. Such technology shocks are likely to consist of a country-specific (idiosyncratic) and a global (common) component. However, to the extent that the other variables in the VAR, which are expressed in relative terms in our baseline specification, respond to the identified shock, we are likely to pick up the idiosyncratic component—a positive response of relative output serves as an ex-post criterion indicating that we are indeed identifying a positive innovation in relative technology. Common innovations to technology, instead, can be expected to affect all countries similarly and to have a negligible effect on relative variables. Such shocks may induce an adjustment of relative variables only, if there are substantial asymmetries across countries, notably in the net foreign asset position. We assess this possibility in our calibrated business cycle model, but do not find import quantitative effects.[8] Note that the

[6] Using the level rather than the difference specification, we obtain very similar results—notably for the terms of trade and net exports. Results are available upon request.

[7] Below we study a business cycle model with flexible prices (baseline case). Sensitivity analysis suggests that price rigidities do not alter the transmission mechanism in a quantitatively important way, see section 4.4.

[8] See section 4.4. Earlier work also provides evidence in support of this finding regarding the trade balance. 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.

business cycle model implies that relative labor productivity is stationary, which is why we focus on U.S. labor productivity rather than on relative labor productivity to achieve identification via long-run restrictions.[9]

In the baseline specification we only identify technology shocks. To assess their importance relative to monetary policy shocks, we consider an alternative specification in which we also identify (relative) monetary policy shocks, i.e. non-systematic innovations to the relative short-run interest rate. In this case we assume that all variables other than the terms of trade and the trade balance are predetermined relative to the interest rate. In the appendix we provide more details on the identification and estimation of the VAR model.

2.2 Results

The right panel of Figure 1 displays four quarter moving averages of the identified technology shocks (solid line) together with a conventional measure for the change in total factor productivity, the demeaned growth rate of the Solow residual (dashed line). We observe a strong co-movement of both time series with a correlation coefficient of about 0.7.

Table 1 about here

Given the estimated model and the identified technology shocks, we use the baseline VAR model to compute counterfactual time series that would have been observed, if technology shocks had 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. The left panel of 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 unconditional cross-correlation function (dashed line); it also resembles an horizontal 'S'. In fact, relative to its unconditional counterpart, the S-shape of the conditional cross-correlation function is more pronounced. This difference 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 these shocks.

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.

[9] Corsetti, Dedola and Leduc (2006) pursue an alternative strategy and identify relative technology shocks assuming that these are the only shocks having long-run effect on relative labor productivity. They report very similar results, notably for the behavior of international relative prices.

We also investigate how conditioning on technology shocks alters additional moments which have received some attention in the international business cycle literature: the standard deviations of the terms of trade, net exports, (relative) investment, and (relative) consumption relative to the standard deviation of (relative) output. The left panel of Table 1 displays the results. In the first and the second column, we report the unconditional and conditional standard deviations, respectively. Conditioning on technology shocks increases the volatility of (relative) consumption, the terms of trade, and net exports, but lowers the volatility of (relative) investment.

Figure 2 about here

To assess the contribution of technology shocks to fluctuations of the trade balance and the terms of trade, we perform a business cycle variance decomposition following ACEL. In this case, as a way of comparison, we also identify monetary policy shocks. Again, we compute counterfactual series that would have been the result if either only technology shocks or only monetary policy shocks had occurred. We then compute the variance of these counterfactual series relative to the variance of the original series after applying the HP-filter. The right panel of Table 1 displays the results. In the third and fourth column we report the fraction of the variance that can be attributed to technology and monetary policy shocks, respectively. For all variables, the contribution of technology shocks to the business cycle variance exceeds those of monetary policy shocks.[10]

In order to gain further insights into the international transmission of technology shocks, we compute the impulse response functions of the baseline VAR model. Figure 2 displays the responses to a one-percent increase in U.S. technology. The shaded areas display 90 percent confidence intervals, computed by bootstrap sampling based on 1000 replications. U.S. labor productivity rises significantly and persistently in response to the technology shock. Next, we consider the response of relative variables (U.S. vs. ROW) indicated by 'Δ'. Relative output, investment, and consumption show significant and persistent increases, displaying mild humps, with peak responses occurring between 4 and 9 quarters. The response of relative consumption appears to be mostly driven by the increase in U.S. consumption which displays a very similar pattern. Yet consumption in the rest of the world shows a persistent, albeit insignificant, decline.

The trade balance (U.S. net exports) displays a hump-shaped decline, while the terms of trade fall (appreciate). Note that while the fall in the trade balance is gradual, the U.S. terms of trade appreciate sharply on impact; this particular co-movement underlies the conditional S-curve depicted in the left panel of Figure 1.

[10] 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. Regarding the results for output, note that we consider relative output only. ACEL report a contribution of (neutral) technology and monetary policy shocks to the variance of output of 13 and 14 percent, respectively.

The real exchange rate also appreciates significantly in response to the shock. This appreciation, i.e. the fact that the price of U.S. consumption rises relative to the price of ROW consumption, is particularly remarkable, given that U.S. consumption exceeds ROW consumption at the same time. Such a negative co-movement of the real exchange rate and the consumption differential is hard to reconcile with efficient risk-sharing across countries as we discuss below.[11] Finally, we find no significant responses for the remaining variables (not shown): relative inflation, the short-term interest rate differential, and oil price inflation.

Overall, these responses are robust with respect to variations of the sample period and to the inclusion of additional variables in the VAR model.[12] They will therefore play a key role in our assessment of the transmission mechanism implied by different specifications of the business cycle model outlined in the next section. In addition, we use simulated data obtained from the calibrated business cycle model to assess the performance of the VAR: we find that the VAR estimates are quite close to the true responses, see Appendix B.

3 The model

In this section we analyze the international transmission of technology shocks in a standard two-country business cycle model, a variant of the model originally proposed by BKK. In the next sub-section 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. We then calibrate the model to match conditional moments obtained from the estimated VAR model.

3.1 Setup

The world economy consists of two countries, $i \in \{1, 2\}$, 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.[13] 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 $\pi(s^t)$.

[11] As both the real exchange rate and the terms of trade appreciate, the currency in which export prices are set is unlikely to play a key role in accounting for the appreciation of the terms of trade, see Obstfeld and Rogoff (2000).

[12] Enders, Müller and Scholl (2008) identify technology shocks using an alternative strategy based on sign restrictions. They also find an appreciation of the real exchange rate and the terms of trade.

[13] 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.

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

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

subject to a budget constraint, which depends on the structure of the international asset markets. As discussed below, the discount factor $\beta_i(s^t)$ 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

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

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 $z_i(s^t)$ measures the level of 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 $\omega > 0.5$ the extent to which the composition of final goods is biased towards domestically produced intermediate 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, the budget constraint of household 1 reads as follows

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

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

To ensure stationarity of bond holdings, we follow Mendoza (1991) and Schmitt-Grohé and Uribe (2003) by assuming that the time discount factor depends on the sequence of consumption and leisure. Specifically, we make the following assumption regarding the functional form:

$$\begin{aligned} \beta_i(s^{t+1}) &= (1 + \psi[\check{c}_i(s^t)^{\mu}(1 - h_i(s^t))^{1-\mu}])^{-1} \beta_i(s^t) \qquad t \geq 0 \\ \beta_i(s^0) &= 1, \end{aligned}$$

where $\check{c}_i(s^t) = c_i(s^t)/z_i(s^t)$, such that the steady-state interest rate is independent of the level of technology, and $\psi > 0$ is set to determine the discount factor in steady state.[14]

[14]Note that households do not internalize the effect of consumption and labor on the discount factor. Regarding the

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}, the budget constraint of household 1 reads as

$$\begin{aligned} & c_1(s^t) + x_1(s^t) + q_1^a(s^t) \sum_{s_{t+1}} Q(s^t, s_{t+1}) B_1(s^t, s_{t+1}) \\ & = q_1^a(s^t)[w_1(s^t) n_1(s^t) + r_1(s^t) k_1(s^t)] + q_1^a(s^t) B_1(s^{t-1}, s_t). \end{aligned} \tag{9}$$

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

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 budget constraint (8) or (9); 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

$$a_1(s^t) + a_2(s^t) = y_1(s^t), \tag{10}$$

$$b_1(s^t) + b_2(s^t) = y_2(s^t); \tag{11}$$

for final goods

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

and, under incomplete financial markets

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

holds, or under complete financial markets

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

endogenous discount factor, Bodenstein (2006) emphasizes that it ensures the uniqueness of the steady state—in contrast to other assumptions which induce stationarity of bond holdings. While he warns against excluding the multiplicity of steady states a priori, note that an endogenous discount factor will generally pick the symmetric one. 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 that induce implausibly large jumps in consumption and output in response to technology shocks.

