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International Risk-Sharing and the Transmission of Productivity Shocks[1]

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Abstract

A central puzzle in international finance is that real exchange rates are volatile and, in stark contradiction to efficient risk-sharing, negatively correlated with relative consumptions across countries. This paper shows that a model with incomplete markets and a low price elasticity of imports can account for these properties of real exchange rates. The low price elasticity stems from introducing distribution services, which drive a wedge between producer and consumer prices and lowers the impact of terms-of-trade changes on optimal agents' decisions.

In our model, two very different patterns of the international transmission of productivity shocks generate the observed degree of risk-sharing: one associated with an improvement, the other with a worsening of the country's terms of trade and real exchange rate. We provide VAR evidence on the effect of technology shocks to U.S. manufacturing, identified through long-run restrictions, in support of the first transmission pattern. These findings are at odds with the presumption that terms-of-trade movements foster international risk-pooling.

JEL classification: F32, F33, F41

Keywords: incomplete asset markets, distribution margin, consumption-real exchange rate anomaly.

1 Introduction

International macroeconomists have long brooded over several empirical puzzles, struggling to reconcile theoretical predictions with the evidence.[1] Why are exchange rates so volatile relative to fundamentals? Why isn't consumption more correlated across countries? Recent research has successfully addressed these questions, showing that international business-cycle models, when augmented with nominal rigidities, are capable of generating very volatile real exchange rates and a realistic pattern of international correlations of consumption.[2]

However, these models still predict a high degree of risk-sharing, namely that the cross-country consumption ratio will be perfectly and positively correlated with the real exchange rate.[3] This prediction has been shown to be at odds with the data: for the OECD countries, the correlation between relative consumption and the real exchange rate is generally low and even negative.[4] This evidence is obviously hard to replicate with models assuming complete international asset markets. But, as emphasized by Chari, Kehoe and McGrattan [2002], it is also an outstanding challenge to models restricting international trade in assets and allowing for different market frictions and imperfections — such as nominal price rigidities.

This paper addresses the following two questions: To what extent can the large fluctuations in real exchange rates and terms of trade that characterize the international economy be related to the observed low degree of international consumption risk-sharing? How does this affect the connection of business cycles across countries in the presence of asset market frictions?

We answer the first question building a two-country model where asset markets are incomplete, and because of a low price elasticity of imports, the terms of trade and the real exchange rate are highly volatile in response to

[1]See Backus, Kehoe and Kydland [1995] and Obstfeld and Rogoff [2001] for a statement of the main puzzles in the international business-cycle literature.

[2]Chari, Kehoe and McGrattan [2002] obtain these results in a model in which prices are sticky in the importer currency.

[3]As discussed in Section 2, this is the main implication of efficient risk-sharing in the presence of real exchange rate fluctuations, rather than a high cross-country correlation of consumption. Intuitively, consumption should be higher (its marginal utility lower) in countries where its relative price is lower.

[4]Backus and Smith [1993] first documented this empirical regularity for the G7 countries.

productivity shocks. An important feature of our model is the presence of distribution services, produced with the intensive use of local inputs. As in Corsetti and Dedola [2002], distributive trade contributes to generate a low price elasticity of imports, while making such elasticity market-specific — so as to account for equilibrium deviations from the law of one price.

If markets are incomplete, large swings in international prices may have large, uninsurable effects on relative wealth. Country-specific shocks that move the terms of trade and the real exchange rate change the equilibrium valuation of domestic income relative to the rest of the world. When calibrated to replicate the U.S. real exchange rate volatility, we find that our model generates a degree of risk-sharing and international spillovers consistent with the data. The predicted correlation between the real exchange rate and relative consumption is negative, and the comovements in aggregates across countries are broadly consistent with those in the data. These results are reasonably robust to extensive sensitivity analysis.

Given this finding, we answer the second question this way. First, we show that our model is capable of generating a low degree of risk-sharing for two very different patterns of the international transmission of productivity shocks, corresponding to two sets of parameters values, both plausible. A crucial condition to achieve the above result is a low enough price elasticity of imports. In our benchmark calibration, for a price elasticity slightly above 1/2, international spillovers in equilibrium are large and positive. A productivity increase in Home tradables leads to a large depreciation of the terms of trade and the real exchange rate, reducing relative domestic wealth and driving foreign consumption above domestic consumption. We call this the *positive transmission.*

For a price elasticity slightly below 1/2, international spillovers are still large but, strikingly, negative. Following a productivity increase, the Home terms of trade and the real exchange rate appreciate, reducing relative wealth and consumption abroad. This occurs because of a combination of an unconventionally sloped demand curve and nontrivial general equilibrium effects. With this low price elasticity, when the terms of trade worsens and Home tradables are cheaper, there is less world demand for them. Because of home bias in consumption, Home tradables are mainly demanded domestically. A terms-of-trade depreciation that reduces relative Home wealth to the extent that this negative effect more than offsets the positive substitution effect will cut world demand. Therefore, a productivity increase in Home tradables has to be matched with an increase in their relative price to generate enough demand to clear world markets. We call this the *negative transmission.*

Second, we ask whether the international transmission of productivity shocks to tradables in the U.S. data bear any resemblance with any of the above mechanisms. We answer this question with structural VARs, applying long-run restrictions to identify technology shocks to manufacturing (our measure of tradables) — in doing so, we extend the seminal work by Galí [1999] to an open-economy framework. Our VAR analysis yields two important findings. First, we provide novel evidence in support of the prediction of a *negative conditional correlation* between relative consumption and the real exchange rate. Following a permanent positive shock to U.S. labor productivity in manufacturing, U.S. output and consumption increase relative to the rest of the world, while the real exchange rate appreciates.[5] Second, the same productivity shock *improves the terms of trade*, as suggested by our model under the negative transmission.

In light of these results, the Backus-Smith evidence appears less puzzling yet more consequential for the construction of open-economy general-equilibrium models. Our VAR evidence questions the international transmission mechanism in a wide class of general equilibrium models, with potentially strong implications for welfare and policy analysis. In fact, if a positive shock to productivity translates into a higher, rather than lower, international price of exports, foreign consumers will be negatively affected. Terms of trade movements do not contribute at all to consumption risk-sharing. Gains from international portfolio diversification may thus well be large, relative to the predictions of standard open-economy models.

The text is organized as follows. The following section presents the key implications of standard two-goods open-economy models for the link between relative consumption and the real exchange rate and briefly summarizes some evidence on their correlations for industrialized countries. In Section 3, we introduce the model, whose calibration is presented in Section 4.

[5] Conditional on a productivity increase in tradables, an appreciation of the real exchange rate and an increase in domestic consumption are also predicted by the Balassa-Samuelson model with no terms-of-trade effect (because of perfect substitutability of domestic and foreign tradables). Yet, as shown by our numerical experiments, a model with high elasticity of substitution between tradables cannot generate either enough volatility of the real exchange rate and terms of trade or replicate the negative Backus-Smith unconditonal correlation.

Section 5 explores the quantitative predictions of the model in numerical experiments. Section 6 presents the VAR evidence on the effects of productivity shocks in the open-economy. Finally, Section 7 summarizes and qualifies the paper results, suggesting directions for further research.

2 International consumption risk-sharing: reconsidering the Backus-Smith puzzle

In this section, we explore the real exchange rate-consumption puzzle in some detail. First, we restate Backus and Smith's [1993] risk-sharing result and have a brief look at the data for most OECD countries. We then study a simple endowment two-country, two-good model under financial autarky. In this framework, we show that the link between relative consumption and the real exchange rate can have either sign depending on the price-elasticity of tradables: a low elasticity can generate the negative pattern observed in the data. Moreover, a low price elasticity has other desirable implications. Since it means that quantities are not very sensitive to price movements, this feature is consistent with high volatility of the real exchange rate and the terms of trade, relative to fundamentals and endogenous macroeconomic variables — in accord with an important set of stylized facts of the international economy.

2.1 Stating the puzzle

As pointed out by Backus and Smith [1993], an internationally efficient allocation implies that the marginal utility of consumption, weighted by the real exchange rate, should be equalized across countries:

$$\frac{P_t^*}{P_t} U'\left(C_t\right) = U'\left(C_t^*\right), \tag{1}$$

where the real exchange rate (RER) is customarily defined as the ratio of foreign (P_t^*) to domestic (P_t) price level, expressed in the same currency units (via the nominal exchange rate), U denotes the utility function, and C_t and C_t^* denote domestic and foreign consumption, respectively. Intuitively, a benevolent social planner would allocate consumption across countries such that the marginal benefits from an extra unit of foreign consumption equal its marginal costs, which is given by the domestic marginal utility of consumption times the relative price of C_t^* in terms of C_t, the real exchange rate $\frac{P_t^*}{P_t}$.

If a complete set of state-contingent securities is available, the above condition holds in a decentralized equilibrium independently of trade frictions and good-market imperfections (including shipping and trade costs, as well as sticky prices or wages) that can cause large deviations from the law of one price and purchasing power parity (PPP). It is only when PPP holds (i.e., $RER = 1$) that efficient risk-sharing implies equalization of the *ex-post* marginal utility of consumption — consistent with the simple notion that complete markets imply high correlation of cross-country consumption.

Under the additional assumption that agents have preferences represented by a time-separable, constant-relative-risk-aversion utility function of the form $\frac{C^{1-\sigma} - 1}{1-\sigma}$, with $\sigma > 0$, (1) translates into a condition on the correlation between the (logarithm of the) ratio of Home to Foreign consumption and the (logarithm of the) real exchange rate.[6] Against the hypothesis of perfect risk-sharing, many studies have found this correlation to be significantly below one, or even negative, in the data (in addition to Backus and Smith [1993], see for instance Kollman [1995] and Ravn [2001]).

Table 1 reports the correlation between real exchange rates and relative consumption for OECD countries relative to the U.S. and to an aggregate of the OECD countries, respectively. Since we use annual data, we report the correlations for both the HP-filtered and first-differenced series. As shown in this table, real exchange rates and relative consumption are negatively correlated for most OECD countries. The highest correlation is as low as 0.53 (Switzerland vis-à-vis the rest of the OECD countries), and most correlations are in fact negative — the average of the table entries is -0.25.

Consistent with other studies, Table 1 presents strong *prima facie* evi-

[6]Clearly, one can envision shocks, e.g., taste shocks, that move the level of consumption and the marginal utility of consumption in opposite directions. These shocks may help in attenuating the link between the real exchange rate and relative consumption. However, it would be quantitatively quite challenging to identify shocks with this property, which can account for the low or negative correlations reported in Table 1 below.

Likewise, Lewis [1996] rejects nonseparability of preferences between consumption and leisure as an empirical explanation of the low degree of risk-sharing.

dence against open-economy models with a complete set of state-contingent securities. Given that debt and equity trade, the most transparent means of consumption smoothing, are far less operative across borders than within them, a natural first step to account for the apparent lack of risk-sharing is to assume that financial assets exist only on a limited number of securities. Restricting the set of assets agents have available to hedge country-specific risk breaks the tight link between real exchange rates and the marginal utility of consumption implied by (1). It should be therefore an essential feature of models trying to account for the stylized facts summarized in Table 1.

Unfortunately, it is now well understood that allowing for incomplete markets may not be enough to bring models in line with these facts. First, in the face of transitory shocks, trade in an international, uncontingent bond may provide agents with an instrument to largely duplicate the efficient allocation (e.g., see Baxter and Crucini [1993]). Intuitively, if agents in one country get a positive output shock, they will want to lend to the rest of the world, thus driving cross-country consumption toward equalization. This result has generally been derived in one-good models, abstracting from movements in relative prices. However, terms-of-trade movements can also impinge on the international transmission of shocks and even ensure perfect risk-sharing independently of trade in financial assets — a point underscored by Cole and Obstfeld [1991] and Corsetti and Pesenti [2001a,b]. Positive productivity shocks in one country that moderately depreciate the domestic terms of trade and the real exchange rate will allow consumption abroad to increase to some extent, though less than domestic consumption, thus resulting in a tight positive link between international relative prices and cross-country consumption.

In light of these considerations, the so-called Backus-Smith anomaly provides an important test of open economy models with frictions — more specifically, of the international transmission mechanism envisioned in the theory. To account for the anomaly, it seems that terms-of-trade movements need to hinder risk-sharing and reduce the scope for risk-pooling in response to country-specific shocks provided by the assets available to agents. In what follows, following Cole and Obstfeld [1991], we will develop a simple setting to provide an intuitive account of the determinants of the comovements between the real exchange rate and relative consumption with incomplete financial markets.

