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 cross-country consumption ratios. This paper shows that a standard international business cycle model with incomplete asset markets and a low price elasticity of tradables can account quantitatively for these properties of real exchange rates. The low price elasticity stems from distribution services, intensive in local inputs, which drive a wedge between producer and consumer prices and lower the impact of terms-of-trade changes on optimal agents' decisions.

Two very different patterns of the international transmission of positive technology shocks generate the observed degree of risk-sharing: one associated with a strengthening, the other with a deterioration of the terms of trade and real exchange rate. Suggestive evidence on the effect of productivity changes in U.S. manufacturing is found in support of the first transmission pattern, questioning the presumption that terms-of-trade movements invariably foster international risk-pooling.

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Introduction

The development of international financial markets in the last decades has provided households with an increasing number of instruments to insure their consumption streams against country-specific shocks. Nonetheless, a large body of evidence weighs in against an efficient degree of international risk-pooling.[1] While there are different possible ways to build empirical analysis of international risk sharing, a crucial testable implication in a world economy characterized by large deviations from purchasing power parity is that domestic households should consume more when their consumption basket is relatively cheap.[2] As first shown by Backus and Smith [1993], this is clearly at odds with the data. For most OECD countries, the correlation between relative consumption and the real exchange rate (i.e., the relative price of consumption across countries) is generally low, and even negative. The most striking illustration of such finding is presented in Figure 1, plotting (the log of) quarterly U.S. consumption relative to the other OECD countries and the U.S. real trade-weighted exchange rate in the period 1973-2001. The swings in the dollar in real terms are not associated with movements of the consumption ratio in the same direction; on the contrary the two variables tend to comove negatively. So, why isn't domestic consumption higher relative to foreign consumption when its relative price is lower?

An obvious element in the explanation is that international financial markets are not developed enough. Yet, theory offers convincing arguments to doubt that incomplete asset markets per se be sufficient to bring open economy models in line with the Backus-Smith evidence on (the lack of) risk sharing. To start with, Cole and Obstfeld [1991] call attention on the role of movements in the terms of trade in insuring against production risk independently of trade in assets. In addition, several contributions have shown that the equilibrium allocation in economies that only trade in international, uncontingent bonds may be quite close to the first best (e.g. see Baxter and Crucini [1993]). In fact, trade in bonds insures that the real rate of currency depreciation and the growth rate of relative consumption are highly and positively correlated in expectations, although not necessarily period by period ex-post, as is the case when markets are complete.

In light of these considerations, the Backus-Smith evidence provides an important challenge to dynamic general equilibrium models. To account for it, the envisioned international transmission mechanism should be consistent with international price movements that hinder risk-sharing, and reduce the scope for risk-pooling against country-specific shocks provided by the assets available

[1] E.g., see Lewis [1996].

[2] As discussed in Section 2, this is the main implication of efficient risk-sharing in the presence of real exchange rate (PPP) fluctuations — as opposed to a high cross-country correlation of consumption.

to agents. This way, if risk-sharing is only partial, large swings in international prices may have large, uninsurable effects on relative wealth.

In this paper, we study the link between the high exchange rate volatility characteristic of the international economy (the exchange rate volatility puzzle) and the observed low degree of international consumption risk-sharing (the Backus-Smith puzzle), deriving implications for the connection of business cycles across countries. First, we build a two-country model similar to that of Stockman and Tesar [1995], but in which asset markets are incomplete and, as in Burstein, Eichenbaum and Rebelo [2003] and Corsetti and Dedola [2002], the introduction of distribution services produced with the intensive use of local inputs contributes to generate a realistically low price elasticity of tradables. In this setting, the terms of trade and the real exchange rate are highly volatile in response to productivity shocks. Second, we complement our model with statistical evidence on the US economy, investigating the response of the real exchange rate and the terms of trade to innovations to productivity in the data.

Our theoretical and numerical analysis yields two novel and important results. *First*, when we calibrate our model to match the U.S. real exchange rate volatility, we find that it generates a low degree of risk-sharing. The predicted correlation between the real exchange rate and relative consumption is negative, and the comovements in aggregates across countries are broadly in line with those in the data. The main predictions of the model are robust to extensive sensitivity analysis.

Second, depending on the value of the price elasticity of tradables, our model predicts a low degree of risk-sharing for two very different patterns of the international transmission of productivity shocks, each corresponding to a plausible set of parameters values. In our benchmark calibration, for a price elasticity slightly above 1/2, international spillovers in equilibrium are large and positive. This *positive transmission* is a standard prediction of the international business cycle literature: a productivity increase in the domestic tradable sector leads to a deterioration of the terms of trade and a depreciation of the real exchange rate. However, in our baseline economy the deterioration is so large on impact that relative domestic wealth decreases, driving foreign consumption above domestic consumption. For a price elasticity slightly below 1/2, instead, international spillovers are still large but — strikingly — negative. With a *negative transmission*, following a productivity increase, the home terms of trade and the real exchange rate appreciate, reducing relative wealth and consumption abroad.