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 behavior of a domestic variable relative to its foreign counterpart. We assume that domestic and foreign technologies, written in logs using 'hats', follow the joint process

$$\begin{bmatrix} \hat{z}_1(s^t) \\ \hat{z}_2(s^t) \end{bmatrix} = \begin{bmatrix} \rho_1 & \rho_2 \\ \rho_2 & \rho_1 \end{bmatrix} \begin{bmatrix} \hat{z}_1(s^{t-1}) \\ \hat{z}_2(s^{t-1}) \end{bmatrix} + \begin{bmatrix} \varepsilon_1(s^t) \\ \varepsilon_2(s^t) \end{bmatrix}, \tag{12}$$

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

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 the cointegrating vector $\begin{bmatrix} 1 & -1 \end{bmatrix}$.
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

$$\tilde{z}(s^t) = \rho\tilde{z}(s^{t-1}) + \varepsilon(s^t), \qquad \varepsilon(s^t) \sim N(0, \sigma^2_{\varepsilon_1} + \sigma^2_{\varepsilon_2} - 2\sigma_{\varepsilon_1\varepsilon_2}) \tag{13}$$

with $\rho = \rho_1 - \rho_2$. In the symmetric two-country model only the technology differential matters for the dynamics of relative variables, the terms of trade and the 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 (13) in calibrating the model. Below we show that global shocks are likely to play a quantitatively negligible role for the variables of interest even if we assume that the net foreign asset position in steady state is different from zero.

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 a stylized fact of international business cycles and one of the dimensions in which the prediction of the model has been shown to square well with the evidence. In addition, we consider three more moments in order to pin down the structural model parameters: the standard deviations of the terms of trade, net exports, and investment conditional on technology shocks, which are reported in the second column of Table 1.[15] Simple experimentation shows that the corresponding statistics implied by the model are 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 therefore to pin down values for these model parameters in order to match the conditional S-curve and the mentioned volatilities obtained from the VAR model. This 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.[16] Other parameters have little bearing on the targeted moments 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 8×1 vector, where the first five elements contain the empirical cross-correlation function between two lags and leads and the last three elements contain the standard deviation of the terms of trade, net exports and relative investment (relative to output). Let $m(\lambda)$ denote the corresponding theoretical moments obtained from a simulation of the model (averages over 40 simulations of 150 observations, corresponding to the number of observations used in the VAR). As the theoretical moments depend on $\lambda = \{ \begin{array}{ccc} \sigma & \chi & \rho \end{array} \}$, we find values for these parameters by solving the following problem

$$\min_{\lambda} \left(m(\lambda) - m_d\right)' W \left(m(\lambda) - m_d\right), \tag{14}$$

where W is a diagonal weighting matrix containing the inverse of the standard deviation of the elements of m_d. We solve (14) for both asset market structures—complete and incomplete international financial markets.[17]

[15] In addition to the S-curve the volatility of the terms of trade and net exports have received considerable attention in the international business cycle literature. We also target the volatility of investment in order to pin down investment adjustment costs.

[16] 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 usage of these series which are likely to be contaminated by measurement error.

[17] Canova and Sala (2006) stress identification issues that may arise in the calibration and estimation of richly specified

Table 2 about here

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 the cross-country technology differential, ρ, obtained by solving (14). The set of parameter values obtained under the assumption that financial markets are complete defines an economy which is characterized by the standard transmission mechanisms, as we show below. The elasticity of substitution between intermediate goods, σ, takes a value of about 3. This is larger than 1.5, the value used in the benchmark economy of BKK, but still within the range of values frequently used in the literature. Investment adjustment costs are absent, while the persistence of technology differentials is moderate: $\rho = 0.68$.

Figure 3 about here

In contrast, assuming that financial markets are incomplete, the set of parameter values obtained by solving (14) is quite distinct. The elasticity of substitution between intermediate goods, σ, takes a value of 0.23.[18] There is also evidence for investment adjustment costs with $\chi = 0.34$. Christiano et al. (2005), using the same specification in a different context, report an estimate of approximately 2.5. Finally, technology differentials appear quite persistent with $\rho = 0.98$.[19] 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 obtained under complete markets.[20] 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. This is noteworthy, given that we match 2 leads and lags and the contemporaneous correlation together with three additional moments.[21]

DSGE models. We conduct experiments showing that under the criterion function (14) the structural parameters σ, ρ and χ are fairly well identified. Results are available upon request.

[18] 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). Another recent paper which suggests a relatively low elasticity of substitution between intermediate goods is Kollmann (2006). Note, moreover, that such a low *de facto* elasticity may conform to a higher nominal elasticity in an economy with a distribution sector, see CDL.

[19] Note 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.

[20] More generally, this local minimum has properties similar to the global minimum under complete markets. However, the global optimum defines an economy 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.

[21] Relative to the cross-correlation function reported by BKK, the S-curve which characterizes the complete markets calibration 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.

Table 3 about here

In order to further assess the performance of the calibrated model we turn to the implied volatility of key variables, reported in table 3. As an empirical benchmark, we reproduce in the left column the figures obtained from the VAR model under the counterfactual assumption that technology shocks are the only source of business cycle fluctuations. In the second and third column of table 3 we report the theoretical counterparts obtained from the calibrated model under the assumption that financial markets are complete or incomplete, respectively. We find that under the complete markets calibration the model greatly underpredicts the volatility of the terms of trade. Under incomplete markets the model predicts the volatility to be slightly too high, but of the right order of magnitude. Yet as far as the volatility of net exports are concerned, the performance of the model under both calibrations is reversed. Regarding this variable, the model somewhat underpredicts the volatility under complete markets, but misses the order of magnitude under incomplete markets.[22] Regarding investment, the model performs fairly well under both calibrations. It is with respect to the volatility of consumption—the only moment which has not been targeted in the calibration—that one observes a considerable discrepancy in the model performance across calibrations. While the VAR evidence suggests, conditional on technology shocks, a volatility of relative consumption similar to that of relative output, the model predicts the volatility of consumption to be considerably lower under complete markets. Under the incomplete markets calibration, the volatility of consumption is fairly close to that of output, even though it slightly exceeds it. We will provide a discussion of the mechanism which underlie these findings in the following section.

4 The international transmission of technology shocks

Given the calibrated model, we now turn to the international transmission mechanism of technology shocks. First, we compare the responses of the model with those obtained from the estimated VAR model in order to assess the empirical performance of both model calibrations. Next, we discuss the implications of both calibrations for risk-sharing across countries and compute the wealth effect of technology shocks. We conclude this section by exploring the robustness of our results with respect to assuming a non-symmetric steady state and the presence of price rigidities.

4.1 Comparing model and VAR impulse responses

In order to inspect the international transmission mechanism under both calibrations, we compute the impulse responses to a technology shock originating in the domestic economy (country 1 or 'home').

[22] These findings are reminiscent of those reported by Backus et al. (1995) for a complete markets economy. They stress that a low value of the trade price elasticity may go some way to solve the price-variability anomaly, yet comes at the expense of counterfactual low values for the volatility of net exports.

Specifically, we study the effects of an increase of relative technology by 0.5%, as this induces an increase of relative output similar to what we observe for the empirical impulse response functions.[23] Figure 4 displays the results for the complete markets calibration (solid line) and the incomplete markets calibration (dashed line). The response of domestic labor productivity as well as the responses of relative output, investment and consumption is remarkably more persistent in the second case. Domestic consumption increases under both calibrations.[24]

Yet foreign consumption increases only under the complete markets calibration, but falls under the incomplete markets calibration. Similarly, the response of the trade balance is quite distinct in both cases. It displays a lasting, hump-shaped decline under the incomplete markets calibration, but falls sharply on impact and moves into surplus after about four quarters under the complete markets calibration.