2.2 Model-related issues in the literature

This section presents and discusses a few key equilibrium relations, with the goal of providing an intuitive yet analytical account of the mechanisms underlying our numerical results below. We will first relate the sign and magnitude of the transmission of shocks across borders to the price elasticity of tradables. We then conclude with a brief discussion of the links between the international transmission and risk-sharing.

Assume a two-country world. For the sake of clarity, it is convenient to focus on the extreme case of financial autarky, whereas the trade balance must be identically equal to zero period by period. Furthermore, we abstract from nontradables altogether. Under these simplifications, utility from consumption is

$$C_t = C_{\mathrm{T},t}(j) = \left[a_{\mathrm{H}}^{1-\rho} C_{\mathrm{H},t}(j)^{\rho} + (1-a_{\mathrm{H}})^{1-\rho} C_{\mathrm{F},t}(j)^{\rho}\right]^{\frac{1}{\rho}},$$

where $C_{\mathrm{H},t}$ ($C_{\mathrm{F},t}$) is the domestic consumption of Home (Foreign) produced good and a_{H} (a_{F}^{*}) is the share of the domestically produced good in the consumption aggregator.

The domestic and international demand for the Home produced tradable are given by

$$\begin{aligned} C_{\mathrm{H}} &= \frac{a_{\mathrm{H}} P_{\mathrm{H}}^{\frac{\rho}{\rho-1}-1}}{a_{\mathrm{H}} P_{\mathrm{H}}^{\frac{\rho}{\rho-1}} + (1-a_{\mathrm{H}}) P_{\mathrm{F}}^{\frac{\rho}{\rho-1}}} PC = \frac{a_{\mathrm{H}}}{a_{\mathrm{H}} + (1-a_{\mathrm{H}}) \tau^{\frac{\rho}{\rho-1}}} \frac{PC}{P_{\mathrm{H}}}, \\ C_{\mathrm{H}}^{*} &= \frac{(1-a_{\mathrm{F}}^{*}) P_{\mathrm{H}}^{\frac{\rho}{\rho-1}-1}}{a_{\mathrm{F}}^{*} P_{\mathrm{F}}^{\frac{\rho}{\rho-1}} + (1-a_{\mathrm{F}}^{*}) P_{\mathrm{H}}^{\frac{\rho}{\rho-1}}} P^{*}C^{*} = \frac{(1-a_{\mathrm{F}}^{*})}{a_{\mathrm{F}}^{*} \tau^{\frac{\rho}{\rho-1}} + (1-a_{\mathrm{F}}^{*})} \frac{P^{*}C^{*}}{P_{\mathrm{H}}}, \end{aligned}$$

where $P_{\mathrm{H},t}$ ($P_{\mathrm{F},t}$) is the price of the Home (Foreign) good, $\tau = \dfrac{P_{\mathrm{F}}}{P_{\mathrm{H}}}$ is the terms of trade, and the consumption-based price indices P and P^{*} are

$$\begin{aligned} P &= \left[a_{\mathrm{H}} P_{\mathrm{H}}^{\frac{\rho}{\rho-1}} + (1-a_{\mathrm{H}}) P_{\mathrm{F}}^{\frac{\rho}{\rho-1}}\right]^{\frac{\rho-1}{\rho}}, \\ P^{*} &= \left[(1-a_{\mathrm{F}}^{*}) P_{\mathrm{H}}^{*\frac{\rho}{\rho-1}} + a_{\mathrm{F}}^{*} P_{\mathrm{F}}^{*\frac{\rho}{\rho-1}}\right]^{\frac{\rho-1}{\rho}}. \end{aligned}$$

Owing to financial autarky, consumption expenditure has to equal current income, i.e., $\dfrac{PC}{P_{\mathrm{H}}} = Y_{\mathrm{H}}$ and $\dfrac{P^{*}C^{*}}{P_{\mathrm{H}}} = \dfrac{P_{\mathrm{F}}}{P_{\mathrm{H}}} Y_{\mathrm{F}}^{*}$. From these expressions, domestic and foreign demand for Home goods simplify to:

$$\begin{aligned} C_{\mathrm{H}} &= \frac{a_{\mathrm{H}}}{a_{\mathrm{H}} + (1 - a_{\mathrm{H}})\,\tau^{1-\omega}} Y_{\mathrm{H}}, \\ C_{\mathrm{H}}^{*} &= \frac{1 - a_{\mathrm{H}}^{*}}{a_{\mathrm{H}}^{*}\tau^{1-\omega} + (1 - a_{\mathrm{H}}^{*})} \tau Y_{\mathrm{F}}^{*}. \end{aligned}$$

where the demand's price elasticity coincides with $\omega = (1-\rho)^{-1}$, the elasticity of substitution across the two goods. Taking the derivative with respect to the relative price of Foreign goods in terms of Home goods τ:

$$\frac{\partial C_{\mathrm{H}}}{\partial \tau} = (\omega - 1) \frac{a_{\mathrm{H}}\,(1 - a_{\mathrm{H}})\,\tau^{-\omega}}{\left[a_{\mathrm{H}} + (1 - a_{\mathrm{H}})\,\tau^{1-\omega}\right]^{2}} Y_{\mathrm{H}} > 0 \iff \omega > 1,$$

it is clear that the Home demand C_{H} can be either increasing or decreasing in the terms of trade τ, depending on ω. When $\omega > 1$, a fall in the relative price of the domestic tradable — an increase in τ — will increase its domestic demand — in this case the positive substitution effect from lower prices is larger in absolute value than its negative income effect from a lower valuation of Y_{H}.[7] Conversely, when $\omega < 1$ the negative income effect will more than offset the substitution effect. Thus, a terms-of-trade depreciation will bring about a decrease in the domestic demand of the Home tradable.

As regards the Foreign demand for the Home goods, instead, substitution (SE) and income effects (IE) are always both positive. Namely, the Slutsky equation for the Foreign demand C_{H}^{*} for Home tradables is

$$\frac{\partial C_{\mathrm{H}}^{*}}{\partial \tau} = \left[\underbrace{\omega a_{\mathrm{F}}^{*}\tau^{1-\omega}}_{SE} + \underbrace{1 - a_{\mathrm{F}}^{*}}_{IE} \right] \frac{1 - a_{\mathrm{F}}^{*}}{\left(a_{\mathrm{F}}^{*}\tau^{1-\omega} + 1 - a_{\mathrm{F}}^{*}\right)^{2}} Y_{\mathrm{F}}^{*} > 0;$$

[7] Formally, by a straightforward derivation of the Slutsky equation, the substitution effect is given by the derivative of the compensated demand function x_{H}, for a given utility level $u = \left[a_{\mathrm{H}} + (1 - a_{\mathrm{H}})\,\tau^{1-\omega}\right]^{-\frac{1}{1-\omega}} Y$:

$$x_{\mathrm{H}} = a_{\mathrm{H}} \left[a_{\mathrm{H}} + (1 - a_{\mathrm{H}})\,\tau^{1-\omega}\right]^{\frac{\omega}{1-\omega}} u,$$

so that

$$\frac{\partial x_{\mathrm{H}}}{\partial \tau} = \omega \frac{a_{\mathrm{H}}\,(1 - a_{\mathrm{H}})\,\tau^{-\omega}}{\left[a_{\mathrm{H}} + (1 - a_{\mathrm{H}})\,\tau^{1-\omega}\right]^{2}} Y_{\mathrm{H}}.$$

since $a_F^* \leq 1$, C_H^* is always increasing in τ for any ω.

These very basic relations have notable general equilibrium implications.[8] First, for $\omega < 1$ but large enough that world demand $C_H + C_H^*$ is still increasing in τ (i.e., decreasing in the relative price of Home goods), an increase in domestic output Y_H will bring about a terms-of-trade depreciation and a fall in domestic consumption relative to its foreign counterpart. If ω is reduced further, however, world demand will be falling in τ (): an increase in Y_H will be matched by a corresponding increase in world demand only if the terms of trade *appreciates*. Domestic consumption will then rise relative to its Foreign counterpart. Second, for those values of ω, around which the slope of world demand changes sign and is then rather flat, a small change in Y_H will bring about large movements in the terms of trade and the real exchange rate.

We can explore these points more formally by looking at the equilibrium condition in the market for Home tradables:

$$\begin{aligned} Y_H &= C_H + C_H^* \\ Y_H &= \frac{a_H}{a_H + (1-a_H)\,\tau^{1-\omega}} Y_H + \frac{1-a_F^*}{a_F^* \tau^{1-\omega} + (1-a_F^*)} \tau Y_F^*. \end{aligned}$$

By taking a log-linear approximation around a symmetric equilibrium in which $a_H = a_F^*$ and $Y_H = Y_F^*$, the link between relative output (endowment) changes and the terms of trade and the real exchange rate in general equilibrium can be expressed as

$$\widehat{\tau} = \frac{\widehat{Y_H} - \widehat{Y_F^*}}{1 - 2a_H\,(1-\omega)}, \tag{2}$$

$$\widehat{RER} = \frac{2a_H - 1}{1 - 2a_H(1-\omega)} \left(\widehat{Y_H} - \widehat{Y_F^*}\right), \tag{3}$$

where a "$\frown$" represents a variable's percentage deviation from the symmetric values. In this simple setting PPP deviations are due only to cross-country differences in the consumption basket.

For given movements in relative output, the coefficients in the above expressions change sign with ω and the volatility of the terms of trade and the real exchange rate follow a hump-shaped pattern. This feature will be

[8] We are grateful to Fabrizio Perri for suggesting this line of reasoning.

important for understanding our empirical and theoretical results in the following sections. Allowing for home bias in consumption ($a_{\mathrm{H}} > 1/2$) and $0 < \omega < \dfrac{2a_{\mathrm{H}} - 1}{2a_{\mathrm{H}}} < 1$, the ratio on the right-hand side of (3) is negative and *increasing* in ω. The domestic and world demand schedules for Home tradables are negatively sloped, so that the real exchange rate and the terms of trade will move in opposite direction with respect to relative output.

Following a productivity increase, the Home terms of trade and the real exchange rate appreciate. With this low price elasticity, when the terms of trade worsen and Home tradables are cheaper, there is less world demand for them. Owing to home bias in consumption, Home tradables are mainly demanded domestically. A terms-of-trade depreciation reduces relative Home income so much that this negative income effect more than offsets the positive substitution effect and makes world demand decreasing in the terms of trade. Hence, a productivity increase in Home tradables has to be matched with an increase in their relative price to generate enough demand to clear world markets.

Moreover, since the substitution effect is increasing in the price elasticity ω the demand schedule becomes flatter for larger $\omega' s$. Hence, in this region a higher ω raises (in absolute value) the coefficient relating $\widehat{Y}_{\mathrm{H}} - \widehat{Y}^*_{\mathrm{F}}$ to $\widehat{RER}$ and $\widehat{\tau}$: the higher the price elasticity, the higher the volatility of the real exchange rate and the terms of trade in terms of changes in relative output.

As the price elasticity gets larger, so that $\omega > \dfrac{2a_{\mathrm{H}} - 1}{2a_{\mathrm{H}}} > 0$, the ratio on the right-hand side of (3) becomes positive and *decreasing* in ω. The slope of world demand is now positive and increasing in ω. As a result, a higher ω reduces the coefficient relating $\widehat{Y}_{\mathrm{H}} - \widehat{Y}^*_{\mathrm{F}}$ to $\widehat{RER}$ and $\widehat{\tau}$: in this region, the larger the price elasticity, the lower the volatility of the real exchange rate and the terms of trade in terms of changes in relative output.

2.3 Implications for risk-sharing

What are the implications of the above pattern of the international transmission via relative prices for risk-sharing and the comovements between the real exchange rate and relative consumption? With incomplete markets, the scope for insurance against country-specific shocks is limited, and agents will be exposed to relative wealth shocks induced by equilibrium movements in international relative prices. But as emphasized by the above analysis, relative price movements are major determinants of both the sign and the magnitude of the international transmission of shocks.