The latter pattern of international transmission is due to a combination of an unconventionally sloped demand curve, and nontrivial general equilibrium effects arising from market incompleteness. Because of home bias in consumption, domestic tradables are mainly demanded by domestic households. With a low price elasticity, a terms-of-trade depreciation that reduces domestic wealth relative to the rest of the world would actually result in a drop of the world demand for domestic goods — the negative wealth effect in the home country would more than offset any global positive substitution and wealth effect. Therefore, for the world markets to clear, a larger supply of domestic tradables must be matched by an increase in their relative price, that is, an appreciation of the terms of trade — driving up domestic wealth and demand. Strikingly, our numerical results suggest that the overall performance of the model is best when the calibration implies a negative transmission mechanism.

To investigate whether the international transmission of productivity shocks to tradables in the U.S. data bear any resemblance to the above patterns, we close our paper with some suggestive evidence. Two findings stand out. 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 shock that increases permanently U.S. labor productivity in manufacturing (our measure of tradables) relative to the rest of the world, U.S. relative output and consumption increase, while the real exchange rate appreciates.[3] Second, the same increase in productivity improves the terms of trade, as suggested by our model under the negative transmission.

In light of the results in this paper, the Backus-Smith evidence appears less puzzling yet more consequential for the construction of open-economy general-equilibrium models, with potentially strong implications for welfare and policy analysis. In fact, if the international transmission mechanism is such that 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 will not contribute at all to consumption risk-sharing. Thus gains from international portfolio diversification may well be large relative to the predictions of standard open-economy models.

The paper 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. Section 5 explores the quantitative predictions of the model in numerical experiments. Section 6 presents the sta-

[3] 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 a high price elasticity of tradables cannot generate either enough volatility of the real exchange rate and terms of trade or replicate the negative Backus-Smith unconditonal correlation.

tistical evidence on the effects of shocks to productivity in the open economy. Finally, Section 7 summarizes and qualifies the paper's results, suggesting directions for further research.

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

In this section, we first restate the Backus and Smith [1993] puzzle, looking at the data for most OECD countries. Second, we reconsider the general equilibrium link between relative consumption and the real exchange rate in the framework of a simple endowment economy with incomplete markets and tradable goods only, in the spirit of Cole and Obstfeld [1991]. The goal of our exercise is to provide an intuitive yet analytical account of the determinants of the comovements between the real exchange rate and relative consumption conditional on endowment (supply) shocks. Using our framework, we will show that the link between these variables can have either sign depending on the price elasticity of tradables: a low elasticity can generate the negative pattern observed in the data. But since a low price elasticity also means that quantities are not very sensitive to price movements, a negative correlation between the real exchange rate and relative consumption will be associated with a high volatility of the real exchange rate and the terms of trade relative to fundamentals and other endogenous macroeconomic variables — in accord with an important set of stylized facts of the international economy. These results shed light on the main mechanisms driving our quantitative results in the second part of our paper.

1.1 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:

$$\frac{P_t^*}{P_t} U_{c,t} = U^*_{c^*,t}, \tag{1}$$

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), $U_{c,t}$ ($U^*_{c^*,t}$) denotes the marginal utility of consumption, 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, given by the domestic marginal utility of consumption times the real exchange rate $\frac{P_t^*}{P_t}$, i.e., the relative price of C_t^* in terms of C_t.

If a complete set of state-contingent securities is available, the above condition holds in a decentralized equilibrium independently of trade frictions and goods 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 — corresponding to the simple notion that complete markets imply a high cross-country correlation of 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 domestic to foreign consumption and the (logarithm of the) real exchange rate.[4] Against the hypothesis of perfect risk-sharing, many empirical studies have found this correlation to be significantly below one, or even negative (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 the 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 median of the table entries in the first two columns are -0.30 and -0.27, respectively.

Consistent with other studies, Table 1 presents strong *prima facie* evidence at odds with 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 that agents can use to hedge country-specific risk breaks the tight link between real exchange rates and the marginal utility of consumption implied by (1). It should therefore be an essential feature of models trying to account for the stylized facts summarized in Table 1.

[4] Lewis [1996] rejects nonseparability of preferences between consumption and leisure as an empirical explanation of the low correlation of consumption across countries.