Figure 4 about here

Regarding the responses of the terms of trade and the real exchange rate, one also observes a change in the sign across calibrations. Under the complete markets calibration the terms of trade and the real exchange rate depreciate, while both appreciate under the incomplete markets calibration. In other words, the model induces the standard transmission mechanism only in the first case. Interestingly, while it predicts a positive co-movement of the consumption differential and the real exchange rate in this case, we observe a negative co-movement under the incomplete markets calibration.

A comparison of the model responses with those obtained from the estimated VAR model displayed in Figure 2 suggests that the model performance under the incomplete markets calibration dominates the complete markets calibration. Most importantly, in the former case the response of international relative prices conforms well with the evidence. Moreover, the negative co-movement of relative consumption with the real exchange rate as well as the decline in foreign consumption, which characterize the empirical transmission mechanism, is obtained only under the incomplete markets calibration. As a caveat we note that the model fails to deliver the right order of magnitude for the response of the trade balance under both calibrations.

To sum up, while the model delivers the S-curve under both calibrations (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 under the incomplete markets calibration turns the process under the complete markets calibration upside down. Put differently, we find that the model

[23]Note that Figure 2 displays the effects of one percent increase in U.S. technology according to the VAR model. The implied increase in relative technology may be lower to the extent that the identified shock contains a global component.

[24]Recall also that in calibrating the model we have relied on relative variables only. In order to compute the 'level' responses, we specify the parameters governing (12): 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 $\rho_2 = 1 - \rho_1$.

predicts a terms of trade appreciation and a lasting, hump-shaped decline of the trade balance only under the incomplete markets calibration—in line with the time series evidence. This has important consequences for the extent of risk-sharing as we discuss below.[25]

4.2 Implications for implicit risk-sharing under incomplete financial markets

Depending on the calibration, the model predicts the opposite sign for the responses of the terms of trade, the trade balance and foreign consumption. These responses reflect a fundamental difference as to how country-specific risk is shared internationally. To see this, it is important to recall that the difference in the transmission of technology shocks is not the result of different asset market structures *per se*. This follows from results established by earlier literature, showing that—all else equal—moving from complete to incomplete financial markets does generally not affect the equilibrium allocation very much. In fact, if there is no trade in a complete set of state contingent securities across countries, there are nevertheless two mechanism through with implicit risk-sharing may be achieved. First, Baxter and Crucini (1995) show in a one-good model that intertemporal trade in a single non-contingent bond allows to achieve allocations close to the one obtained under complete markets. A condition for this result to hold is that technology shocks are not too persistent.

Second, Cole and Obstfeld (1991) consider risk-sharing in a two-good world and find that terms of trade movements can also provide implicit risk-sharing under incomplete markets. Specifically, if the elasticity of substitution between domestic and foreign goods is unity, the allocation under incomplete markets is identical to the allocation obtained under complete markets within their model. 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, such that the wealth effect of the domestic technology shock is spread equally across countries.

Our calibrated model under incomplete markets, however, is characterized by a low elasticity of substitution and very persistent shocks to relative technology. We find that in this case the relative price

[25] Apart from different assumptions regarding international asset markets, the difference in the transmission mechanism is governed by three parameters: σ, χ and ρ. The value of ρ, by governing the persistence of technology differentials, implicity determines the amount of technology spillovers across countries. In order to assess to what extent different technology processes are driving our results, we computed impulse response functions of the model under the complete (incomplete) markets calibration while assuming instead a high (low) value for $\rho \in \{0.68, 0.98\}$. Overall, we found the impulse response functions of the complete market calibration to be qualitatively unchanged. Regarding the incomplete markets calibration, we also found our results fairly robust with respect to assuming a lower value of ρ. In particular, the terms of trade and the real exchange continued to appreciate, after a short phase of depreciation during the first two periods after the shock. An exception is the response of foreign consumption which we found to be positive once a low ρ was assumed. Results are available on request. It should be noted, however, that assuming identical technology processes results in the model failing to deliver the S-curve under *both* calibrations.

of the home good appreciates in response to a technology shock. This has dramatic consequences for risk-sharing, because terms-of-trade movements not only fail to provide implicit risk-sharing, but instead amplify the wealth effect of technology shocks. The appreciation raises the value of domestic output relative to foreign output, despite the fact that domestic output is now produced under a more favorable technology. As a consequence foreign consumption falls.

CDL analyze the possibility of such a 'negative' international transmission mechanism in more detail. 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 increase in the price of domestic goods, in turn, supports the initial rise in domestic absorption as it transfers wealth from foreign to domestic residents.

4.3 Wealth effects

We now turn to a more formal assessment of the explicit or implicit risk-sharing arrangements operating under the transmission mechanisms implied by both calibrations. Following King (1991), we compute the dynamic Hicksian decomposition of the consumption and labor responses to a domestic technology shock into a wealth and a substitution effect. We proceed as follows. First, we calculate the change in lifetime utility triggered by the technology shock. Second, we compute the permanent lump-sum transfer that would induce the same change in lifetime utility assuming counterfactually that no shock occurs.[26] Finally, we calculate the percentage change in steady-state consumption and labor induced by the transfer payment. These changes as well as the transfer (in percentage of steady-state consumption) provide measures for the wealth effect of the technology shock.

Table 4 about here

The results are reported in Table 4. The left column reports the dynamic Hicksian decomposition for the complete markets calibration. We find that a transfer of 0.24% of steady-state consumption would make the domestic agent as well off as the 0.5% positive technology shock. Similarly, the foreign agent would have to receive the same percentage of her steady-state consumption to be indifferent

[26] We assume that both the domestic and the foreign household obtain the same transfer payment such that equilibrium relative prices are not affected by the counterfactual experiment.

between the transfer and the shock in the home country. These payments would induce symmetric changes in consumption and labor that are reported (in percent) in rows 3 to 6. In contrast, in the incomplete-markets case one would have to take away some of the foreign agents' resources, indicating that she is harmed by the domestic technology shock. The negative transfer would result in lower consumption and higher labor.

This illustrates the fundamental differences in the transmission mechanism of the model under both calibrations. The wealth effect of the domestic technology shock on the home economy is positive under both calibrations. Given full risk-sharing under complete markets, there is a positive wealth effect of the domestic technology shock also on the foreign economy. Under the incomplete markets calibration, in contrast, there are no signs of implicit risk-sharing. In fact, the opposite happens: the terms of trade appreciation lowers the value of foreign output which, in turn, is reflected in a negative wealth effect experienced by foreign residents.

We also conduct a counterfactual experiment disentangling the effects of the asset market structure and the parameter values on the wealth effects. In the third column of Table 4, we report the wealth effects of a technology shock in the home country in a counterfactual setting with the parameter values as in the complete markets case, but with incomplete markets. Relative to the first column, moving from complete to incomplete markets does hardly affect the wealth effects, showing that in this counterfactual scenario foreign residents are able to reap benefits of the technology shock—thereby confirming the results discussed in section 4.2 above.

4.4 Sensitivity analysis

In this section we explore the robustness of the predictions of the model in case that i) prices are sticky and ii) the net foreign asset position in the steady state is different from zero under incomplete markets.[27] As discussed above, both features are likely to characterize actual economies and it is not clear whether they impact on the international transmission of technology shocks in a quantitatively important way.

To allow for price rigidities, we introduce monopolistic competition in the intermediate good sector, assuming that producers are restricted in adjusting prices by the Calvo mechanism. We set the average price duration to four quarters. To close the model, we specify a Taylor type interest rate feedback rule with an interest rate semi-elasticity with respect to inflation and output of 1.5 and 0.5, respectively. Concerning net foreign assets, we consider a version of the model linearized around a steady state where the stock of debt of the domestic economy is equal to 22.6% of GDP, i.e. the value reported for the U.S. in 2004 by Lane and Milesi-Ferretti (2007).