From the balance-trade condition it is easy to write relative consumption as a function of the terms of trade:

$$\tau C_{\mathrm{F}} = C_{\mathrm{H}}^{*} \Longleftrightarrow \tau \left(\frac{P_{\mathrm{F}}}{P}\right)^{-\omega} C = \left(\frac{P_{\mathrm{F}}^{*}}{P^{*}}\right)^{-\omega} C^{*} \Longleftrightarrow \frac{C}{C^{*}} = \left[\frac{a_{\mathrm{F}}^{*}\tau^{1-\omega} + 1 - a_{\mathrm{F}}^{*}}{a_{\mathrm{H}}\tau^{\omega} + (1-a_{\mathrm{H}})\,\tau}\right]^{\frac{\omega}{1-\omega}};$$

we can then derive a log-linearized relationship between the real exchange rate and relative consumption as follows:

$$\widehat{RER} = \frac{2a_{\mathrm{H}} - 1}{2a_{\mathrm{H}}\omega - 1}\left(\widehat{C} - \widehat{C^{*}}\right). \tag{4}$$

The crucial result highlighted by the above expression is that the relation between real exchange rates and relative consumption can also have either sign, depending again on the values of a_{H} and ω. It will be *negative* if, for a given share of the domestically produced good in the consumption aggregator a_{H}, the elasticity of substitution ω is low enough. Specifically, assume again that countries' preferences are characterized by home bias in consumption. Then the ratio on the right-hand side of (4) will be negative when $\omega < \dfrac{1}{2a_{\mathrm{H}}} < 1$.

Based on the mechanism discussed above, when $\dfrac{2a_{\mathrm{H}} - 1}{2a_{\mathrm{H}}} < \omega$ a Home endowment (productivity) shock reduces the relative price of Home exports, worsening the Home terms of trade and depreciating the Home real exchange rate. With $\omega > \dfrac{1}{2a_{\mathrm{H}}}$, consumption abroad increases by less than consumption at Home. Contrast our simplified model presented above with the benchmark economies constructed by Cole and Obstfeld [1991] and Corsetti and Pesenti [2001a], where $\omega = 1$ and $a_{\mathrm{H}} = a_{\mathrm{H}}^{*} = \frac{1}{2}$. These contributions build examples where productivity shocks to tradables bring about relative price movements that exactly offset changes in output, leaving cross-country relative wealth unchanged. The international transmission is positive: higher productivity in the Home country lowers international prices of the Home goods one-to-one with the increase in Home output, raising consumption abroad in proportion to consumption at Home. Even under financial autarky, agents can achieve the optimal degree of international risk-sharing.

But optimal risk-sharing via terms-of-trade movements is likely to be an extreme case, since according to the evidence, both the sign of the transmission and the magnitude of relative price movements appear to be different from what is required to support an efficient allocation. Even when the international transmission is positive — as is required in the examples by Cole and Obstfeld and Corsetti and Pesenti — equilibrium fluctuations in real exchange rates and the terms of trade of the magnitude of those observed in the data may be *excessive* relative to the benchmark case of optimal transmission.

As the price elasticity is reduced and $\frac{2a_{\mathrm{H}}-1}{2a_{\mathrm{H}}} < \omega < \frac{1}{2a_{\mathrm{H}}}$, the fall in the international price of the Home goods is more pronounced in equilibrium, and consumption rises *more* in the Foreign country than in the Home country. The international transmission of shocks is extremely positive, with a magnified spillover in favor of the countries that do not experience the endowment shock. Notably, an "excessively positive" international transmission of productivity shock generates an empirical pattern of low risk-sharing that rationalizes the Backus-Smith anomaly: a terms of trade and real exchange rate depreciation will be reflected in a reduction in relative consumption across countries. Likewise, a further reduction in $\omega < \frac{2a_{\mathrm{H}}-1}{2a_{\mathrm{H}}}$ entails a negative international transmission. A terms of trade appreciation in response to a productivity shock raises domestic real import and consumption, while reducing wealth abroad — again in line with the Backus-Smith evidence, but at odds with risk-sharing via relative price movements.

Before concluding this section, we note that nominal rigidities do not seem to play a crucial role in explaining the Backus-Smith puzzle — as pointed out by Chari, Kehoe and McGrattan [2002] in a model with local currency pricing (LCP) (exporters fix their price in the currency of the market of destination). To see why, consider a version of our simple economy with production and price stickiness in the form of LCP. It is easy to see that the correlation between the real exchange rate and relative consumption will remain strongly positive, irrespective of the value of ω. Under financial autarky, the balanced trade condition implies that relative consumption is proportional to the inverse of the terms of trade. A shock that increases Home consumption relative to Foreign consumption must thus appreciate the terms of trade to ensure zero net exports; but since prices are fixed in local currencies, a terms of trade appreciation can only occur because of a nominal currency depreciation that, again owing to local-currency price-stickiness, will coincide with a real depreciation! In what follows, we will abstract from nominal rigidities.

To summarize, we have built a stylized two-country, two-good model with financial autarky and endowment (productivity) shocks. We have shown that, depending on the price elasticity of imports., the correlation between relative consumption and the real exchange rate can have either sign. By emphasizing a low price elasticity, the analysis suggests what we see as a promising modelling strategy to address the Backus-Smith anomaly. As shown below, our strategy consists of building a model in which a low price elasticity of imports is not exclusively related to a low elasticity of substitution between tradables ω but is an implication of assuming a realistic structure of the goods market with distributive trade. In the next sections we will study the quantitative implications of our model, assuming that only uncontingent bonds are traded internationally. In particular, we want to check whether versions of the model, with and without a retailing sector, can give rise to international spillovers of productivity shocks consistent with the low degree of risk-sharing implied by the Backus-Smith anomaly, when ω is set to match the observed volatility of the real exchange rate relative to that of output. This framework leads to empirically plausible predictions that find striking support in the data.

3 The model

Our world economy consists of two countries of equal size, denoted H and F, each specialized in the production of an intermediate, perfectly tradable good. In addition, each country produces a nontradable good. The nontraded good is either consumed or used to make intermediate tradable goods H and F available to domestic consumers. In what follows, we describe our setup focusing on the Home country, with the understanding that similar expressions also characterize the Foreign economy — whereas starred variables refer to Foreign firms and households.

3.1 Firms' problem

Firms producing Home tradables (H) and Home nontradables (N) are perfectly competitive and employ a technology that combines domestic labor and capital inputs, according to the following Cobb-Douglas functions:

$$Y_{\mathrm{H}} = Z_{\mathrm{H}} K_{\mathrm{H}}^{1-\nu} L_{\mathrm{H}}^{\nu}$$

and

$$Y_{\mathrm{N}} = Z_{\mathrm{N}} K_{\mathrm{N}}^{1-\zeta} L_{\mathrm{N}}^{\zeta},$$

where Z_{H} and Z_{N} are exogenous random disturbance following a statistical process to be determined below. We assume that capital and labor are freely mobile across sectors.

The problems of the firms in the traded and nontraded goods' sectors are standard: they hire labor and capital from households to maximize their profits:

$$\pi_{\mathrm{H}} = \overline{P}_{\mathrm{H},t} Y_{\mathrm{H},t} - W_t L_{\mathrm{H},t} - R_t K_{\mathrm{H},t}$$

and

$$\pi_{\mathrm{N}} = P_{\mathrm{N},t} Y_{\mathrm{N},t} - W_t L_{\mathrm{N},t} - R_t K_{\mathrm{N},t},$$

where $\overline{P}_{\mathrm{H},t}$ is the *wholesale* price of the Home traded good and $P_{\mathrm{N},t}$ is the price of the nontraded good. W_t denote the wage rate, while R_t represents the capital rental rate.

Firms in the distribution sector operate under perfect competition. They buy tradable goods and distribute them to consumers using nontraded goods as the only input in production.[9] In the spirit of Erceg and Levin [1996] and Burstein, Neves and Rebelo [2001], we assume that bringing one unit of traded goods to Home (Foreign) consumers requires η units of the Home (Foreign) nontraded goods.

[9]For symmetry, distribution costs should also be incurred in bringing nontraded goods to consumers. For notational and computational simplicity, we ignore distribution costs for nontraded goods, noting that these are homothetic to change in the level of productivity in the nontradable sector.

3.2 The Household's Problem

3.2.1 Preferences

The representative Home agent in the model maximizes the expected value of her lifetime utility, given by:

$$E\left\{\sum_{t=0}^{\infty} U\left[C_t, \ell_t\right] \exp\left[\sum_{\tau=0}^{t-1} -\nu\left(U\left[C_t, \ell_t\right]\right)\right]\right\} \tag{5}$$

where instantaneous utility U is a function of a consumption index, C, and leisure, $(1-\ell)$. Foreign agents' preferences are symmetrically defined. These preferences guarantee the presence of a locally unique steady state, independent of initial conditions.[10]

The full consumption basket, C_t, in each country is defined by the following CES aggregator

$$C_t \equiv \left[a_{\mathrm{T}}^{1-\phi} C_{\mathrm{T},t}{}^{\phi} + a_{\mathrm{N}}^{1-\phi} C_{\mathrm{N},t}{}^{\phi}\right]^{\frac{1}{\phi}}, \qquad \phi < 1, \tag{6}$$

where a_{T} and a_{N} are the weights on the consumption of traded and nontraded goods, respectively. ϕ is the constant elasticity of substitution between $C_{\mathrm{N},t}$ and $C_{\mathrm{T},t}$, a consumption index of traded goods given by

$$C_{\mathrm{T},t} \equiv \left[a_{\mathrm{H}}^{1-\rho} C_{\mathrm{H},t}{}^{\rho} + a_{\mathrm{F}}^{1-\rho} C_{\mathrm{F},t}{}^{\rho}\right]^{\frac{1}{\rho}}, \qquad \rho < 1. \tag{7}$$

The weights on Home and Foreign traded goods are given by a_{H} and a_{F} and ρ determines the constant elasticity of substitution between these goods.

3.2.2 Price indexes

A notable feature of our specification is that, because of distribution costs, there is a wedge between the producer price and the consumer price of each good. Let $\overline{P}_{\mathrm{H},t}$ and $P_{\mathrm{H},t}$ denote the price of the Home traded good at the *producer* and *consumer* level, respectively. Let $P_{\mathrm{N},t}$ denotes the price of the

[10]A unique invariant distribution of wealth under these preferences will allow us to use standard numerical techniques to solve the model when only a non-contingent bond is traded internationally (see Obstfeld [1990], Mendoza [1991], and Schmitt-Grohé and Uribe [2001]).

nontraded good that is necessary to distribute the tradable one. With competitive firms in the distribution sector, the consumer price of the traded good is simply

$$P_{\mathrm{H},t} = \overline{P}_{\mathrm{H},t} + \eta P_{\mathrm{N},t}. \tag{8}$$

We hereafter write the utility-based price indexes of tradables:

$$P_{\mathrm{T},t} = \left[a_{\mathrm{H}} P_{\mathrm{H},t}{}^{\frac{\rho}{\rho-1}} + a_{\mathrm{F}} P_{\mathrm{F},t}{}^{\frac{\rho}{\rho-1}} \right]^{\frac{\rho-1}{\rho}}, \tag{9}$$

and the utility-based CPIs:

$$P_t = \left[a_{\mathrm{T}} P_{\mathrm{T},t}{}^{\frac{\phi}{\phi-1}} + a_{\mathrm{N}} P_{\mathrm{N},t}{}^{\frac{\phi}{\phi-1}} \right]^{\frac{\phi-1}{\phi}}. \tag{10}$$

Foreign prices, denoted with an asterisk and expressed in the same currency as Home prices, are similarly defined. Observe that the law of one price holds at the wholesale level but not at the consumer level, so that $\overline{P}_{\mathrm{H},t} = \overline{P}^*_{\mathrm{H},t}$ but $P_{\mathrm{H},t} \neq P^*_{\mathrm{H},t}$. In the remainder of the paper, the price of Home aggregate consumption P_t will be taken as the numeraire. Hence, the real exchange rate will be given by the price of Foreign aggregate consumption P^*_t in terms of P_t.

3.2.3 Budget constraints and asset markets

Home and Foreign agents hold an international bond, B_{H}, which pays in units of Home aggregate consumption and is zero in net supply. They derive income from working, $W_t \ell_t$, from renting capital to firms, $R_t K_t$, and from the proceeds from holding the international bond, $(1 + r_t) B_{\mathrm{H},t}$, where r_t is the real bond's yield, paid at the beginning of period t but known at time $t - 1$. The individual flow budget constraint for the representative agent in the Home country is therefore:[11]

$$P_{\mathrm{H},t} C_{\mathrm{H},t} + P_{\mathrm{F},t} C_{\mathrm{F},t} + P_{\mathrm{N},t} C_{\mathrm{N},t} + B_{\mathrm{H},t+1} + \overline{P}_{\mathrm{H},t} I_{\mathrm{H},t} \leq W_t \ell_t + R_t K_t + (1 + r_t) B_{\mathrm{H},t}, \tag{11}$$

[11] The notation conventions follow Obstfeld and Rogoff [1996, ch.10]. Specifically, $B_{\mathrm{H},t}$ denotes the Home agent's bonds accumulated during period $t - 1$ and carried over into period t.