1.2 Into the puzzle: supply shocks, international transmission and risk sharing in a simple endowment economy

1.2.1 International transmission and the volatility of relative prices

Building on a simple setting similar to Cole and Obstfeld [1991], we now consider a two-country, two-good endowment economy under the extreme case of financial autarky. We will refer to the two countries as 'Home' and 'Foreign', denoted H and F. For the Home representative consumer, consumption is given by the following CES aggregator

$$C = C_{\mathrm{T}} = \left[a_{\mathrm{H}}^{1-\rho} C_{\mathrm{H}}^{\rho} + a_{\mathrm{F}}^{1-\rho} C_{\mathrm{F}}^{\rho}\right]^{\frac{1}{\rho}}, \qquad \rho < 1, \tag{2}$$

where $C_{\mathrm{H},t}$ ($C_{\mathrm{F},t}$) is the domestic consumption of Home (Foreign) produced good, a_{H} is the share of the domestically produced good in the Home consumption expenditure, a_{F} is the corresponding share of imported goods, with $a_{\mathrm{F}} = 1 - a_{\mathrm{H}}$. Let $P_{\mathrm{H},t}$ ($P_{\mathrm{F},t}$) denote the price of the Home (Foreign) good, and $\tau = \dfrac{P_{\mathrm{F}}}{P_{\mathrm{H}}}$ the terms of trade, the relative price of Foreign goods in terms of Home goods. Therefore, an increase in τ implies a depreciation of the terms of trade. The consumption-based price index P is

$$P = P_{\mathrm{T}} = \left[a_{\mathrm{H}} P_{\mathrm{H}}^{\frac{\rho}{\rho-1}} + (1 - a_{\mathrm{H}})\, P_{\mathrm{F}}^{\frac{\rho}{\rho-1}}\right]^{\frac{\rho-1}{\rho}}. \tag{3}$$

Let Y_{H} denote Home (tradable) output. In financial autarky, consumption expenditure has to equal current income, i.e., $\dfrac{PC}{P_{\mathrm{H}}} = Y_{\mathrm{H}}$. Domestic demand for Home goods can then be written:

$$C_{\mathrm{H}} = a_{\mathrm{H}} \left(\frac{P_{\mathrm{H}}}{P}\right)^{-\omega} C = \frac{a_{\mathrm{H}}}{a_{\mathrm{H}} + (1 - a_{\mathrm{H}})\, \tau^{1-\omega}} Y_{\mathrm{H}}$$

where the demand's price elasticity coincides with the elasticity of substitution across the two goods, $\omega = (1 - \rho)^{-1}$. Analogous expressions can be derived for the Foreign country.

Now, taking the derivative of C_{H} with respect to τ:

$$\frac{\partial C_{\mathrm{H}}}{\partial \tau} = \underbrace{\omega \frac{a_{\mathrm{H}}(1 - a_{\mathrm{H}})\, \tau^{-\omega}}{\left[a_{\mathrm{H}} + (1 - a_{\mathrm{H}})\, \tau^{1-\omega}\right]^2} Y_{\mathrm{H}}}_{SE} \underbrace{- \frac{a_{\mathrm{H}}(1 - a_{\mathrm{H}})\, \tau^{-\omega}}{\left[a_{\mathrm{H}} + (1 - a_{\mathrm{H}})\, \tau^{1-\omega}\right]^2} Y_{\mathrm{H}}}_{IE} > 0 \iff \omega > 1, \tag{4}$$

makes it clear that the Home demand for the Home good 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 raise its domestic demand. This is the case when the positive substitution effect (SE) from lower prices is larger in absolute value than the negative income effect

(IE) from a lower valuation of Y_{H}.[5] Conversely, when $\omega < 1$ the negative income effect will more than offset the substitution effect. Thus, a terms-of-trade depreciation will reduce the domestic demand for the Home tradable. The foreign demand for Home tradables C_{H}^{*}, instead, will always be increasing in τ: independently of ω, the substitution and income effects in this case are both positive.[6]

These considerations help us understanding the link between relative prices and world demand.[7] As long as the negative income effects in the Home country is not too strong, the world demand for Home goods $C_{\mathrm{H}}+C_{\mathrm{H}}^{*}$ will be decreasing in their relative price, i.e. increasing in τ. For ω sufficiently high, then, the equilibrium Home terms of trade needs to depreciate in response to a positive shock to Home output Y_{H}. The international transmission through terms of trade adjustment is therefore *positive*: foreign consumption of Home tradables will rise, responding to the fall in the relative price of imports. However, when ω is sufficiently below 1 and the Home bias in consumption is sufficiently high (i.e., a_{H} is large relative to a_{H}^{*}), the response of world demand for the Home goods to relative price movements will be dominated by the strong negative income effects of its domestic component: world demand will be falling in τ. In other words, the negative income effect of worsening terms of trade on Home demand will more than offset any positive substitution effects worlwide and income effects abroad.[8] For a positive supply shock to Y_{H} to be matched by an increase in world demand for the Home goods, the Home terms of trade needs to *appreciate*. The international transmission in this case is *negative* : a positive domestic supply shock has a negative impact on consumption and welfare abroad.

To analyze the relation between international transmission and price volatility, we take a log-linear approximation of the market clearing condition for Home tradables ($Y_{\mathrm{H}} = C_{\mathrm{H}} + C_{\mathrm{H}}^{*}$) around

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[5]Formally, by a straightforward derivation of the Slutsky equation, the substitution effect is obtained from the compensated demand function x_{H} :

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

[6]Using self-explanatory notation:

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

[7]We are grateful to Fabrizio Perri for suggesting this line of exposition.