The upper row of Figure 5 displays the results for the complete markets calibration. It shows the

[27] Benigno (2009) and Benigno and Thoenissen (2008) also consider this case.

response of the terms of trade and the trade balance to a 0.5% technology shock in the first two panels; the third panel depicts the cross-correlation functions for the terms of trade and the trade balance. The solid line shows the results for the baseline case without price rigidities, while the dashed line gives the responses for the sticky price economy.

Figure 5 about here

The second row shows the results for the incomplete markets case. We compare results from the baseline case (solid line), with results from a sticky price version (dashed line) and the version of the model where net foreign assets are different from zero in steady state (dashed-dotted line). Both modifications of the model turn out to be of limited importance from a quantitative point of view, for the responses of the terms of trade and the trade balance are close to the baseline specification and the cross-correlation function for the trade balance and the terms of trade is hardly altered. These results lend support to our approach to analyze the international transmission mechanism of technology shocks in a real and symmetric model.

In the third row of Figure 5 we consider the dynamics triggered by a 0.5% global shock in the asymmetric model. If net foreign assets were zero in steady state, a global shock that increases domestic and foreign technology by the same amount would not affect relative variables. We find that for the asymmetric model, a global shock alters both the terms of trade and the trade balance, but the effects are quantitatively limited. This supports our interpretation of the results from the VAR model, whereby we consider the dynamics of relative variables triggered by a U.S. technology shocks as being mostly driven by an idiosyncratic component. Finally, in the right panel of the third row we compute the cross-correlation function for the trade balance and the terms of trade assuming that country-specific innovations to technology are correlated.[28] Also this modification has little bearing on the shape of the S-curve.

5 Conclusion

In this paper we analyze the international transmission of technology shocks by confronting the transmission mechanism of a standard international business cycle model with time series evidence for the post-Bretton Woods period.

In a first step, we estimate a VAR model and identify technology shocks assuming that these are the only shocks affecting U.S. labor productivity in the long run. We use the VAR model to compute several statistics. First, we compare the cross-correlation function for the U.S. trade balance and the terms of trade (S-curve) conditional on technology shocks with its unconditional counterpart and find

[28] Specifically, we assume that innovations to technology are distributed as in Heathcote and Perri (2002), who assume a correlation of 0.29.

it to be more pronounced. Second, conditional on technology shocks the volatilities of the terms of trade, consumption, and the trade balance increase while the volatility of investment falls. Third, a positive technology shock appreciates the terms of trade and induces a lasting, hump-shaped decline of the trade balance. Moreover, it increases consumption in the U.S., but depresses consumption in the rest of the world, appreciating simultaneously the U.S. real exchange rate.

We calibrate a prototypical international business cycle model to match the S-curve conditional on technology shocks as well as the relative volatility of the terms of trade, the trade balance and investment, both under complete and incomplete financial markets. Under both asset market structures the calibrated model delivers the S-curve. However, the parameter value for the elasticity of substitution between domestic and foreign goods is quite distinct. It is about three in the complete markets economy and about one fourth under incomplete markets. Similarly, the persistence of relative technology is much higher in the latter case. To assess the ability of the model under both calibrations to account for the transmission of technology shocks apparent from the data, we study the impulse response functions to a technology shock. It turns out that the transmission process is fundamentally different. Under the complete markets calibration, the model predicts a depreciation of the terms of trade and a sharp decline of the trade balance as well as an increase in foreign consumption. Under the incomplete markets calibration, in contrast, the model generates an appreciation of the terms of trade and a lasting, hump-shaped decline in the trade balance as well as a fall in foreign consumption. The main result of our analysis may thus 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, the trade balance, and foreign consumption are concerned, the transmission mechanism under the incomplete markets calibration turns the responses under the complete markets calibration upside down. The model's predictions are qualitatively in line with the time series evidence only under the incomplete markets calibration. Note, however, that this result is not evidence against the assumption of complete markets *per se*, but, more generally, against the standard transmission mechanism which may also be obtained under incomplete financial markets for a calibration different from the one suggested above.

Finally, analyzing the wealth effects triggered by a technology shock under both calibrations highlights that much is at stake regarding the international transmission mechanism. 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. Importantly, it appears promising to move beyond the prototypical business cycle model and to reassess the role of the terms of trade and the extent of risk-sharing in models with an extensive margin in internationally traded goods. Ghironi and Melitz (2005), for instance, show that the terms of trade may also appreciate in response to an increase in aggregate technology because of entry of new firms competing for a fixed amount of labor input.

Appendix

A Data

The data are obtained from the Bureau of Economic Analysis (National Income and Product Accounts, NIPA) and the Bureau of Labor Statistics (BLS), as far as the United States are concerned. For the rest of the world and the real exchange rate, we use data from the OECD (2007). The sample covers the period 1973:1 to 2006:4.

U.S. data

For the U.S. we use labor productivity: output per hour in the non-farm business sector (BLS: PRS85006093), net exports: nominal net exports (NIPA: A019RC1) divided by nominal GDP (NIPA: A191RC1), real output: gross domestic output (NIPA: A191RC1) divided by its implicit deflator (NIPA: A191RD3), real investment: gross private domestic investment (NIPA: A006RC1) divided by its implicit deflator (NIPA: A006RD3), real consumption: personal consumption expenditure (NIPA: A002RC1) divided by its implicit deflator (NIPA: A002RD3), inflation: calculated using the implicit GDP deflator (NIPA: A191RD3), short-term interest rate: Federal Funds Rate (p.a.), quarterly (Federal Reserve Board: H15. Provided by www.freelunch.com), real exchange rate: log of inverse of real effective exchange rate as provided by the OECD (Main Economic Indicators), terms of trade: log of relative price of imports to exports—calculated on the basis of the implicit deflators of imports of goods and services (NIPA: A021RD3) and exports of goods and services (NIPA: A020RD3).
Solow residuals are calculated on the basis of hours in non-farm business sector (BLS: PRS85006033), 'Gross domestic product (market prices), volume', and 'Capital Stock, total economy', both from the OECD Economic Outlook. We assume a capital share of 0.36.

ROW data

The time series used for the VAR are constructed from data for the U.S. relative to a sample representing the 'rest of the world' (ROW). In practice this comprises the euro area, the U.K., Japan, and Canada. The following quarterly data are taken from the OECD Economic Outlook: Real output: 'Gross domestic product (market prices), volume', real investment: 'Private fixed investment (excl. stockbuilding), volume', real consumption: 'Private consumption, volume', inflation: calculated using 'Deflator for GDP at market prices', short-term interest rate: 'Interest rate, short-term', oil price: 'Crude oil import price (cif), $ per barrel'.

ROW aggregation

In order to avoid national basis effects, we construct the rest of the world series by first calculating quarterly growth rates and aggregating these series weighted by each country's GDP share in the group's total GDP. Euro area growth rates include West-Germany until 1990Q4, and unified Germany from 1991Q1 onwards. The weights are calculated at annual purchasing power parity (PPP) values in the year 2000, based on data from the International Monetary Fund (2007). The aggregated growth rates are then cumulated from the normalized base year, in order to transform the series into levels.

B The VAR model

This appendix discusses our identification strategy drawing on ACEL. In addition, we report results for the effects of monetary policy shocks and results from simulations assessing the VAR performance.