Note that we assume that investment is carried out in Home tradable goods and that the capital stock, K, can be freely reallocated between the traded (K_{H}) and nontraded (K_{N}) sectors:[12]

$$K = K_{\mathrm{H}} + K_{\mathrm{N}}.$$

Moreover, contrary to the consumption of tradables, we assume that investment is not subject to distribution services. The price of investment is therefore the wholesale price of the domestic traded good, $\overline{P}_{\mathrm{H},t}$. The law of motion for the aggregate capital stock is given by:

$$K_{t+1} = I_{\mathrm{H},t} + (1-\delta)K_t \tag{12}$$

The household's problem then consists of maximizing lifetime utility, defined by (5), subject to the constraints (11) and (12).

3.3 Competitive Equilibrium

Let $s_t = \{B_{\mathrm{H}}; \mathbf{Z}\}$ denote the state of the world at time t, where $\mathbf{Z} = \{Z_{\mathrm{H}}, Z_{\mathrm{F}}, Z_{\mathrm{N}}, Z^*_{\mathrm{N}}\}$. A competitive equilibrium is a set of Home agent's decision rules $C_{\mathrm{H}}(s)$, $C_{\mathrm{F}}(s)$, $C_{\mathrm{N}}(s)$, $I_{\mathrm{H}}(s)$, $l(s)$, $B_{\mathrm{H}}(s)$; a set of Foreign agent's decision rules $C^*_{\mathrm{H}}(s)$, $C^*_{\mathrm{F}}(s)$, $C^*_{\mathrm{N}}(s)$, $I^*_{\mathrm{H}}(s)$, $l^*(s)$, $B^*_{\mathrm{H}}(s)$; a set of Home firms' decision rules $K_{\mathrm{H}}(s)$, $K_{\mathrm{N}}(s)$, $L_{\mathrm{H}}(s)$, $L_{\mathrm{N}}(s)$; a set of Foreign firms' decision rules $K^*_{\mathrm{H}}(s)$, $K^*_{\mathrm{N}}(s)$, $L^*_{\mathrm{H}}(s)$, $L^*_{\mathrm{N}}(s)$; a set of pricing functions $P_{\mathrm{H}}(s)$, $P_{\mathrm{F}}(s)$, $\overline{P}_{\mathrm{H}}(s)$, $\overline{P}_{\mathrm{F}}(s)$, $P_{\mathrm{N}}(s)$, $P^*_{\mathrm{N}}(s)$, $W(s)$, $W^*(s)$, $R(s)$, $R^*(s)$, $r(s)$ such that (i) the agents' decision rules solve the households' problems; (ii) the firms' decision rules solve the firms' problems; and (iii) the market-clearing conditions hold.

3.4 The volatility of international relative prices

We conclude this section showing how the introduction of a distribution sector affects the volatility of the terms of trade and the sources of real exchange rate fluctuations. From the representative consumer's first-order conditions (regardless of frictions in the asset and goods markets), optimality

[12] We also conduct sensitivity analysis on our specification of the investment process, below.

requires that the relative price of the imported good in terms of the domestic tradable at consumer level be equal to the ratio of marginal utilities:

$$\frac{P_{\mathrm{F},t}}{P_{\mathrm{H},t}} = \frac{\overline{P}_{\mathrm{F},t} + \eta P_{\mathrm{N},t}}{\overline{P}_{\mathrm{H},t} + \eta P_{\mathrm{N},t}} = \frac{1 - a_{\mathrm{H}}}{a_{\mathrm{H}}} \left(\frac{C_{\mathrm{H},t}}{C_{\mathrm{F},t}} \right)^{\frac{1}{\omega}}, \tag{13}$$

where $\omega = (1 - \rho)^{-1}$ is equal to the elasticity of substitution between Home and Foreign tradables in the consumption aggregator $C_{\mathrm{T},t}$. Note that $C_{\mathrm{H},t}/C_{\mathrm{F},t}$ is the inverse of the ratio of real imports to nonexported tradable output net of investment. In analogy to the literature, we will refer to this as the (tradable) import ratio. Also, because of distribution costs, the relative price of imports in terms of Home exports at the consumer level does not coincide with the terms of trade $\overline{P}_{\mathrm{F},t}/\overline{P}_{\mathrm{H},t}$ — as does in most standard models (e.g. Lucas [1982]).

Let μ denote the size of the distribution margin in steady state, i.e.,

$$\mu = \frac{\eta}{1 + \eta}$$

By log-linearizing (13), we get:

$$\widehat{TOT_t} = \frac{1}{\omega (1 - \mu)} \left(\widehat{C_{\mathrm{H},t}} - \widehat{C_{\mathrm{F},t}} \right). \tag{14}$$

where a "$\widehat{\ }$" represents a variable's percentage deviation from its steady state; TOT denotes the terms of trade (measured at the producer-price level).

Equation (14) sheds light on how both ω and μ impinge on the *magnitude* of the international transmission of country-specific shocks through the equilibrium changes in the terms of trade. First, it is well known that, for any given change in $\widehat{C_{\mathrm{H},t}} - \widehat{C_{\mathrm{F},t}}$, a lower ω transpires into larger changes in the terms of trade. An interesting and novel feature of our model is that a larger distribution margin μ (i.e., a larger η) has a similar effect. Accounting for distributive trade introduces a novel amplification channel of fluctuations in international relative prices for given variability in real quantities.

Second, for given ω and μ, large movements in the difference between the real consumption of domestic and imported tradables $\widehat{C_{\mathrm{H},t}} - \widehat{C_{\mathrm{F},t}}$ (the inverse of the import ratio) will be reflected in highly volatile terms of trade and deviations from the law of one price.[13] Interestingly, it will be shown below

[13] In particular, the tradable import ratio will display more variability, *ceteris paribus*, when changes in absorption of domestic and imported tradables have opposite sign.

that in the U.S. data the absolute standard deviation of this ratio is very close to that of the terms of trade (4.13 and 3.68 per cent, respectively).

A final observation is in order, concerning real exchange-rate fluctuations. They reflect movements in the terms of trade and in the relative price of non-traded goods. This is clearly shown by the following log-linear form of the real exchange rate:

$$\widehat{RER_t} = (1-\mu)(2a_{\mathrm{H}}-1)\widehat{TOT_t} + \Omega\left(\widehat{q_t^*} - \widehat{q_t}\right) + \mu\widehat{P_{\mathrm{N},t}^*}, \tag{15}$$

where Ω is a positive constant and q represents the relative price of non-traded goods.[14] In our numerical results below, it is the first component that turns out to dominate real exchange-rate movements. In other words, in our framework the real exchange rate inherits the pattern of volatility in the terms of trade so that TOT and RER are always tightly related.

4 Model calibration

In the next section we employ standard numerical techniques to solve the model developed above, with the goal of quantifying the link between the real exchange rate and the level of consumption across countries when the economy is hit by shocks to sectoral productivity.

Table 2 reports our benchmark calibration, which we assume symmetric across countries. Several parameters' values are similar to those adopted by Stockman and Tesar [1995] and Chari, Kehoe, and McGrattan [2002], who calibrate their models to the United States relative to a set of OECD countries. Throughout the exercise, we will carry out sensitivity analysis and assess the robustness of our results under the benchmark calibration. In particular, we are interested in the sensitivity of our results to changes in the elasticity of substitution for tradables ω.

Productivity shocks We previously defined the exogenous state vector as $\mathbf{Z} \equiv \{Z_{\mathrm{H}}, Z_{\mathrm{F}}, Z_{\mathrm{N}}, Z_{\mathrm{N}}^*\}'$. We assume that disturbances to technology follow a trend-stationary AR(1) process

$$\mathbf{Z}' = \boldsymbol{\lambda}\mathbf{Z} + \mathbf{u}, \tag{16}$$

[14] Namely, $\Omega = a_{\mathrm{N}}\overline{q}^{\frac{\phi}{\phi-1}}/(a_{\mathrm{T}} + a_{\mathrm{N}}\overline{q}^{\frac{\phi}{\phi-1}}) > 0$, where $\overline{q}$ denotes a steady-state value and $\frac{1}{1-\phi}$ is the elasticity of substitution between tradables and nontradables.

whereas $\mathbf{u} \equiv (u_{\mathrm{H}}, u_{\mathrm{F}}, u_{\mathrm{N}}, u_{\mathrm{N}}^{*})$ has variance-covariance matrix $V(\mathbf{u})$, and $\boldsymbol{\lambda}$ is a $4x4$ matrix of coefficients describing the autocorrelation properties of the shocks. Since we assume a symmetric economic structure across countries, we also impose symmetry on the autocorrelation and variance-covariance matrices of the above process.

Consistent with our model and other open-economy studies (e.g., Backus, Kehoe and Kydland [1995]), we identify technology shocks with Solow residuals in each sector, using annual data in manufacturing and services from the OECD STAN database. Since hours are not available for most other OECD countries, we use sectoral data on employment. An appendix describes our data in more detail.

The bottom panel of Table 2 reports our estimates of the parameters describing the process driving productivity. As found by previous studies, our estimate technology shocks are fairly persistent. On the other hand, we find that spillovers across countries and sectors are not negligible.[15]

Preferences and production Consider first the preference parameters. Assuming a utility function of the form:

$$U\left[C_t\left(j\right), \ell_t(j)\right] = \frac{\left[C_t^{\alpha}\left(j\right)\left(1-\ell_t(j)\right)^{1-\alpha}\right]^{1-\sigma}-1}{1-\sigma}, \qquad 0<\alpha<1, \qquad \sigma>0, \tag{17}$$

we set α so that in steady state, one-third of the time endowment is spent working; σ (risk aversion) is set equal to 2. Following Schmitt-Grohe and Uribe [2001], we assume that the endogenous discount factor depends on the average per capita level of consumption, C_t, and hours worked, ℓ_t,and has the following form:

$$\nu\left(U\left[C_t, \ell_t\right]\right) = \ln\left(1+\psi\left[\alpha \ln C_t + (1-\alpha)\ln(1-\ell_t)\right]\right),$$

whereas ψ is chosen such that the steady-state real interest rate is 4 percent per annum, equal to 0.08.

[15] The persistence of the estimated shocks, though in line with estimates both in the closed (e.g., Cooley and Prescott [1995]) and open-economy (Heathcote and Perri [2002]) literature, is higher than that reported by Stockman and Tesar [1995]. The difference can be attributed to the fact that they compute their Solow residuals out of HP-filtered data - while we and most of the literature compute them using data in (log) levels.

The value of ϕ is selected based on the available estimates for the elasticity of substitution between traded and nontraded goods. We use the estimate by Mendoza [1991] of a sample of industrialized countries and set that elasticity equal to 0.74. Stockman and Tesar [1995] estimate a lower elasticity (0.44), but their sample includes both developed and developing countries.

According to the evidence for the U.S. economy in Burstein, Neves and Rebelo [2001], the share of the retail price of traded goods accounted for by local distribution services ranges between 40 percent and 50 percent, depending on the industrial sector. We follow their calibration and set it equal to 50 percent.

As regards the weights of domestic and foreign tradables in the tradables consumption basket (C_{T}), a_{H} and a_{F} (normalized $a_{\mathrm{H}} + a_{\mathrm{F}} = 1$) are chosen such that imports are 5 percent of aggregate output in steady state. This corresponds to the average ratio of U.S. imports from Europe, Canada, and Japan to U.S. GDP between 1960 and 2002. The weight of traded and nontraded goods, a_{T} and a_{N}, are chosen as to match the share of nontradables in U.S. consumption basket. Over the period 1967-2002, this share is equal to 53 percent on average. Consistently, Stockman and Tesar [1995] suggest that the share of nontradables in the consumption basket of the seven largest OECD countries is roughly 50 percent.

The elasticity of substitution between Home and Foreign tradables
The quantitative literature has proposed a variety of values for the elasticity of substitution between traded goods. For instance, Backus, Kydland, and Kehoe [1995] set it equal to 1.5, whereas Heathcote and Perri [2002] estimate it to be 0.9.[16] Here, we set the elasticity of substitution ω to match the volatility of the U.S. real exchange rate relative to that of U.S. output, equal to 3.28 (see Table 4).

Notably, we find two such values for the elasticity ω: $\omega = 0.97$ and $\omega = 1.13$. While apparently close to each other, these values imply quite different dynamics and international transmission patterns for shocks to tradables productivity. These differences will become central to our discussion of the

[16] There is considerable uncertainty regarding the true value of trade elasticities, directly related to this parameter. For instance, Taylor [1993] estimates the value for the U.S. to be 0.39, while Whalley [1985], the study quoted by Backus et al. [1995], reports a value of 1.5. For European countries most empirical studies suggest a value below 1.

evidence in Section 6.