[8]Strong income effects raise the possibility of multiple steady states (e.g., see the discussion in Corsetti and Dedola [2002]). It is worth stressing, however, that the specification of preferences in the model we use in our numerical exercises below always ensure a unique steady state.

a symmetric equilibrium (with $a_{\mathrm{H}} = 1 - a_{\mathrm{H}}^*$ and $Y_{\mathrm{H}} = Y_{\mathrm{F}}^*$). The equilibrium link between relative output (endowment) changes, and the terms of trade/real exchange rate can be expressed as follows:

$$\widehat{\tau} = \frac{\widehat{Y_{\mathrm{H}}} - \widehat{Y_{\mathrm{F}}^*}}{1 - 2a_{\mathrm{H}}(1-\omega)}, \tag{5}$$

$$\widehat{RER} = \frac{2a_{\mathrm{H}} - 1}{1 - 2a_{\mathrm{H}}(1-\omega)} \left(\widehat{Y_{\mathrm{H}}} - \widehat{Y_{\mathrm{F}}^*}\right), \tag{6}$$

where a "^" represents a variable's percentage deviation from the symmetric values. Consistent with our analysis above, these expressions show that, for given movements in relative output, the sign of the response of international relative price changes depending on ω. In addition, they suggest that the volatility of the terms of trade and the real exchange rate follows a hump-shaped pattern in ω.

To see this, assume home bias in consumption ($a_{\mathrm{H}} > 1/2$). For a sufficiently high elasticity of substitution, i.e. $\omega > \frac{2a_{\mathrm{H}} - 1}{2a_{\mathrm{H}}}$, the real exchange rate and the terms of trade both depreciate in response to a positive Home supply shock. This is the region of parameters' values in which the world demand schedule is conventionally sloped, and the international transmission is positive. In this region, higher values of ω reduce the coefficient relating $\widehat{Y}_{\mathrm{H}} - \widehat{Y}_{\mathrm{F}}^*$ to $\widehat{RER}$ and $\widehat{\tau}$: the larger the price elasticity, the lower the volatility of the real exchange rate and the terms of trade relative in response to shocks to relative output.

Conversely, for a sufficiently low price elasticity of imports, that is, for $0 < \omega < \frac{2a_{\mathrm{H}} - 1}{2a_{\mathrm{H}}} < 1/2$, a Home supply shock cause both the real exchange rate and the terms of trade to appreciate in equilibrium. As shown above, underlying this result is a weak substitution effect relative to the income effect of changes in relative prices, so that the domestic and world demand schedules for Home tradables are negatively sloped. In this region of parameters' values, a higher elasticity of substitution tends to raise the volatility of international prices.

Note that the response of international relative prices to output shocks tend to become stronger as ω approaches $\frac{2a_{\mathrm{H}} - 1}{2a_{\mathrm{H}}}$ from either side, whereas the slope of the demand function becomes flatter and flatter before changing sign. For ω around the cutoff point, the coefficient relating $\widehat{Y}_{\mathrm{H}} - \widehat{Y}_{\mathrm{F}}^*$ to $\widehat{RER}$ and $\widehat{\tau}$ in the above expressions becomes quite high in absolute value, driving up the volatility of the real exchange rate and the terms of trade in response to shocks to relative output. An important implication of our analysis is that there will be two values of ω (below and above $\frac{2a_{\mathrm{H}} - 1}{2a_{\mathrm{H}}}$) that yield the same volatility of the terms of trade and real exchange rate: one associated with positive, the other associated with negative international transmission.

1.2.2 Risk sharing

So far, we have shown that there can be different patterns of relative price movements in response to supply shocks, shaping the sign and magnitude of the international transmission mechanism. We can now derive the implications of our results for risk-sharing, looking at the equilibrium comovements between the real exchange rate and relative consumption. With incomplete markets the scope for insurance against country-specific shocks is limited, and equilibrium movements in international relative prices will expose consumers to potentially strong relative wealth shocks.

In our simple model with financial autarky, we can use the balanced-trade condition to derive an expression for relative consumption as a function of the terms of trade:

$$\tau C_{\mathrm{F}} = C_{\mathrm{H}}^{*} \Longleftrightarrow \frac{C}{C^{*}} = \left[\frac{(1 - a_{\mathrm{H}}^{*})\,\tau^{1-\omega} + a_{\mathrm{H}}^{*}}{a_{\mathrm{H}}\tau^{\omega} + (1 - a_{\mathrm{H}})\,\tau} \right]^{\frac{\omega}{1-\omega}} ; \tag{7}$$

from this, we can then derive the following log-linearized relationship between the real exchange rate and relative consumption:

$$\widehat{RER} = \frac{2a_{\mathrm{H}} - 1}{2a_{\mathrm{H}}\omega - 1} \left(\widehat{C} - \widehat{C^{*}} \right). \tag{8}$$

The relation between real exchange rates and relative consumption can have either sign, depending on the values of a_{H} and ω. Specifically, with home bias in consumption, it will be negative when $\omega < \frac{1}{2a_{\mathrm{H}}} < 1$.