Identification and further results

Using a star to denote ROW variables, we partition the seven dimensional vector of endogenous variables, Y_t, as follows:

$$Y_t = \begin{pmatrix} \Delta \ln(\text{Output}_t/\text{Hours}_t) \\ \Delta \ln(\text{Output}_t/\text{Output}_t^*) \\ \Delta \ln(\text{Oil price}_t) \\ \text{Inflation}_t - \text{Inflation}_t^* \\ \text{Short rate}_t - \text{short rate}_t^* \\ \ln(\text{Terms of Trade}_t) \\ \Delta\text{Net Exports}_t/\text{GDP}_t \end{pmatrix} = \begin{bmatrix} \Delta a_t \\ \left.\begin{matrix} \Delta dy_t \\ \pi_t^{oil} \\ d\pi_t \end{matrix}\right\} \equiv Z_{1t} \\ dR_t \\ \left.\begin{matrix} p_t \\ \Delta nx_t \end{matrix}\right\} \equiv Z_{2t} \end{bmatrix} = \begin{bmatrix} \Delta a_t \\ Z_{1t} \\ dR_t \\ Z_{2t} \end{bmatrix}.$$

The structural VAR model is given by

$$A(L)Y_t = \varepsilon_t, \tag{B.1}$$

where a constant is omitted to simplify the exposition and $A(L)$ denotes a matrix polynomial in the lag operator L. We include four lags of each variable. The fundamental economic shocks contained in the 7×1 vector ε_t are assumed to be mutually uncorrelated. To fix ideas, let A_i denote the matrix of coefficients on $L^i Y_t$ such that A_0 captures the contemporaneous interaction of variables. Moreover, let $\alpha_{i,kl}$ denote an element of A_i with k and l indicating the row and column, respectively. We assume without loss of generality that U.S. technology shocks are the first element in ε_t and, in our baseline specification, do not attach any particular structural interpretation to the other elements in ε_t.[29] We

[29] The estimated innovations are then identified only up to a particular transformation defined by an arbitrary orthonormal matrix, see, for instance, the discussion in ACEL.

may therefore assume a lower-triangular structure for A_0 from the second row onwards:

$$\underset{7\times 7}{A_0} = \begin{pmatrix} \underset{1\times 1}{1} & \underset{1\times 3}{\alpha_{0,12}} & \underset{1\times 1}{\alpha_{0,13}} & \underset{1\times 2}{\alpha_{0,14}} \\ \underset{3\times 1}{\alpha_{0,21}} & \underset{3\times 3}{\alpha_{0,22}} & \underset{3\times 1}{0} & \underset{3\times 2}{0} \\ \underset{1\times 1}{\alpha_{0,31}} & \underset{1\times 3}{\alpha_{0,32}} & \underset{1\times 1}{1} & \underset{1\times 2}{0} \\ \underset{2\times 1}{\alpha_{0,41}} & \underset{2\times 3}{\alpha_{0,42}} & \underset{2\times 1}{\alpha_{0,43}} & \underset{2\times 2}{\alpha_{0,44}} \end{pmatrix}, \tag{B.2}$$

where $\alpha_{0,22}$ and $\alpha_{0,44}$ are lower triangular with the elements of the main diagonal normalized to one. Formalizing the assumption that only technology shocks affect labor productivity in the long run, we have for the elements of the long-run multiplier $A(1)$:

$$\sum_{i=0}^{4} \alpha_{i,1n} = 0, \text{ for } n = 2, 3, 4, \tag{B.3}$$

see Christiano, Eichenbaum and Vigfusson (2003) for a more detailed discussion. In an alternative specification of the VAR model, we also identify monetary policy shocks. As discussed in the main text, we assume that all variables except for the trade balance and the terms of trade are predetermined relative to the interest rate differential; formally we have three more zero restrictions: $\alpha_{0,13} = 0$ and $\alpha_{0,14} = 0$.

The estimation of the structural VAR model follows Shapiro and Watson (1988) and ACEL; we impose the long-run restrictions given by (B.3) on the first equation of (B.1) which then reads as follows:

$$\Delta a_t = -\sum_{i=1}^{4} \alpha_{i,11} L^i \Delta a_t - \sum_{i=0}^{3} \alpha'_{i,12} L^i \Delta Z_{1t} - \sum_{i=0}^{3} \alpha'_{i,14} L^i \Delta dR_t - \sum_{i=0}^{3} \alpha'_{i,15} L^i \Delta Z_{2t} + \varepsilon_t^a$$

Note that as $\alpha_{0,12}, \alpha_{0,13}, \alpha_{0,14} \neq 0$, the VAR cannot be estimated recursively by OLS.[30] We therefore use $Y_{t-1}, \ldots Y_{t-4}$ as instruments in a two-stage least squares regression to estimate the first equation. When estimating the remaining equations recursively, we use the residuals from the previous equations to instrument the contemporaneous variables in each equation. Results are shown and discussed in the main text except for the effects of a (relative) monetary policy shock, which are displayed in Figure B.1.

Figure B.1 about here

[30] To understand the relationship between α and α', note that

$$\begin{aligned} & \alpha_0 Z_t + \alpha_1 Z_{t-1} + \alpha_2 Z_{t-2} + \alpha_3 Z_{t-3} + \alpha_4 Z_{t-4} \\ = \; & \alpha_0 Z_t + \alpha_1 Z_{t-1} + \alpha_2 Z_{t-2} + \alpha_3 Z_{t-3} + \underbrace{(\alpha_0 + \alpha_1 + \alpha_2 + \alpha_3 + \alpha_4)}_{=0} Z_{t-4} - (\alpha_0 + \alpha_1 + \alpha_2 + \alpha_3) Z_{t-4} \\ = \; & \alpha_0 \Delta Z_t + \underbrace{(\alpha_0 + \alpha_1)}_{\alpha'_1} \Delta Z_{t-1} + \underbrace{(\alpha_0 + \alpha_1 + \alpha_2)}_{\alpha'_2} \Delta Z_{t-2} + \underbrace{(\alpha_0 + \alpha_1 + \alpha_2 + \alpha_3)}_{\alpha'_3} \Delta Z_{t-3}. \end{aligned}$$

VAR performance

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 (2007). 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 if our calibrated business cycle model is used as the data generating process. We consider a vector of endogenous variables which includes four variables: the change in domestic labor productivity, relative output, the terms of trade and net exports.[31]

Figure B.2 about here

We generate data using the calibrated business cycle model under the complete markets calibration. Specifically, we simulate the model for 150 periods (using an additional 100 periods to initialize the model) on which we estimate the VAR model. Results for the response of the terms of trade, net exports and the S-curve are displayed in Figure B.2. The dashed line displays the true impulse responses (S-curve) while the solid lines display the mean of the estimated response functions over 500 repetitions.[32]

A final issue concerns the existence of a VAR representation of the DSGE model. We check this using the approach of Fernández-Villaverde, Rubio-Ramírez, Sargent and Watson (2007). 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 the $n \times 1$ 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 observable variables. The condition for invertibility is that the eigenvalues of $A - BD^{-1}C$ are strictly less than one in modulus. We find that these conditions to be satisfied for both calibrations.

Acknowledgements

We would like to thank Enrique Mendoza (the editor), Giancarlo Corsetti, Luca Dedola, Philip Jung, Dirk Krüger, Keith Küster, Christian Offermanns, Elvira Prades, Morten Ravn, two anonymous refer-

[31] As there are only two shocks in the model, for which we assume the distribution used in Heathcote and Perri (2002), we add measurement error to avoid stochastic singularity as, for instance, in Ireland (2004). We set the standard deviation of the measurement error to 3%.

[32] Under the incomplete markets calibration the performance of the VAR deteriorates somewhat due to the high autocorrelation of relative technology. However, the shape of the cross-correlation function and the signs of the impulse responses are correctly estimated.

ees, and the seminar participants at the ECB, EEA Congress in Budapest, German Economic Association Meeting in Bayreuth, EUI, Open Macroeconomics & Development Meeting in Aix-en-Provence, 2^{nd} German Workshop in Macroeconomics, ASSET in Lisbon, Simposio de Análisis Económico in Oviedo, and 5th Workshop on Macroeconomic Dynamics in Rome for very helpful comments on earlier drafts. Zeno Enders thanks the European Investment Bank for financial support. The usual disclaimer applies.

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 Economics*, 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.

Benigno, G. and Thoenissen, C.: 2008, Consumption and real exchange rates with incomplete markets and non-traded goods, *Journal of International Money and Finance* **27**, 926–948.

Benigno, P.: 2009, Price stability with imperfect financial integration, *Journal of Money, Credit and Banking* **41**(s1), 121–149.

Bodenstein, M.: 2006, Closing open economy models, *FRB International Finance Discussion Paper 896*.

Canova, F. and Sala, L.: 2006, Back to square one: Identification issues in DSGE models, *ECB Working Paper 583*.

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.: 2007, Assessing structural VARs, *in* D. Acemoglu, K. Rogoff and M. Woodford (eds), *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.: 2006, Productivity, external balance and exchange rates: evidence on the transmission mechanism among G7 countries, *in* L. Reichlin and K. West (eds), *NBER International Seminar on Macroeconomics 2006*.