5 Real exchange rate volatility and the international transmission of productivity shocks

In this section, we analyze the unconditional correlation between quantities and international prices, as well as their relative volatilities, when productivity shocks hit both the traded- and the nontraded-good industry simultaneously. Throughout our exercises, we will compute statistics by logging and filtering the model's artificial time series using the Hodrick and Prescott filter and averaging moments across 100 simulations. Our goal is to verify whether our model can match the empirical second moments reported in Tables 3 and 4. The statistics for the data are all computed with the United States as the home country and an aggregate of the OECD comprising the European Union, Japan, and Canada as the foreign country.[17] We have already mentioned that in the data these correlations (volatilities) are substantially lower (higher) than predicted by standard open-economy models.

5.1 Volatilities and correlation properties

Tables 3 and 4 report H-P-filtered statistics for the data, the baseline economy, and some variations on the baseline economy. Overall, we find that the benchmark model, with 50 percent distribution margin, generates volatilities and correlations that match the data qualitatively. The model performs relatively better when ω is set to the lower value 0.97. The real exchange rate and the terms of trade are volatile, highly cross-correlated, and negatively correlated with relative output and consumption. The cross-country correlations of output and consumption are positive, with the former larger than the latter. However, along some dimensions, the model does less well quantitatively: while the correlation between relative consumption and international prices is about right, it generates too negative a correlation between relative output and international prices, too much volatility in the terms of trade, and too little volatility in net exports.

[17] Here we follow Heathcote and Perri [2002]. See the Data Appendix for details.

In Table 3, we see that, remarkably, in our benchmark economy the correlation between relative consumption and the real exchange rate/the terms of trade is negative, as in the data. For instance, when $\omega = 0.97$, the model generates a correlation between relative consumption and the real exchange rate equal to -0.55, very close to -0.45 for the U.S.[18] The correlation between relative consumption and the terms of trade is more negative in our model than in the data (-0.73 and -0.53). These two results are similar under the relatively higher ω. Thus, the level of price elasticity that is consistent with highly volatile international prices brings about a pattern of risk-sharing in line with the data. The link between volatility and risk-sharing, derived in Section 2 in a very simple setting under financial autarky, holds quantitatively in our baseline economy with capital accumulation and international borrowing and lending. The bond available to agents in our model economy is traded only after the resolution of uncertainty and does not provide them with ex-ante insurance against country-specific income shocks but only with the possibility of reallocating wealth and smooth consumption across time.

This (not perfectly) negative correlation is specifically driven by the interaction of productivity shocks across sectors. As discussed in Section 2, when the price elasticity is sufficiently low, a productivity shock to the tradable sector moves the real exchange rate and relative consumption in opposite directions. Conversely, a positive supply shock in the nontraded goods sector — consistent with the Balassa-Samuelson hypothesis — lowers the price of nontradables and therefore depreciates the real exchange rate. The higher consumption of Home nontradables drives up domestic aggregate consumption both in absolute terms and relative to consumption abroad. Hence, *conditional* on shocks to nontradables, the correlation between relative consumption and the real exchange rate is *positive*. The unconditional Backus-Smith correlation predicted by our baseline model can be understood as a weighted average of two *conditional* correlations — but there is no presumption that it should be as low as in the data.

A potentially controversial implication of the model, however, is that a negative correlation between the real exchange rate and relative consumption

[18]The model can also get close to the Backus-Smith statistics even when we look at first-differenced data. As Ravn [2001] argues, the availability of an international bond should imply that the (expected) relative *growth rate* of consumption across countries be positively and strongly correlated with the (expected) *real rate* of currency depreciation. However, in our economy this correlation is -0.47 (-0.58) when ω equals 0.97 (1.13).

corresponds to a different pattern of correlations of the real exchange rate with the relative consumption of sectoral goods. Namely, relative consumption of tradables is more negatively correlated with the real exchange rate than aggregate consumption. The opposite is true for the relative consumption of nontradables. For instance, with $\omega = 0.97$, such correlations are -0.87 for tradables, and 0.14 for nontradables.

Irrespective of the value of ω, in our baseline economy the real exchange rate and the terms of trade are tightly related. Their correlation is positive, though higher than it is in the data (0.97 against 0.6). This is an important result relative to alternative models that — like ours — allow for deviations from the law of one price but do so by assuming sticky prices in the buyer's currency. As argued by Obstfeld and Rogoff [2001], these models can generate high exchange rate volatility as well, but at the cost of inducing a negative correlation between the real exchange rate and the terms of trade.

The terms of trade are very volatile, even more than in the data. With the lower ω its volatility relative to output is 3.06, compared to 1.79 in the data. In this sense, our model thus suggests that high volatility of the international prices *per se* cannot be a measure of their 'disconnect' from fundamentals. In this vein, we see in Table 4 that the volatility of the import ratio (IR), defined as the ratio of real imports to nonexported tradable output net of investment (empirically, we compute this ratio using manufacturing output), has a standard deviation of 4.13 percent in the data. In the two benchmark parameterizations this ratio has a standard deviation of 2.71 and 4.45 percent, respectively. As in Backus et al. [1995] and Heathcote and Perri [2002], the variability of international prices is related to the variability of the IR, which, in turn, is increasing in ω (see equation (14)).[19]

Moreover, with $\omega = 0.97$ the model is consistent with the ranking of variability in international prices observed in the data. The real exchange rate displays higher volatility than the terms of trade owing to the contribution to exchange rate fluctuations of deviations from the law of one price at consumer prices as well as of movements in the relative price of nontradables. This stylized fact has proved very hard to replicate for models that abstract

[19] Interestingly, the data support the tight and negative link between the terms of trade and the real exchange rate, on the one hand, and the import ratio, on the other hand, predicted by the theory. In the data these correlations stand at -0.68 and -0.41, respectively, against -1 and -0.97 predicted by the model with $\omega = 0.97$ — for the higher ω, these statistics are substantially similar (-1 and -0.96).

from the above features (see Heathcoate and Perri [2002]). We found that the relative price of nontradables across countries is not the main driving force behind the high volatility of the model's real exchange rate. First, we see in Table 3 that the volatility of the relative price of nontradables is in line with that in the data. Second, we computed the ratio of the standard deviation of the relative price of nontradables across countries to the standard deviation of the real exchange rate. We found this ratio to be roughly 20 percent, slightly lower than the findings of Betts and Kehoe [2001], who calculate this ratio to be 35 to 44 percent for a weighted average of U.S. bilateral real exchange rates.[20]

Consider now the rest of the statistics for the baseline economy in Table 3 and 4. As is well known, most open-economy models, including those driven by monetary shocks with sticky prices, predict a strong and positive link between real exchange rates and relative output. As Stockman [1998] points out, this prediction is at odds with the data: for instance, in Table 3 that correlation is -0.23. A similar problem also occurs for the theoretical predictions regarding the correlation between the terms of trade and relative output. Our model faces an analogous problem when $\omega = 1.13$. In this case, the correlation between the real exchange rate (the terms of trade) and relative output is 0.75 (0.89). However, movements in relative output are negatively correlated (although more than in the data) with the real exchange rate and the terms of trade, under the relatively lower ω. This is due to the fact that, under this parameterization, productivity increases in the tradable sector bring about an appreciation of the terms of trade and the real exchange rate. Likewise, this mechanism accounts for the ability of the model to match the observed positive correlation between net exports and the real exchange rate and the terms of trade. Below, we discuss in more detail the international transmission in the model.

In Table 4, we see that in the model the cross-country correlation of output is very close to that in the data (0.45 and 0.49 for $\omega = 0.97$), and higher than that of consumption. While the cross-correlation of consumption is lower (0.13 and 0.32), and that of investment and employment higher than in the data (0.47 and 0.46, compared to 0.08 and 0.32), the model does much

[20]Following a different procedure, Engel [1999] finds that deviations from the law of one price in traded goods virtually account for all of the volatility of the U.S. real exchange rate.

better in this dimension than the standard real business cycle model. Backus, Kehoe and Kydland [1995] call this empirical incongruity of the model the quantity anomaly. Even under the assumption that the only traded asset is a bond, this class of models predicts that consumption should be more correlated across countries than output and that the cross-country correlation of investment and labor is negative (see Heathcote and Perri [2002]).

Finally, a minor discrepancy between the benchmark model and the data is that consumption, investment, and employment are only slightly less volatile relative to output in the model than in data, while net exports are half as volatile in the model as in the data (0.29 and 0.63). However,the model with the lower ω is consistent with the countercyclicality of net exports in the data (-0.52 and -0.51).

Tables 3 and 4 also report results for an economy with Arrow-Debreu securities. Since the volatility of the real exchange rate is to a large extent independent of the price elasticity of imports, we only report the results obtained with the lower value 0.97, which basically replicate the parameterization in Stockman and Tesar [1995]. As should be expected, including distribution services in such an environment is not enough to account for the Backus-Smith anomaly. The correlation between the real exchange rate and relative consumption is approximately equal to one.

Nevertheless, this model generates a negative correlation between relative output and the real exchange rate, as is the case in the data. This results from the fact that a productivity increase in Home tradables leads to a rise in relative output, a worsening of the terms of trade, and an appreciation of the real exchange rate. This appreciation stems from an increase in the relative price of nontradables and is associated with a fall in relative consumption in the period following the shock, which is driven by a drop in the consumption of nontradables. On the other hand, contrary to the data, the correlation between the terms of trade and relative output is positive, while that between the real exchange rate and the terms of trade is negative.

5.2 Sensitivity analysis

Besides analyzing our setup absent retailing, we assess the sensitivity of our results to specification of the investment process and to removing the spillovers of the shocks across the two countries. So far, we have assumed that investment is carried out solely in the domestically produced tradable goods. In this section, we will allow for a more general specification in which investment is a composite good of Home and Foreign tradable goods. This is potentially important since it gives households one more means to smooth consumption across countries. Agents can therefore more easily counteract the effects of incomplete asset markets. As a result, we may expect the allocation to be closer to the first-best outcome, which dictates a tight positive link between real exchange rates and relative consumption. We report the results of these exercises in Tables 3 and 4.

Changing the distribution margin and the elasticity of substitution Abstracting from distribution and setting $\eta = 0$, we find again two values of ω (equal to 0.31 and 0.43*)*, as in our benchmark economy, for which the relative volatility of the real exchange rate is the same as in the data. With respect to the Backus-Smith anomaly, the model is still close to the data, with the correlation between the real exchange rate and relative consumption equal to -0.39 (-0.76) for $\omega = 0.31$ (0.43). The reason for this is that the need to combine tradables with retailing lowers the price elasticity of imports, in the same fashion as a low substitutability between Home and Foreign traded goods is associated with a muted response of prices to quantities — see the discussion in Sections 2.2 and 2.3.

With $\eta = 0$, however, there are no deviations from the law of one price, contradicting an important stylized fact of the international economy (e.g., see Engel [1999]). As a consequence, movements in the relative price of nontradables across countries contribute much more to real exchange-rate fluctuations than in the benchmark economy. The standard deviation of the relative price of nontradables across countries is now 78 percent of that of the real exchange rate, a fraction much higher than in the data. Moreover, the relative price of nontradables is now over twice as volatile as in the economy with distribution and in the data (3.66, 1.71 and 1.73).

An interesting issue is whether the Backus-Smith anomaly, in an incomplete-markets framework, can be accounted for by Balassa-Samuelson effects exclusively, according to which exchange-rate fluctuations are driven only by movements in the relative price of nontradables. To address this issue, we report results for $\eta = 0$ and a rather high value of ω, equal to 10 — to make tradables more homogeneous across countries and reduce the role of the terms of trade in exchange-rate fluctuations. With such a high elasticity of substitution, while the correlation between the real exchange rate and relative output becomes very negative (-0.73), that with relative consumption remains close to one, at 0.86. In addition, both the real exchange rate and the terms of trade are a great deal less volatile than output (0.97 and 0.18), while their cross-correlation is substantially lower than in the data (0.21).

Absence of Spillovers Removing the estimated large spillovers of the technology shocks does not substantially affect our main results. Once we calibrate the economy such that the real exchange rate is as volatile as in the data, we again find that the model predicts a negative correlation between relative consumption and the real exchange rate. For instance, under the lower ω, that correlation is -0.59, compared to -0.55 under our benchmark calibration. However, one significant impact of removing spillovers is that consumption is now less correlated across countries.