We have seen above that, for a given change in the terms of trade and the real exchange rate, the international transmission of shocks can be positive or negative, depending on whether ω is above or below $\frac{2a_{\mathrm{H}} - 1}{2a_{\mathrm{H}}}$. But this cutoff point is smaller than $\frac{1}{2a_{\mathrm{H}}}$. Hence, a negative correlation between the real exchange rate and relative consumption can correspond to different patterns of the international transmission.

In response to a Home supply shock, the Home terms of trade improves and the real exchange rate appreciates, while Home consumption rises relative to Foreign consumption for $\omega < \frac{2a_{\mathrm{H}} - 1}{2a_{\mathrm{H}}}$; the Home terms of trade and exchange rate depreciates, driving Foreign consumption above domestic consumption for $\frac{2a_{\mathrm{H}} - 1}{2a_{\mathrm{H}}} < \omega < \frac{1}{2a_{\mathrm{H}}}$. Depending on the size of equilibrium movements in prices, consumption at Home may or may not fall — i.e. accounting for the Backus Smith evidence in this case does not necessarily imply 'immiserizing growth.'

Contrast these results with the benchmark economy constructed by Cole and Obstfeld [1991], which is a special case of our economy with $\omega = 1$ and $a_{\mathrm{H}} = a_{\mathrm{H}}^{*} = 1/2$. This contribution — as well as Corsetti and Pesenti [2001a] — build examples where productivity shocks to tradables bring about relative price movements that *exactly* offset changes in output, leaving cross-country relative wealth unchanged. 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 should be 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 is the case when $\frac{2a_{\mathrm{H}}-1}{2a_{\mathrm{H}}} < \omega < \frac{1}{2a_{\mathrm{H}}}$. Our analysis above unveils that an "*excessively positive*" international transmission of productivity shock generates an empirical pattern of low risk-sharing and can therefore rationalize the Backus-Smith anomaly: a terms-of-trade and real exchange rate depreciation will be reflected in a reduction in relative consumptions.

Risk-sharing is of course hindered by a negative transmission, which prevails when $\omega < \frac{2a_{\mathrm{H}}-1}{2a_{\mathrm{H}}}$. In this case, 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.

1.3 The way ahead

Our stylized two-country, two-good model with financial autarky and endowment (productivity) shocks shows that, depending on the price elasticity of tradables, the correlation between relative consumption and the real exchange rate can have either sign. By emphasizing a low price elasticity, our results above suggests what we see as a promising modelling strategy to address the Backus-Smith anomaly. In what follows, we develop a dynamic model with capital accumulation and international trade in one uncontingent bond, in which a low price elasticity of tradables is not exclusively related to a low elasticity of substitution ω but is an implication of assuming a realistic structure of the goods market with distributive trade. We will study the quantitative implications of our model assuming standard parameter values, and setting ω to match the observed volatility of the real exchange rate relative to that of output. We are especially interested in verifying whether, under our calibration of ω, our 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. Our framework leads to empirically plausible predictions that find striking support in the data.

Before proceeding, it is worth stressing that our explanation of the Backus-Smith puzzle abstracts from nominal rigidities and demand shocks — consistent with previous results from leading contributions. Namely, in a two-country model where the only internationally traded asset is a nominal bond, Chari, Kehoe and McGrattan [2002] emphasize that allowing for sticky prices set by producers in the currency of the market of destination does not help at all in addressing the Backus-Smith anomaly. To see why, consider a version of our simple economy with production and prices fixed in local currencies. 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 counterpart of the balanced trade condition (7) 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.

The standard Mundell-Fleming-Dornbusch model suggests a way to rationalize the Backus-Smith observation as a consequence of demand shocks. In this model, shocks to demand that drive domestic expenditure and consumption up appreciate the currency in real terms. Some external demand needs to be crowded out in order to make "more room" for domestic demand. Thus, this model seems consistent with the above evidence, but only to the extent that international business cycles and real exchange rate fluctuations can be described as mainly driven by demand shocks. However, in Chari, Kehoe and McGrattan [2002] the correlation between relative consumption and the real exchange rate remains close to 1 even when allowing for demand shocks (monetary shocks and government spending) or nonseparability between consumption and leisure. Nonetheless, 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 in (1), in principle generating the observed Backus-Smith correlation even in models assuming complete asset markets and efficient international risk sharing. However, it would be quite challenging to identify empirically shocks with the property of accounting for the low or negative correlations reported in Table 1, while at the same time bringing about comovements in aggregates across countries broadly in line with the evidence.