Corsetti, G., Dedola, L. and Leduc, S.: 2007, International risk sharing and the transmission of productivity shocks, *Review of Economic Studies* **75**(2), 443–473.

Corsetti, G., Dedola, L. and Leduc, S.: 2008, High exchange-rate volatility and low pass-through, *Journal of Monetary Economics* **55**(6), 1113–1128.

Enders, Z., Müller, G. J. and Scholl, A.: 2008, How do fiscal and technology shocks affect real exchange rates? New evidence for the United States. CFS Working Paper 2008/22.

Fernández-Villaverde, J., Rubio-Ramírez, J., Sargent, T. J. and Watson, M. W.: 2007, A, B, C's (and D's) for understanding VARs, *American Economic Review* **97**(3), 1021–1026.

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

Ghironi, F. and Melitz, M.: 2005, International trade and macroeconomic dynamics with heterogeneous firms, *Quarterly Journal of Economics* **120**, 865–915.

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.

International Monetary Fund: 2007, World economic outlook database, http://www.imf.org/external/pubs/ft/weo/2007/01/data/index.aspx.

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.

King, R. G.: 1991, Value and capital in the equilibrium business cycle programme, *in* L. W. McKenzie and S. Zamagni (eds), *Value and Capital Fifty Years Later*, Macmillan, Houndmills, Basingstoke, Hampshire, pp. 279–309.

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, *CEPR Discussion Paper 5512*.

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

Lane, P. R. and Milesi-Ferretti, G. M.: 2007, The external wealth of nations mark II: revised and extended estimates of foreign assets and liabilities, 1970-2004, *Journal of International Economics* **73**(2), 223–250.

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.

OECD: 2007, Economic Outlook 82, Main Economic Indicators vol. 2007, on *SourceOECD*.

Raffo, A.: 2008, Net exports, consumption volatility, and international real business cycle models, *Journal of International Economics* **75**, 14–29.

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

Schmitt-Grohé, S. and Uribe, M.: 2003, Closing small open economy models, *Journal of International Economics* **61**, 163–185.

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.

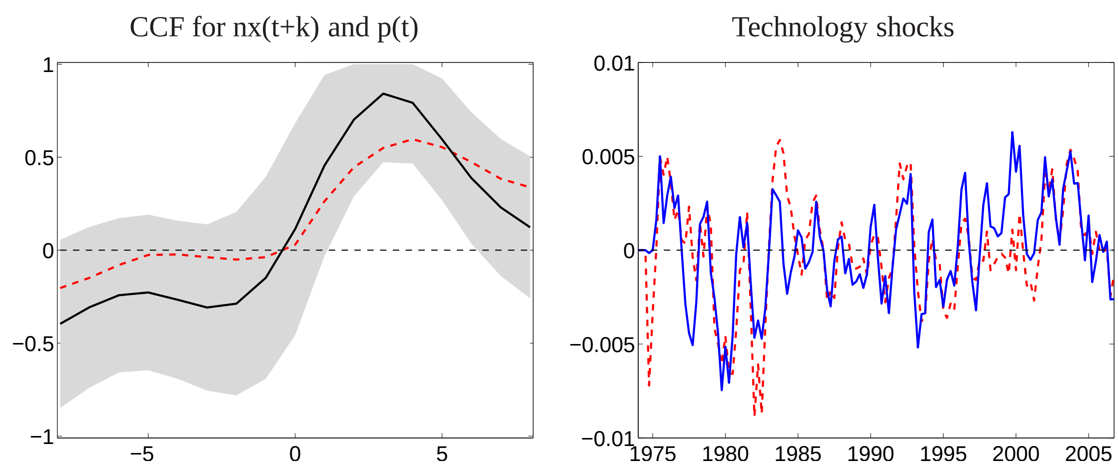

Figure 1: Technology shocks and the S-curve. *Notes:* Left panel displays cross-correlation function for the terms of trade and the trade balance (ccf); vertical axis: correlation; horizontal axis: k; Dashed line: unconditional ccf, computed after applying HP-filter to raw time series; Solid line: ccf conditional on technology shocks, computed after applying HP-filter to counterfactual time series obtained from the VAR model; shaded area: bootstrapped 90 percent confidence intervals. Right panel displays four-quarter moving average of technology shocks; Solid line: shocks identified in baseline VAR model; dashed line: growth rate of Solow residual.

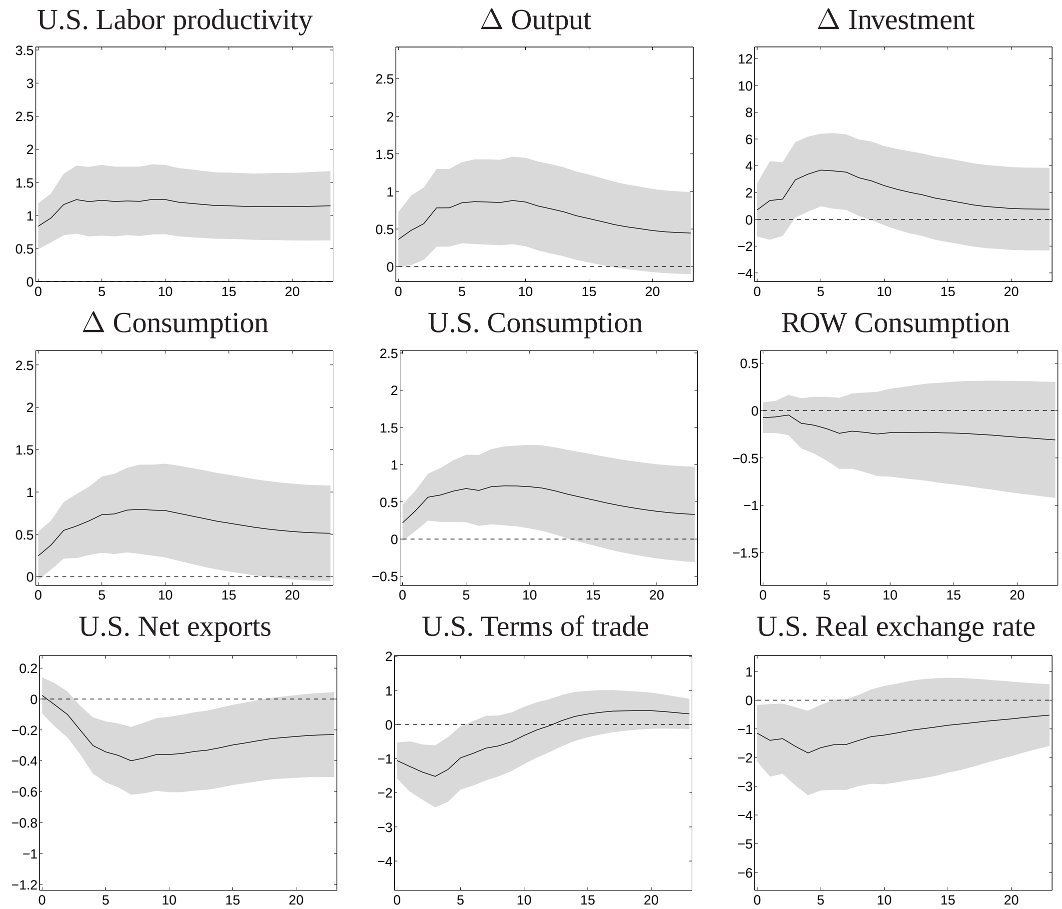

Figure 2: Effect of U.S. technology shock. *Notes:* 'Δ' indicates that response is in relative terms (U.S. vs. ROW); solid line: point estimate; shaded areas: bootstrapped 90 percent confidence intervals. Vertical axes: percent, except for net exports (percentage points of GDP). Horizontal axes: quarters.