Changing the investment specification In our last exercise, we verify the sensitivity of our main results to the specification of the investment process. First, we assume that, as for the consumption of traded goods, investment is given by the following CES aggregator

$$I_{\mathrm{T},t}(j) \equiv \left[a_{\mathrm{H}}^{1-\rho} I_{\mathrm{H},t}(j)^{\rho} + a_{\mathrm{F}}^{1-\rho} I_{\mathrm{F},t}(j)^{\rho}\right]^{\frac{1}{\rho}},$$

where $I_{\mathrm{H},t}$ ($I_{\mathrm{F},t}$) is the level of investment in terms of the domestic (imported) traded good. In the exercise, we follow our baseline calibration strategy and set a_{H} and a_{F} such that imports (which now also include investment) are 5 percent of aggregate output in steady state. Throughout, we continue to assume that distribution services are required only to bring tradables to consumers. We report the results in Tables 3 and 4 in the columns under the heading "CES Investment." Second, we report results with an economy with no capital accumulation ("No Capital").

With the more general CES specification, the values of ω needed to reproduce the volatility of the real exchange rate relative to that of output are smaller than under the benchmark calibration. Because goods can now be imported from abroad for investment purposes and since physical investment is not subject to distribution services, a lower elasticity of substitution is necessary to lower the price elasticity of imports. However, the model still succeeds in generating a significant departure from the complete markets outcome. Although the real exchange rate and relative consumption are not as negatively correlated as under our benchmark model, their correlation remains well below unity. For instance, when $\omega = 0.32$, the model predicts a slightly negative correlation of -0.03.

Finally, excluding capital does not substantially change the match of the model along most dimensions. However, consumption becomes more volatile than output (1.09), while the volatility and cross-country correlation of employment are very low (0.12 and -0.52).

5.3 The international transmission of productivity shocks to tradables

In our model, given a value for the distribution margin μ, there are two values of price elasticity and thus of ω that generate a real exchange-rate volatility matching the evidence. In this subsection, we analyze the difference between these two parameterizations, by looking at theoretical impulse responses to a shock to the traded goods sector. In the next section, we will compare these responses to the estimated ones from an identified *VAR*.

Our experiments consist of shocking the exogenous process for sectoral productivity once at date 0, when both countries are at their symmetric, deterministic steady state. The size of the shock is one standard deviation, corresponding to an increase in productivity by 0.4 percentage point. To focus on the effect of productivity innovations in the Home tradable sector, we set the correlation of shocks across sectors and countries equal to zero.

Figure 1 draws the responses of the following economic variables: (a) the real exchange rate; (b) the terms of trade; (c) relative consumption; (d) relative aggregate output; (e) the ratio of net exports to output. The two columns in Figure 1 report impulse responses for $\omega = 0.97$ and $\omega = 1.13$, respectively.

Consider first the impulse responses under the higher ω (first column in the figure). Since for this value of the price elasticity world demand for Home tradables is increasing in its relative price, the increase in the supply of Home traded goods relative to the Foreign goods worsens the Home country's terms of trade. Note that an adverse effect of productivity shocks on the real exchange rate and the terms of trade is predicted by all standard models with product specialization and homothetic preferences (e.g., Lucas [1982] and Backus et al. [1995]).[21] The notable feature of our specification with incomplete markets is that a relatively low price elasticity of imports (also owing to the presence of retailing) magnifies the deterioration of the Home terms of trade and real exchange rate, increasing the ensuing negative wealth effect for the domestic household. As a result, consumption abroad rises by more than domestic consumption, while domestic output rises relative to the foreign one. Thus, the real exchange rate, the terms of trade and relative output on the one hand, and relative consumption on the other move in the opposite direction, as the large terms of trade worsening entails an *excessively positive* transmission of the productivity shock in favor of the Foreign country.

The response of the economy to an innovation to the productivity of the domestic traded sector is widely different when $\omega = 0.97$. In this case, relative output still rises, but the real exchange rate and the terms of trade now appreciate. Remember from Section 2 that for a low enough price elasticity (low enough ω), world demand for Home tradables will be negatively sloped in the terms of trade, owing to a prevailing negative income effect for the domestic household. An increase in the relative supply of Home tradables will thus require in equilibrium a terms-of-trade appreciation to bring about market clearing. And as the terms of trade improve, Home consumption rises by more than Foreign consumption. As a result, the real exchange rate, the terms of trade and relative consumption are again negatively correlated, but now relative output will move in the same direction as relative consumption, though by a lesser amount.

[The wealth effect is therefore crucial in determining the transmission of productivity shocks to tradables across countries. In Table 5, we compute the impact of the wealth effect on the consumption and labor decisions of the Home and Foreign agents, for both values of ω.[22] The table shows that, as

[21] This result is seldom highlighted in models with traded and nontraded goods. A possible explanation is that in these models tradables are very often assumed to be perfectly homogeneous across countries, i.e.. $\omega \rightarrow \infty$, so that there are no terms of trade fluctuations (e.g., see Stockman and Dellas [1989] and Tesar [1993]). With this specification, a technological advance in the traded-good sector typically brings about an appreciation of the domestic currency owing to an increase in the domestic relative price of nontradables, according to the Balassa-Samuelson hypothesis. Notice, however, that these models obviously leave unexplained the terms of trade behavior.

[22] We use the Hicksian decomposition of King [1990], also employed by Baxter and Crucini [1995].

conjectured, the wealth effect switches sign for the two different values of the elasticity of substitution. For the relatively high ω, the Home wealth effect is negative because of the adverse impact of the rise in productivity of Home tradables on the terms of trade. The Home agent cuts consumption and works more, as a result. On the other hand, the wealth effect is positive under the lower parameterization of ω, as the terms of trade appreciate following the shock. In this case the Home agent consumes more and works less.]

To summarize, a productivity shock to the export sector always induces an increase in relative output and (conditional) negative comovements between the real exchange rate, the terms of trade and relative consumption. Depending on the strength of the price-elasticity of imports and thus on the slope of world demand, however, relative consumption can increase or fall in response to a positive shock.

6 Productivity shocks, the real exchange rate and the terms of trade: VAR evidence for the U.S.

In this section we study empirically the comovements between the real exchange rate, the terms of trade, and relative consumption in response to productivity shocks. We adopt a structural VAR approach, extending work by Galí [1999] — where technology shocks are identified via long-run restrictions — to an open-economy context. We focus our study on the U.S. economy vis-à-vis an aggregate of other OECD countries.

A number of recent papers have investigated the effects on closed-economy macroeconomic variables of technology shocks identified using long-run restrictions. Galí [1999] uses the insight from the standard stochastic growth model that only technology shocks should have a permanent effect on labor productivity to identify economy-wide technology shocks in the data, while there are no analogous long-run restrictions with respect to other macroeconomic variables. In particular, other kinds of shocks can have permanent effects on output, consumption, and investment and external variables like the real exchange rate, the terms of trade, and the trade balance.[23]

[23] See Shapiro and Watson [1988], Blanchard and Quah [1989], Altig et al. [2002], and Francis and Ramey [2001], among others. Some open-economy papers, following Blan-

Following these insights, we examine the effects of technology shocks to the U.S. manufacturing sector (a proxy for traded goods) on the real exchange rate, the terms of trade, and relative consumption, by augmenting with these variables the specifications used by the above authors. Moreover, since Chang and Hong [2002] show that using total factor productivity (TFP) instead of labor productivity may affect results for the manufacturing sector, we also assess the robustness of our results to the use of (annual) TFP data. Leaving to the data appendix a more detailed description of data sources, hereafter we briefly describe our approach and discuss the main results.

Over the period 1970 to 2001, we estimate two specifications of the following structural VAR model

$$\begin{bmatrix} \Delta x_t \\ \Delta y_t \end{bmatrix} = \begin{bmatrix} C^{xz}(L) & C^{xm}(L) \\ C^{yz}(L) & C^{ym}(L) \end{bmatrix} \begin{bmatrix} \Delta \varepsilon_t^z \\ \Delta \varepsilon_t^m \end{bmatrix}.$$

where x_t denotes the variable that is assumed to be affected in the long run only by permanent technology shocks, i.e., in our two different specifications, this variable is equal to (the log of) U.S. quarterly manufacturing labor productivity and (the log of) annual manufacturing TFP, respectively, in deviation from labor productivity in an aggregate of other OECD countries; y_t is a 3x1 vector of variables, including (the log of) U.S. consumption relative to that of an aggregate of other OECD countries, (the log of) the U.S. real effective (trade-weighted) exchange rate, and the terms of trade (computed as the nonenergy imports deflator over the exports deflator).

$C(L)$ is a polynomial in the lag operator; ε_t^z denotes the technology shock to manufacturing, and ε_t^m the other structural, non-technology shocks.[24] In addition to the usual assumption that the structural shocks are uncorrelated, positing that $C^{xm}(1) = 0$ is enough to identify ε_t^z. This restricts the unit root in the variable x_t to originate solely in the technology shock. Although not necessary for identification, implicit in this specification is the assumption

chard and Quah [1989], use long-run restrictions derived in the context of the traditional aggregate demand and aggregate supply framework. For instance, Clarida and Galí [1994] identify supply shocks by assuming that demand and monetary shocks do not have long-run effects on relative output levels across countries. While monetary shocks satisfy this assumption in most models, fiscal or preference shocks do not, since they can have long-run effects on output (and hours) in the stochastic growth model.

[24]We include up to four lags for quarterly data and one for annual data, based on a BIC criterion and tests of residual serial correlation.

that all the other variables have a unit root too; this assumption is not rejected by the data over our sample.

Figure 2 shows the effects of the identified technology shocks on the levels of productivity, relative consumption, the real exchange rate, and the terms of trade.[25] The first column is obtained from quarterly data, the second one from annual data. We report standard error bands for the significance levels of 68 percent and 90 percent (corresponding to the darker and lighter shaded areas, respectively).[26]

The first column in Figure 2 shows the impulse responses using Galí's identification scheme, with x_t equal to (relative) U.S. manufacturing labor productivity.[27] Following a positive technology shock to manufacturing, U.S. total consumption increases gradually but permanently relative to the rest of the world. Moreover, the real exchange rate and the terms of trade strongly appreciate on impact and remain permanently stronger, by an amount that is larger in the case of the real exchange rate, but that for both variables outsizes the increase in productivity. The real exchange rate response is somehow less significant in the long run, however.

The second column in Figure 2 reports the effects of a technology shock identified as the only shock that permanently affects TFP in U.S. manufacturing. Our results are broadly robust across different long-run identification schemes. In the annul VAR also a positive technology shock to the U.S. production of tradables appears to lead to an increase in domestic consumption relative to the rest of the world, while improving the terms of trade and appreciating the real exchange rate for at least a year.[28]

To summarize, U.S. consumption relative to the rest of the world and

[25] We also estimated specifications of the model, adding more U.S. and international variables, like GDP, investment, aggregate hours, and net exports. In all cases we obtain very similar results to those discussed in the text.

[26] The standard error bands were computed using a bootstrap Monte Carlo procedure with 500 replications. We thank Yongsung Chang for graciously providing us with his bootstrapping Matlab codes.

[27] Despite the changes in variables and the shorter sample period, the results on productivity and hours are very similar to Galí's results. An identified technology shock to manufacturing leads to an immediate and permanent rise in productivity, while hours worked somehow decline and do not return to near normal for about six quarters.

[28] Using cointegrating techniques, Alquist and Chinn (2002) find that each percentage point increase in the U.S.-Euro area economy-wide labor productivity differential results in a 5-percentage-point real appreciation of the dollar in the long run.

the real exchange rate move in opposite directions, in sharp contrast with the predictions of the perfect risk-sharing hypothesis. Consistent with the Backus-Smith anomaly, the results in this section indicate that following a technology shock to the traded goods' sector, real exchange rates and relative consumption can indeed be negatively correlated. Most interestingly, the appreciation of the real exchange rate, and especially the terms of trade, in response to a positive technology shock to domestic tradables is qualitatively consistent with the transmission mechanism at work in our setup under the lower value of ω. Conversely, it is at odds with the predictions of a vast class of models of international fluctuations, which link increasing world supply of a good to a fall in its relative price.

7 Concluding remarks

In this paper, we develop a model with incomplete asset markets and a low price elasticity of tradables arising from the need to employ distribution services in order to reach final consumers. In numerical exercises with a plausible parameterization of our world economy, we study the international transmission of productivity shocks and account for the high volatility of international prices and the (unconditional) negative link between the real exchange rate and relative consumption observed in the data.

Many contributions in the literature have stressed that movements in the terms of trade in response to country-specific shocks may provide risk insurance to countries specialized in different types of goods. In our model, however, because of deviations from the law of one price and low price-elasticities, these large terms of trade movements are much less effective in providing insurance against production risk and even counterproductive, in the sense of amplifying the wedge in wealth across countries stemming from asymmetric productivity shocks.