2 The model

In this and the next section, we develop our model, which will then be solved by employing standard numerical techniques. Our world economy consists of two countries of equal size, as before denoted H and F, each specialized in the production of an intermediate, perfectly tradable good. In addition, each country produces a nontradable good. This 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.

2.1 The 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:

$$
\begin{aligned}
Y_{\mathrm{H}} &= Z_{\mathrm{H}} K_{\mathrm{H}}^{1-\xi} L_{\mathrm{H}}^{\xi} \\
Y_{\mathrm{N}} &= Z_{\mathrm{N}} K_{\mathrm{N}}^{1-\zeta} L_{\mathrm{N}}^{\zeta},
\end{aligned}
$$

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 problem of these firms is standard: they hire labor and capital from households to maximize their profits:

$$
\begin{aligned}
\pi_{\mathrm{H}} &= \overline{P}_{\mathrm{H},t} Y_{\mathrm{H},t} - W_t L_{\mathrm{H},t} - R_t K_{\mathrm{H},t} \\
\pi_{\mathrm{N}} &= P_{\mathrm{N},t} Y_{\mathrm{N},t} - W_t L_{\mathrm{N},t} - R_t K_{\mathrm{N},t},
\end{aligned}
$$

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 are also perfectly competitive. They buy tradable goods and distribute them to consumers using nontraded goods as the only input in production. 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.

2.2 The Household's Problem

2.2.1 Preferences

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

$$E\left\{\sum_{t=0}^{\infty} U\left[C_t, \ell_t\right] \exp\left[\sum_{\tau=0}^{t-1} -\nu\left(U\left[C_t, \ell_t\right]\right)\right]\right\} \tag{9}$$

where instantaneous utility U is a function of a consumption index, C, and leisure, $(1-\ell)$. Foreign agents' preferences are symmetrically defined. It can be shown that, for all parameter values used in the quantitative analysis below, these preferences guarantee the presence of a locally unique symmetric steady state, independent of initial conditions.[9]

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

$$C_t \equiv \left[a_{\mathrm{T}}^{1-\phi} C_{\mathrm{T},t}{}^{\phi} + a_{\mathrm{N}}^{1-\phi} C_{\mathrm{N},t}{}^{\phi}\right]^{\frac{1}{\phi}}, \qquad \phi < 1, \tag{10}$$

where a_{T} and a_{N} are the weights on the consumption of traded and nontraded goods, respectively and $\dfrac{1}{1-\phi}$ is the constant elasticity of substitution between $C_{\mathrm{N},t}$ and $C_{\mathrm{T},t}$. As in Section 2, the consumption index of traded goods $C_{\mathrm{T},t}$ is given by (2).

2.2.2 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 $P_{\mathrm{N},t}$ denote the price of the 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

$$P_{\mathrm{H},t} = \overline{P}_{\mathrm{H},t} + \eta P_{\mathrm{N},t}. \tag{11}$$

We hereafter write the utility-based CPIs, whereas the price index of tradables is given by (3):

$$P_t = \left[a_{\mathrm{T}} P_{\mathrm{T},t}{}^{\frac{\phi}{\phi-1}} + a_{\mathrm{N}} P_{\mathrm{N},t}{}^{\frac{\phi}{\phi-1}}\right]^{\frac{\phi-1}{\phi}}. \tag{12}$$

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

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

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.

2.2.3 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:[10]

$$\begin{gathered} P_{\mathrm{H},t}C_{\mathrm{H},t} + P_{\mathrm{F},t}C_{\mathrm{F},t} + P_{\mathrm{N},t}C_{\mathrm{N},t} + B_{\mathrm{H},t+1} + \overline{P}_{\mathrm{H},t}I_{\mathrm{H},t} \leq \\ W_t\ell_t + R_tK_t + (1 + r_t)B_{\mathrm{H},t}. \end{gathered} \tag{13}$$

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:[11]

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

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:

$$K_{t+1} = I_{\mathrm{H},t} + (1 - \delta)K_t \tag{14}$$

The household's problem then consists of maximizing lifetime utility, defined by (9), subject to the constraints (13) and (14).

2.3 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 $K^*_{\mathrm{H}}(s)$, $K^*_{\mathrm{N}}(s)$,

[10] $B_{\mathrm{H},t}$ denotes the Home agent's bonds accumulated during period $t - 1$ and carried over into period t.

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

$L^*_{\rm H}(s)$, $L^*_{\rm N}(s)$; a set of pricing functions $P_{\rm H}(s)$, $P_{\rm F}(s)$, $\overline{P}_{\rm H}(s)$, $\overline{P}_{\rm F}(s)$, $P_{\rm N}(s)$, $P^*_{\rm N}(s)$, $W(s)$, $W^*(s)$, $R(s)$, $R^*(s)$, $r(s)$ such that (i) the agents' decision rules solve the households' problems; (ii) the firms' decision rules solve the firms' problems; and (iii) the appropriate market-clearing conditions (for the labor market, the capital market and the bond market) hold.