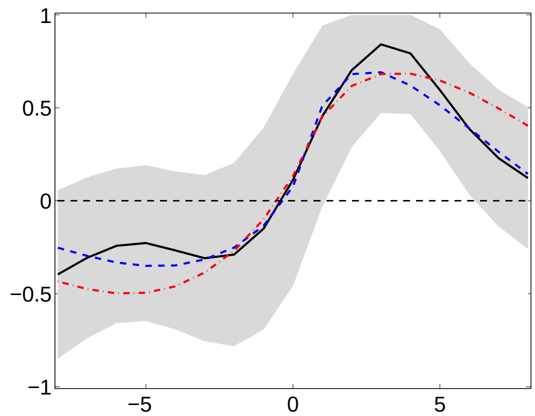

Figure 3: Conditional cross-correlation function for the trade balance and the terms of trade. *Notes:* ccf for nx(t+k) and p(t); vertical axis: correlation; horizontal axis: k; solid line displays ccf conditional on technology shocks, computed after applying HP-filter to counterfactual time series obtained from the VAR model; shaded area: bootstrapped 90 percent confidence intervals. Dashed line: ccf of complete markets calibration; dashed-dotted line: incomplete markets calibration.

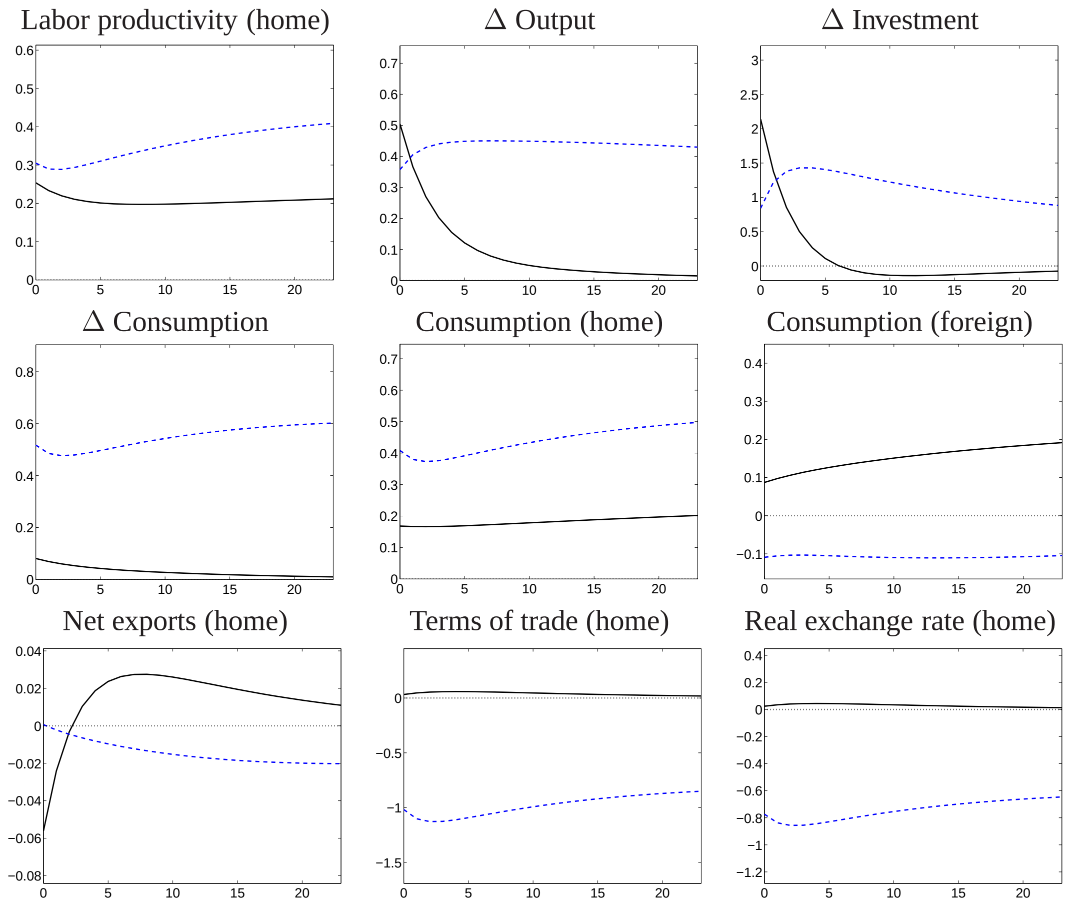

Figure 4: Effect of technology shock in theoretical economies. *Notes:* 'Δ' indicates that response is in relative terms (home vs. foreign); solid line: complete markets calibration; dashed line: incomplete markets calibration; vertical axes: percent, except for net exports (percentage points of output); horizontal axes: quarters.

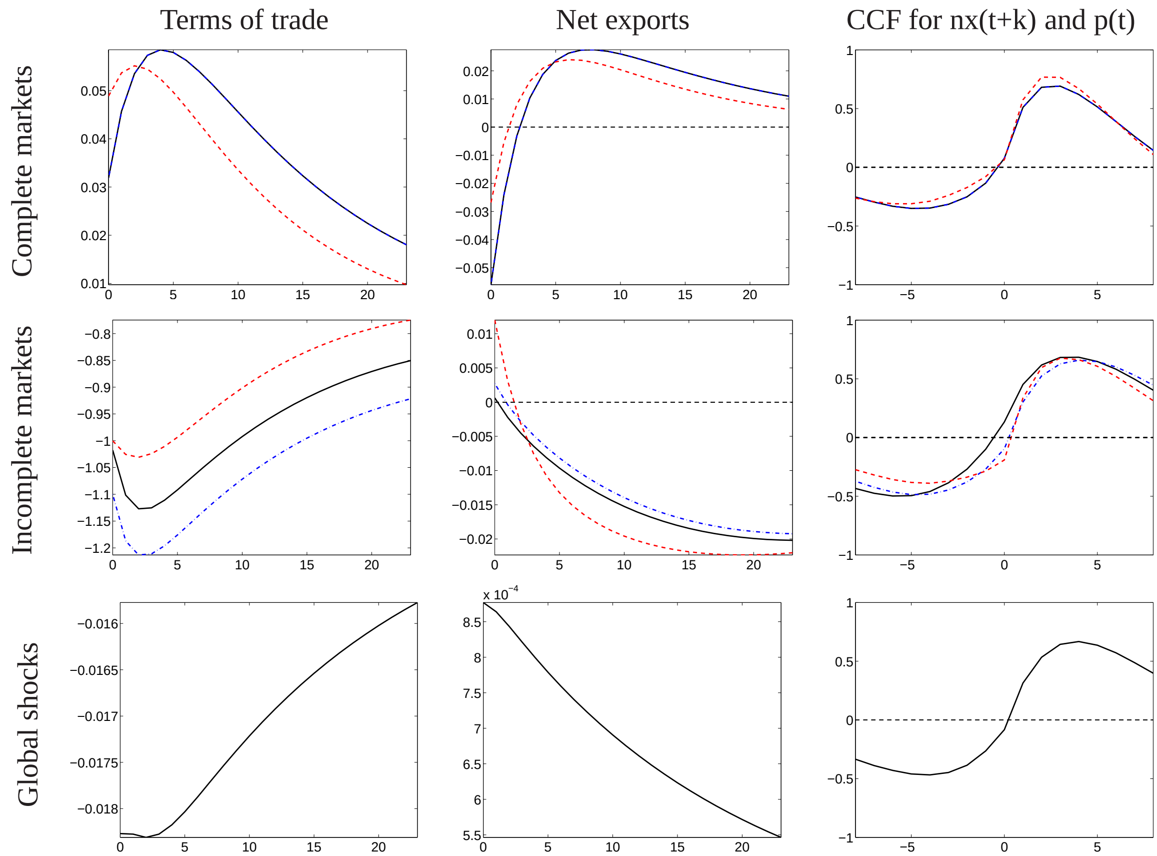

Figure 5: Impulse response and cross-correlation functions for different model specifications. *Notes:* First two rows consider effects of a country-specific (relative) 0.5% technology shock, third row considers 0.5% global shock; solid lines display results for baseline case; dashed lines: sticky price case; dashed-dotted line: non-zero net foreign asset position in steady state.