Using structural VAR techniques, we apply long-run restrictions to identify productivity shocks to manufacturing (our measure of tradable goods). We find evidence supporting our prediction of a negative conditional correlation between relative consumptions and international relative prices. Following a permanent positive shock to U.S. labor productivity in manufacturing, domestic output and consumption increase relative to the rest of the world, while both the terms of trade and the real exchange rate appreciate, consistent with the predictions of our model. This result is reasonably robust to the definition of the terms of trade and the use of TFP instead of labor productivity.

By showing that the terms of trade appreciate in response to a positive productivity shock to tradables, however, our VAR evidence questions the model of international transmission of productivity shocks in most theoretical and empirical contributions to open macro. This result is a challenge to standard open macro models that predict a drop in the international relative price of domestic tradables, generating some degree of risk-sharing even with severe goods and financial markets segmentation. Moreover, several VAR studies have found that the U.S. real exchange rate and terms of trade depreciate following an expansionary monetary policy shocks.[29] Given the relevance of this issue to our understanding of the international transmission of supply shocks and the mechanism of international risk-sharing, further empirical and theoretical work trying to reconcile these apparently conflicting results would prove extremely helpful.

[29] Clarida and Galí [1994], using long-run restrictions, found that a permanent increase in U.S. relative output appreciates the real exchange rate vis-á-vis Japan and Germany, while an expansionary monetary policy triggers a currency depreciation.

References

[1] Alquist, Ron and Menzie David Chinn [2002]. "The Euro and the Productivity Puzzle: An Alternative Interpretation," mimeo, University of Michigan.

[2] Altig, David, Lawrence J. Christiano, Martin Eichenbaum and Jesper Lindé [2002]. "Technology Shocks and Aggregate Fluctuations," mimeo, Northwestern University.

[3] Backus, David K., Patrick J. Kehoe, and Finn E. Kydland [1995]. "International Business Cycles: Theory and Evidence," in Thomas F. Cooley (ed.) *Frontiers of Business Cycle Research,* Princeton University Press, Princeton, 331-56.

[4] Backus, David K., and Gregor W. Smith, [1993]. "Consumption and Real Exchange Rates in Dynamic Economies with Non-traded Goods," *Journal of International Economics* 35, 297-316.

[5] Baxter, M. and Mario Crucini [1993]. "Explaining Saving/Investment Correlations," *American Economic Review* 83, 416-36.

[6] Baxter, M. and Mario Crucini [1995]. "Business Cycles and the Asset Structure of Foreign Trade," *International Economic Review* 36, 821-54.

[7] Blanchard Olivier J. and Danny Quah [1989]. "The Dynamic Effects of Aggregate Demand and Supply Disturbances," *American Economic Review* 19, 655-73.

[8] Burstein, Ariel T., João Neves, and Sergio Rebelo [2001]. "Distribution Costs and Real Exchange Rate Dynamics During Exchange-Rate-Based Stabilizations," *Journal of Monetary Economics*, forthcoming.

[9] Chang, Yongsung, and Jay H. Hong [2002]. "On the Employment Effect of Technology: Evidence from U.S. Manufacturing for 1958-1996," mimeo, University of Pennsylvania.

[10] Chari, V.V., Patrick J. Kehoe, and Ellen McGrattan [2002]. "Can Sticky Prices Generate Volatile and Persistent Real Exchange Rates?" *Review of Economic Studies* 69, 633-63.

[11] Clarida, Richard, and Jordi Galí [1994]. "Sources of Real Exchange Rate Fluctuations: How Important Are Nominal Shocks?" *Carnegie-Rochester Series in Public Policy* 41, 1-56

[12] Cole, Harold L., and Maurice Obstfeld [1991]. "Commodity Trade and International Risk Sharing: How Much Do Finacial Markets Matter?" *Journal of Monetary Economics* 28, 3-24.

[13] Cooley, Thomas F. and Edward C. Prescott [1995]. "Economic Growth and Business Cycles," in T.F. Cooley and E.C. Prescott, eds, *Frontiers of Business Cycle Research*, (Princeton University Press, Princeton), 1-38.

[14] Corsetti, Giancarlo, and Paolo Pesenti [2001a]. "Welfare and Macroeconomic Interdependence," *Quarterly Journal of Economics*, May.

[15] Corsetti, Giancarlo, and Paolo Pesenti [2001b]. "International Dimensions of Optimal Monetary Policy." National Bureau of Economic Research Working Paper no. 8230.

[16] Corsetti Giancarlo and Luca Dedola [2002], "Macroeconomics of International Price Discrimination," European Central Bank Working Paper No. 176.

[17] Engel, Charles [1999]. "Accounting for Real Exchange Rate Changes," *Journal of Political Economy* 107, 507-38.

[18] Erceg, Chris, and Andrew Levin [1996]. "Structures and the Dynamic Behavior of the Real Exchange Rate," mimeo, Board of Governors of the Federal Reserve System.

[19] Francis, Neville, and Valerie A. Ramey [2001]. "Is the Technology-Driven Real Business Cycle Hypothesis Dead? Shocks and Aggregate Fluctuations Revisited," mimeo, University of California, San Diego.

[20] Galí, Jordi [1999]. "Technology, Employment and the Business Cycle: Do Technology Shocks Explain Aggregate Fluctuations?" *American Economic Review* 89, 249-71.

[21] Heathcote, Jonathan and Fabrizio Perri [2002]. "Financial Autarky and International Business Cycles," *Journal of Monetary Economics* 49, 601-27.

[22] King, Robert G. [1990]. "Value and Capital in the Equilibrium Business Cycle Program," in: L. McKenzie and S. Zamagni, eds., *Value and Capital: Fifty Years Later* (Macmillan, London), 279-309.

[23] Kollman, Robert [1995]. "Consumption, Real Exchange Rates and the Structure of International Asset Markets," *Journal of International Money and Finance* 55, 29-57.

[24] Lewis, Karen K. [1996]. "Puzzles in International Financial Markets," in G.M. Grossman and K. Rogoff, eds., *Handbook of International Economics* (Elsevier, Amsterdam), 1913-71.

[25] Lucas, Robert E., Jr. [1982]. "Interest Rates and Currency Prices in a Two-Country World," *Journal of Monetary Economics* 32, 335-59.

[26] Mendoza, Enrique [1991]. "Real Business Cycles in a Small Open Economy," *American Economic Review* 81(4), 797-818.

[27] Obstfeld, Maurice [1990]. "Intertemporal Dependence, Impatience, and Dynamics," *Journal of Monetary Economics* 26, 45-75.

[28] Obstfeld, Maurice, and Kenneth Rogoff [1996]. *Foundations of International Macroeconomics*, Cambridge, MA: MIT Press.

[29] Obstfeld, Maurice, and Kenneth Rogoff [2001]. "The Six Major Puzzles in International Macroeconomics: Is There a Common Cause?" in Ben Bernanke and Kenneth Rogoff (eds.), *NBER Macroeconomics Annual 2000*, Cambridge, MA: MIT Press.

[30] Ravn, Morten [2001]. "Consumption Dynamics and Real Exchange Rates," mimeo, London Business School.

[31] Schmitt-Grohé, Stephanie and Martín Uribe [2001]. "Closing Small Open Economy Models," forthcoming in the *Journal of International Economics*.

[32] Shapiro, Matthew D., and Mark Watson [1988]. "Sources of Business Cycle Fluctuations," *NBER Macroeconomics Annual 1998*, Cambridge, MA: MIT Press.

[33] Stockman, Alan C. [1998]. "New Evidence Connecting Exchange Rates to Business Cycles," Federal Reserve Bank of Richmond *Economic Quarterly* 84, 73-89.

[34] Stockman, Alan C., and Harris Dellas [1989]. "International Portfolio Nondiversification and Exchange Rate Variability," *Journal of International Economics* 26 (3-4), 271-90.

[35] Stockman, Alan C., and Linda Tesar [1995]. "Tastes and Technology in a Two-Country Model of the Business Cycle: Explaining International Comovements," *American Economic Review* 83, 473-86.

[36] Taylor, John [1993]. *Macroeconomic Policy in a World Economy: From Economic Design to Practical Operation*, New York, NY: Norton.

[37] Tesar, Linda [1993]. "International Risk Sharing and Non-Traded Goods," *Journal of International Economics* 35 (1-2), 69-89.

[38] Whalley, John [1985]. *Trade Liberalization Among Major World Trading Areas,* Cambridge, MA: MIT Press.

A Data Sources

In the estimation of the VAR models we use quarterly data from 1970:1 to 2001:4 and annual data from 1970. For the series on labor productivity (quarterly), total factor productivity (annual), and labor input (quarterly and annual) we use the BLS series "Index of output per hour in manufacturing," "Index of total factor productivity in manufacturing,"and "Index of hours in manufacturing," respectively. Hours are put on a per capita basis by dividing by the population of age 16 and above. The quarterly real wage measure is the BLS measure of nominal hourly compensation in manufacturing divided by the BLS producer price index.

To calibrate the process of the shocks for the Home country labor productivity in tradables and nontradables we use the annual BLS series "Index of output per hour in manufacturing" and "Index of output per hour in private services," respectively. For the Foreign country we use an aggregation of the index of manufacturing output and output in services divided by sectoral total employment for OECD countries obtained from the OECD STAN sectoral database.

U.S. GDP and consumption are chain-weighted 1996 dollar NIPA series from the BEA. World GDP and consumption are constant 1995 PPP dollar series for the total of the OECD countries from the OECD Quarterly National Accounts.

The series for U.S. imports and exports at current and constant prices are NIPA series from the BEA. The series for the U.S. real exchange rate is a trade-weighted measure of the real value of the dollar computed by J.P. Morgan; the series for the U.S. (ex-oil) terms of trade is the ratio of the NIPA (non-oil) import price deflator over the export price deflator from the BEA.

Table 1: Correlations between real exchange rates and relative consumptions[a]

	Correlation			
	HP-Filtered		First-Difference	
Country	U.S.	OECD	U.S.	OECD
Australia	-0.01	0.05	-0.09	-0.13
Austria	-0.35	-0.54	-0.20	-0.30
Belgium	-0.12	0.15	-0.11	0.19
Canada	-0.41	-0.10	-0.20	0.02
Denmark	-0.16	-0.27	-0.20	-0.21
E.U.	-0.30	-0.10	-0.23	-0.04
Finland	-0.27	-0.64	-0.40	-0.55
France	-0.18	0.12	-0.21	-0.01
Germany	-0.27	-0.17	-0.13	0.01
Italy	-0.26	-0.51	-0.27	-0.31
Japan	0.09	0.27	0.04	0.08
South Korea	-0.73	-0.50	-0.79	-0.63
Mexico	-0.73	-0.77	-0.68	-0.74
Netherlands	-0.41	-0.20	-0.30	-0.19
New Zealand	-0.25	-0.37	-0.27	-0.28
Portugal	-0.56	-0.73	-0.48	-0.67
Sweden	-0.52	-0.39	-0.34	-0.29
Spain	-0.60	-0.66	-0.41	-0.38
Switzerland	0.16	0.53	0.09	0.32
Turkey	-0.31	-0.25	-0.34	-0.17
U.K.	-0.47	-0.08	-0.40	-0.04
U.S.	N/A	-0.30	N/A	-0.31
Average	-0.30	-0.24	-0.27	-0.20

[a]Data are from the OECD Main Economic Indicators dataset.