3 Model calibration

Table 2 reports our benchmark calibration, which we assume symmetric across countries. Several parameter values are similar to those adopted by Stockman and Tesar [1995], who calibrate their models to the United States relative to a set of OECD countries on annual data. Throughout the exercise, we will carry out sensitivity analysis and assess the robustness of our results under the benchmark calibration.

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

$$\mathbf{Z}' = \boldsymbol{\lambda}\mathbf{Z} + \mathbf{u}, \tag{15}$$

whereas $\mathbf{u} \equiv (u_{\rm H}, u_{\rm F}, u_{\rm N}, u^*_{\rm N})$ 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 cross-country symmetry on the autocorrelation and variance-covariance matrices of the above sectoral 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 estimated technology shocks are fairly persistent. On the other hand, in line with empirical studies, we find that spillovers across countries and sectors are not negligible.[12]

[12] See Costello [1993]. 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 from HP-filtered data - while we and most of the literature compute them using data in (log) levels.

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

$$U\left[C_t, \ell_t\right] = \frac{\left[C_t^{\alpha}(1-\ell_t)^{1-\alpha}\right]^{1-\sigma} - 1}{1-\sigma}, \qquad 0 < \alpha < 1, \qquad \sigma > 0, \tag{16}$$

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:

$$\nu\left(U\left[C_t, \ell_t\right]\right) = \begin{cases} \ln\left(1 + \psi\left[C_t^{\alpha}(1-\ell_t)^{1-\alpha}\right]\right) & \sigma \neq 1 \\ \ln\left(1 + \psi\left[\alpha \ln C_t + (1-\alpha)\ln(1-\ell_t)\right]\right) & \sigma = 1 \end{cases},$$

whereas ψ is chosen such that the steady-state real interest rate is 4 percent per annum, equal to 0.08. This parameter also determines the speed of convergence to the unique nonstochastic steady state.

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] referred to 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.

As regards the weights of domestic and foreign tradables in the tradables consumption basket (C_{T}), a_{H} and a_{F} (normalized to $a_{\mathrm{H}}+a_{\mathrm{F}} = 1$) 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 weights of traded and nontraded goods, a_{T} and a_{N}, are chosen as to match the share of nontradables in the 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.

We calibrate ξ and ζ, the labor shares in the production of tradables and nontradables, based on the work of Stockman and Tesar [1995]. They calculate these shares to be equal to 61 percent and 56 percent, respectively. Finally, we set the depreciation rate of capital equal to 10 percent annually.

Distribution costs and the price elasticity of tradables The introduction of a distribution sector in our model is a novel feature relative to standard business cycle models in the literature. Before delving into numerical analysis, it is appropriate to discuss an important implication of this feature regarding the price elasticity of tradables. From the representative consumer's first-order conditions (regardless of frictions in the asset and goods markets), optimality 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:

$$\frac{P_{\mathrm{F},t}}{P_{\mathrm{H},t}}=\frac{\overline{P}_{\mathrm{F},t}+\eta P_{\mathrm{N},t}}{\overline{P}_{\mathrm{H},t}+\eta P_{\mathrm{N},t}}=\frac{1-a_{\mathrm{H}}}{a_{\mathrm{H}}}\left(\frac{C_{\mathrm{H},t}}{C_{\mathrm{F},t}}\right)^{\frac{1}{\omega}}, \tag{17}$$

where $\omega=(1-\rho)^{-1}$ is equal to the elasticity of substitution between Home and Foreign tradables in the consumption aggregator $C_{\mathrm{T},t}$, and thus to the consumer price elasticity of these goods. 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 can refer to this ratio as the (tradable) import ratio.

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 in most standard models (e.g. Lucas [1982]). Let μ denote the size of the distribution margin in steady state, i.e., $\mu=\eta\frac{P_{\mathrm{N}}}{P_{\mathrm{H}}}$. By log-linearizing (17), we get:

$$\widehat{\tau}_t=\frac{1}{\omega\,(1-\mu)}\left(\widehat{C_{\mathrm{H},t}}-\widehat{C_{\mathrm{F},t}}\right). \tag{18}$$

where the terms of trade τ is measured at the producer-price level so that $\omega\,(1-\mu)$ can be thought of as the producer price elasticity of tradables. Clearly, 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. 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. In our model, a larger distribution margin μ (i.e., a larger η) has a similar effect. Accounting for distributive trade thus results into an amplification channel of fluctuations in international relative prices for any given variability in real quantities. So, 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] Remarkably, it will be shown below 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).[14]

There is considerable uncertainty regarding trade price elasticities. Using time series data, empirical researchers have found estimates that range from about 0.1 to 2 (see the comprehensive study on G-7 countries by Hooper, Johnson and Marquez [2000]). For instance, for the U.S.