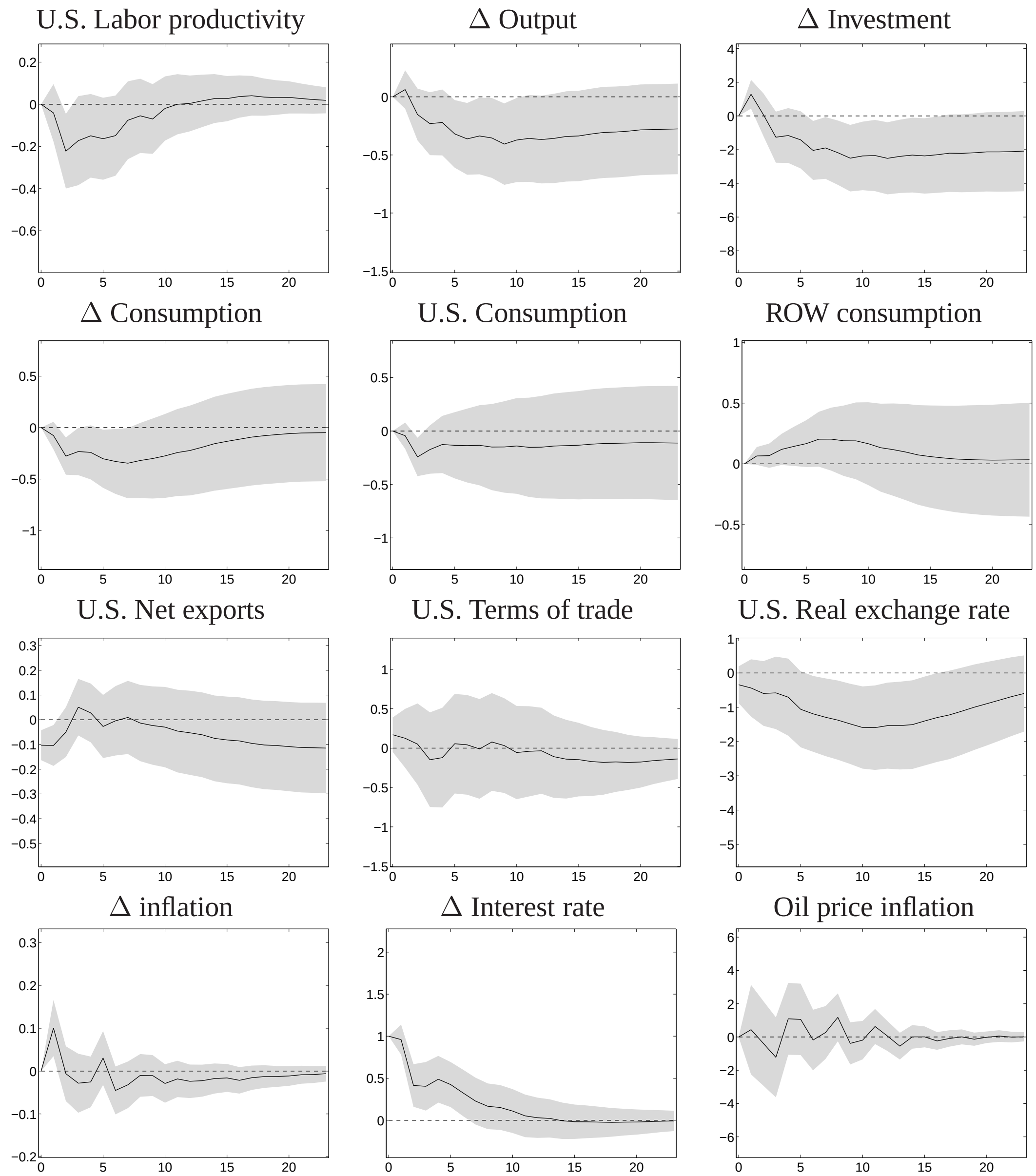

Figure B.1: Effect of monetary policy shock. *Notes:* monetary policy shock is an exogenous increases in (relative) short-term interest rate; responses are measured as described below Figure 2 in main text.

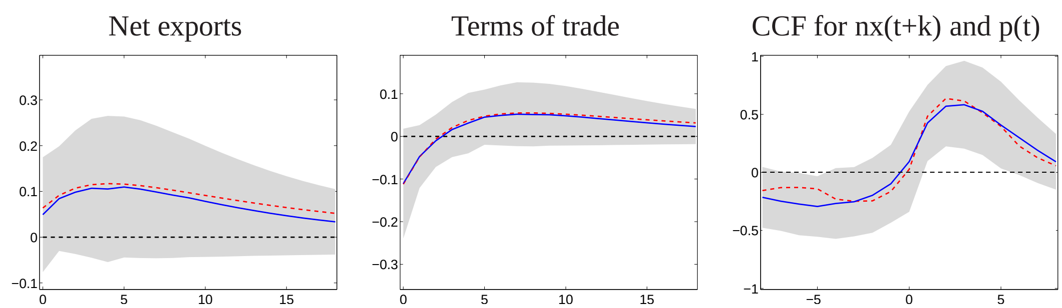

Figure B.2: Performance of VAR model. *Notes:* Estimated (straight line) vs. true (dashed line) responses to one percent increase in domestic technology with bootstrapped 90 percent confidence intervals (shaded area); right panel: ccf for trade balance (t+k) and the terms of trade (t) (k measured on the horizontal axis)

Table 1: Business cycle fluctuations

	Standard deviation relative to Δ output		Business cycle variance decomposition	
	Unconditional	Conditional	Technology shocks	Monetary policy shocks
Terms of trade	2.03	2.43 (1.21)	0.10 (0.11)	0.01 (0.03)
Net exports	0.36	0.42 (0.16)	0.13 (0.11)	0.09 (0.04)
Δ Investment	5.66	3.98 (3.72)	0.14 (0.13)	0.07 (0.05)
Δ Consumption	0.88	1.01 (0.62)	0.10 (0.15)	0.08 (0.07)
Δ Output	–	–	0.08 (0.13)	0.07 (0.05)

Notes: 'Δ' indicates that variable is in relative terms (U.S. vs. ROW). All statistics are computed on HP-filtered series using a smoothing parameter of 1600. Left panel: standard deviations are relative to standard deviation of relative output. Conditional values are computed on counterfactual time series obtained from feeding identified technology shocks into the baseline VAR model. Right panel: fraction of variance accounted for by technology shocks and relative monetary policy shocks, respectively; results are computed using the estimated VAR model where monetary policy shocks are identified in addition to technology shocks; standard errors in parentheses are obtained by bootstrap sampling.

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	
Matching selected moments:	Complete	Incomplete
Elasticity of substitution between intermediate goods	$\sigma = 3.089$	0.230
Investment adjustment costs	$\chi = 0.000$	0.348
Autoregressive coefficient of technology	$\rho = 0.688$	0.987
Loss function:	7.134	6.981

Notes: Standard parameter values are taken from BKK. Values for parameters in the second part of the table are obtained by solving the objective (14); the last line gives its value in the optimum.

Table 3: Key volatilities conditional on technology shocks

	VAR model	Business cycle model calibrated under	
		Complete markets	Incomplete markets
Terms of trade	2.41 (1.38)	0.13	2.75
Net exports	0.42 (0.16)	0.13	0.02
Δ Investment	3.92 (0.99)	4.28	3.27
Δ Consumption	1.01 (0.62)	0.17	1.16

Notes: 'Δ' indicates that variable is in relative terms (U.S. vs. ROW). Entries denote standard deviation scaled by standard deviation of Δ output. All statistics are computed on HP-filtered series using a smoothing parameter of 1600. Left panel: see table 1.

Table 4: Dynamic wealth effects

		Complete markets	Incomplete markets	Counterfactual
Transfer	Home	0.24	0.50	0.24
	Foreign	0.24	-0.03	0.23
Consumption	Home	0.07	0.16	0.08
	Foreign	0.07	-0.01	0.07
Labor	Home	-0.17	-0.35	-0.17
	Foreign	-0.17	0.02	-0.16

Notes: Dynamic wealth effect of a permanent 0.5% shock to technology at home expressed in transfer payments and their effects on consumption and hours; Transfers, measured in percent of steady-state consumption, induce the same change in lifetime utility as the shock. Counterfactual: Parameter values of the complete markets calibration, but incomplete markets.