Table 2. Parameter values

Benchmark Model	
Preferences and Technology	
Risk aversion	$\sigma = 2$
Consumption share	$\alpha = 0.34$
Elasticity of substitution between:	
Home and Foreign traded goods	$\frac{1}{1-\rho} = \{0.97, 1.13\}$
traded and non-traded goods	$\frac{1}{1-\phi} = 0.74$
Share of Home Traded goods	$a_{\mathrm{H}} = 0.72$
Share of non-traded goods	$a_{\mathrm{N}} = 0.45$
Elasticity of the discount factor with respect to C and L	$\psi = 0.08$
Distribution Margin	$\eta = 1$

Productivity Shocks

$$\lambda = \begin{bmatrix} 0.78 & 0.11 & 0.19 & 0.31 \\ 0.11 & 0.78 & 0.31 & 0.19 \\ -0.04 & 0.01 & 0.99 & 0.05 \\ 0.01 & 0.04 & 0.05 & 0.99 \end{bmatrix}$$

Variance-Covariance Matrix (in percent)

$$\lambda = \begin{bmatrix} 0.054 & 0.026 & 0.003 & 0.015 \\ 0.026 & 0.054 & 0.015 & 0.003 \\ 0.003 & -0.001 & 0.008 & 0 \\ -0.001 & 0.003 & 0 & 0.008 \end{bmatrix}$$

Table 3. Exchange rates and prices in the theoretical economies[a]

Statistics	Data	Benchmark Economy		Variations on the benchmark economy: Arrow-Debreu Economy	No Spillover		CES Investment		No Capital		No Distribution		
		! = 0:97	! = 1:13	! = 0:97	! = 0:89	! = 1:18	! = 0:32	! = 0:63	! = 0:97	! = 1:05	! = 0:31	! = 0:43	! = 10
Standard deviation relative to GDP													
Real exchange rate	3.28	3.28	3.28	0.79	3.28	3.28	3.28	3.28	3.28	3.28	3.28	3.28	0.97
Terms of trade	1.79	3.06	4.28	0.61	3.12	4.24	2.59	4.19	3.79	4.13	2.76	4.73	0.18
absolute													
Relative price of nontradables	1.73	1.71	1.46	1.24	1.68	1.48	1.33	1.05	1.23	1.23	3.66	2.35	2.60
Cross-correlations													
Between real exchange rate and													
Relative GDPs	-0.23	-0.97	0.75	-0.48	-0.98	0.75	-0.92	0.77	-0.57	0.82	-0.86	0.85	-0.73
Relative consumptions	-0.45	-0.55	-0.53	0.98	-0.59	-0.43	-0.03	0.40	-0.77	0.66	-0.39	-0.76	0.86
Net exports	0.39	0.94	0.95	-0.74	0.94	0.94	0.84	0.96	0.99	0.99	0.98	0.98	0.35
Terms of trade	0.60	0.97	0.97	-0.12	0.96	0.96	0.99	0.99	0.95	0.99	0.99	0.99	0.21
Between terms of trade and													
Relative GDPs	-0.20	-0.91	0.89	0.82	-0.89	0.90	-0.92	0.83	-0.33	0.93	-0.86	0.88	0.31
Relative consumptions	-0.53	-0.73	-0.72	0.03	-0.77	-0.64	-0.18	0.27	-0.57	0.82	-0.50	-0.85	0.62
Net exports	0.43	0.99	0.99	0.73	0.99	0.99	0.91	0.99	0.97	0.99	0.99	0.99	0.99

[a] RER is the real exchange rate, TOT is the terms of trade.

Table 4. Business cycle statistics in the theoretical economies[a]

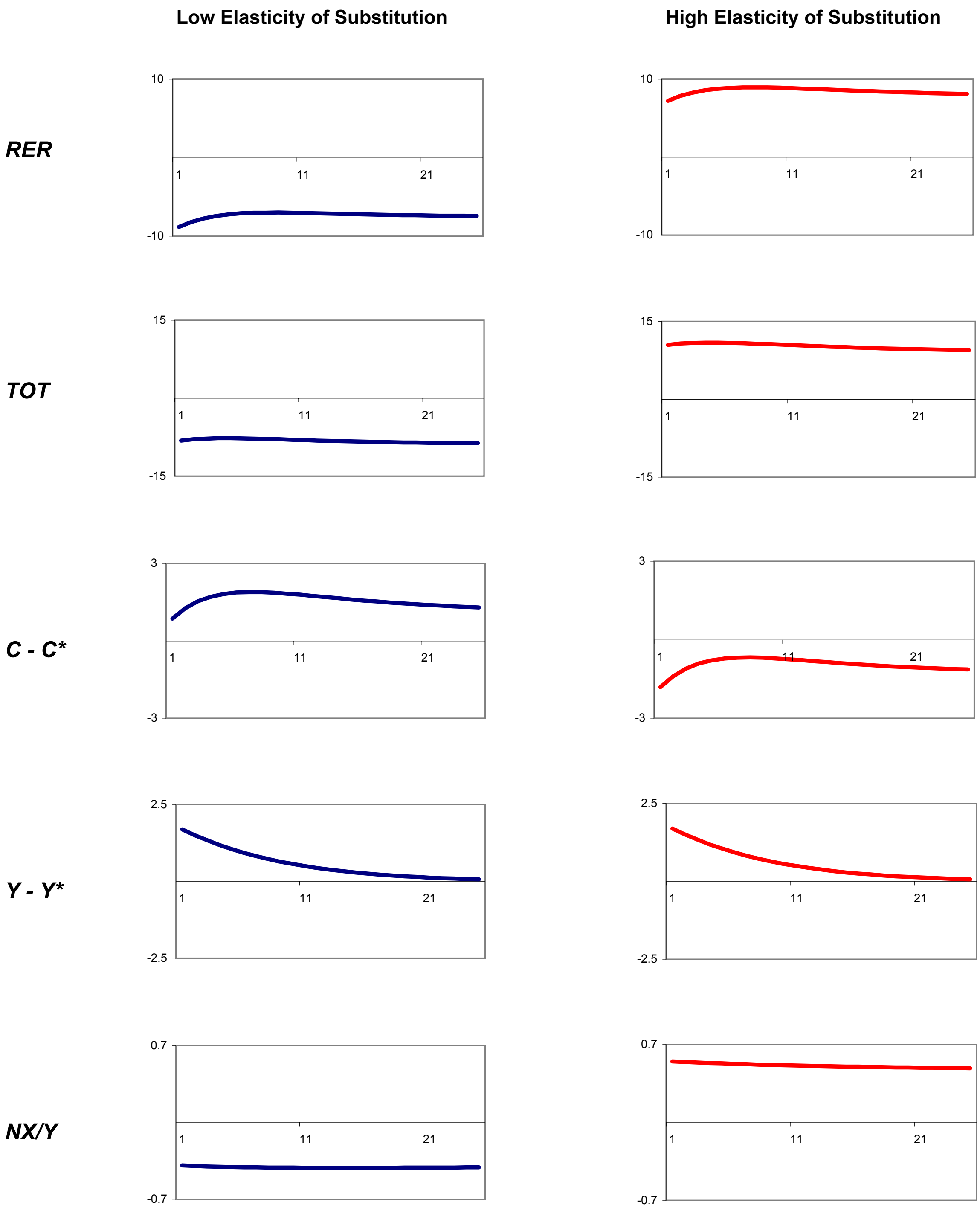
Statistics	Data	Benchmark Economy		Variations on the benchmark economy: Arrow-Debreu Economy	No Spillover		CES Investment		No Capital		No Distribution		
		! = 0:97	! = 1:13	! = 0:97	! = 0:89	! = 1:18	! = 0:32	! = 0:63	! = 0:97	! = 1:05	! = 0:31	! = 0:43	! = 10
Standard deviation relative to GDP													
Consumption	0.92	0.65	0.55	0.55	0.62	0.50	0.58	0.57	1.09	0.92	0.55	0.68	0.52
Investment	4.25	3.87	3.86	3.88	3.74	3.73	4.25	3.63			3.88	3.90	3.92
Employment	1.09	0.67	0.68	0.67	0.64	0.64	0.68	0.61	0.12	0.10	0.67	0.68	0.68
absolute													
Import ratio	4.13	2.71	4.45	0.54	2.54	4.61	0.79	2.43	2.25	2.69	1.57	3.75	3.48
Net exports over GDP	0.63	0.29	0.40	0.04	0.28	0.40	0.05	0.08	0.25	0.21	0.28	0.42	0.23
Cross-correlations													
Between foreign and domestic													
GDP	0.49	0.45	0.43	0.45	0.44	0.42	0.22	0.33	0.49	0.50	0.45	0.43	0.37
Consumption	0.32	0.13	0.14	0.49	-0.12	0.08	0.31	0.68	0.28	0.71	0.38	-0.15	0.50
Investment	0.08	0.47	0.45	0.47	0.48	0.46	0.02	0.50			0.46	0.43	0.35
Employment	0.32	0.46	0.41	0.46	0.48	0.42	0.25	0.65	-0.52	-0.30	0.47	0.41	0.34
Between net exports and GDP	-0.51	-0.52	0.56	0.58	-0.56	0.61	-0.52	0.49	-0.36	0.56	-0.62	0.62	0.15

[a] $! = \frac{1}{1 ¡ ½}$ denotes the elasticity of substitution between Home and Foreign traded goods.

Table 5. Wealth Effects From Shock to Tradables

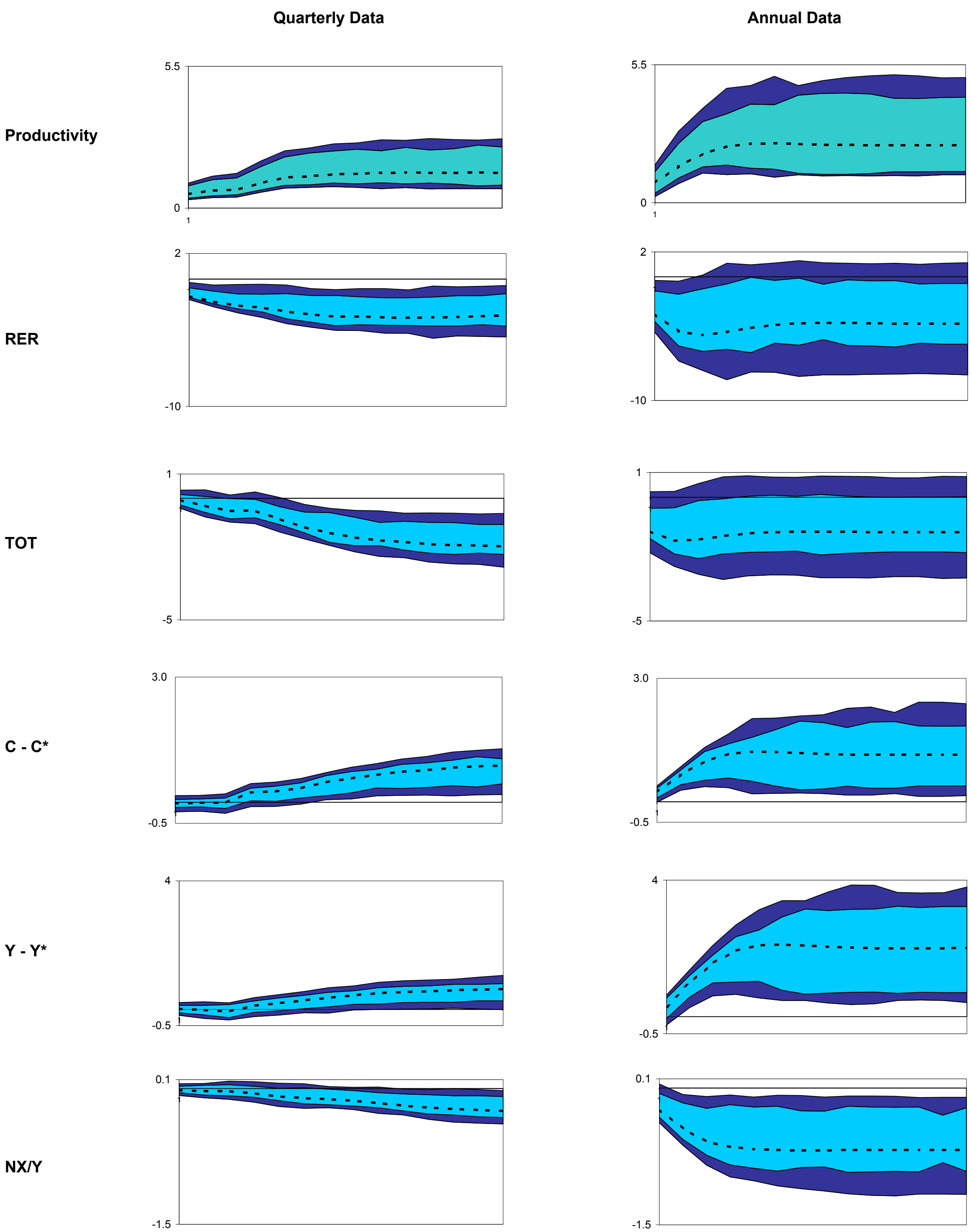
	Wealth Effect: Consumption (in goods unit)		Wealth Effect: Labor (in percent)	
	Home	Foreign	Home	Foreign
Elasticity of Substitution				
$\omega = 0.97$	0.00090	-0.00060	-0.6757	0.4536
$\omega = 1.13$	-0.00050	0.00080	0.3387	-0.5599

Figure 1
Theoretical Responses to a Technology Shock in the Traded-Goods Sector



All series are in percent.

Figure 2
Impulse Responses to a Technology Shock in the Traded-Goods Sector



All series are in percent.