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

[14]Note that under financial autarky the counterpart of condition (4) in our fully-specified model with distribution

Taylor [1993] estimates a value of 0.39, while Whalley [1985] finds 1.5. For European countries most empirical studies suggest values below 1.[15] Correspondingly, there are differences in the quantitative literature. For instance, in a model with traded and nontraded goods similar to ours, Stockman and Tesar [1995] set the parameter ω — directly related to the price elasticity with no distribution costs — equal to 1. Following Whalley [1985], in a model with only tradable goods Backus, Kydland, and Kehoe [1995] set it equal to 1.5, whereas Heathcote and Perri [2002] estimate it as low as 0.9. However, these authors also report sensitivity analysis suggesting that much lower values, in the range of 0.5, can improve their model performance in accounting for features of the international business cycle like the volatility of the terms of trade.

Given the uncertainty surrounding the appropriate parameter value, and the key role this elasticity plays in open economy models, we choose to follow a different route. First, we rely on estimates in the trade literature on distribution costs to pick a value for μ. 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. In their exhaustive survey on the importance of trade costs, Anderson and van Wincoop [2004] report that in industrialized countries representative local distribution costs account for over 55 percent of retail prices. Thus, we follow the calibration in Burstein, Neves and Rebelo [2001] and set distribution costs to 50 percent.

Second, 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 3 below). Therefore, our quantitative analysis below can be interpreted as investigating the link among international price movements, risk sharing and the international transmission conditional on the model being consistent with the observed volatility in real exchange rates. In Section 2.2, we have used a simplified setup to show that the volatility of international prices is hump-shaped in ω, and discussed at length the mechanism underlying this pattern. Consistently, we find two values for the elasticity ω such that the model matches the volatility of the U.S. real exchange rate. In our benchmark calibration

services is:

$$\frac{\partial C_{\mathrm{H}}}{\partial \tau} > 0 \iff \underbrace{\omega\,(1-\mu)\,(1-a_{\mathrm{H}})\left(\frac{P_{\mathrm{F}}}{P_{\mathrm{H}}}\right)^{1-\omega}}_{SE} - \underbrace{(1-a_{\mathrm{H}})\left(\frac{P_{\mathrm{F}}}{P_{\mathrm{H}}}\right)^{1-\omega} - a_{\mathrm{H}}\mu}_{IE} > 0.$$

A positive distribution margin μ reduces the substitution effect (SE) from a deterioration in the terms of trade, while making the income effect (IE) more negative, as the presence of distributive trade causes the consumer price to fall less than one-to-one relative to the relative price of domestic tradables.

[15] Ruhl [2003] shows a way to reconcile these time series estimates with the evidence on the large growth in trade volumes that result from changes in tariffs.

these two values are $\omega = 0.99$ and $\omega = 1.11$. Strikingly both figures are quite close the value assumed by Stockman and Tesar [1995]. Most important, when combined with the calibrated value for μ, the implied price elasticities are well in the range of available estimates. While apparently close to each other, the two possible values for ω imply quite different dynamics and international transmission patterns for shocks to tradables productivity. These differences will become central to our discussion of the evidence discussed at the end of the paper.

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

Our goal in this section is to verify whether our model can match the empirical evidence on the unconditional correlation between international prices and quantities, as well as the their relative volatilities. The evidence is summarized by the statistics reported in the first column of Tables 3 and 4. The statistics for the data — all filtered using the Hodrick and Prescott filter — are 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.[16] Notably, the Backus Smith correlation between relative consumption and the real exchange rate is equal to -0.45.

In what follows, we will show that, different from standard open-economy models, our artificial economy performs quite well in this dimension. Throughout our exercises, we take a first-order Taylor series expansion around the deterministic steady state and simulate our model economy using King and Watson [1998]'s algorithm. We compute the model's statistics by logging and filtering the model's artificial time series using the Hodrick and Prescott filter and averaging moments across 100 simulations. The results for our baseline model and some variations on it are also shown in Tables 3 and 4.

4.1 Volatilities and correlation properties

The real exchange rate and the terms of trade Using our framework, we can write the real exchange rate (RER) in the following log-linear form, reflecting movements in the terms of trade as well as in the relative price of non-traded goods:

$$\widehat{RER}_t = (1-\mu)\left(2a_{\mathrm{H}}-1\right)\widehat{\tau}_t + \mu\left(\widehat{P^*_{\mathrm{N},t}} - \widehat{P_{\mathrm{N},t}}\right) + \Omega\left(\widehat{q^*_t} - \widehat{q}_t\right), \qquad (19)$$

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

where $0 < \Omega < 1$ and $\widehat{q}_t$ represents the relative price of nontradables.[17] In our numerical results, the first two components, arising from home bias in consumption and deviations of the law of one price for the CPI of tradables, dominate real exchange-rate movements.

In our baseline economy the real exchange rate and the terms of trade are tightly related. Their correlation is positive (and equal to 0.97 for both values of ω), though higher than in the data (0.6). A positive sign for this correlation 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 counterfactual negative correlation between the real exchange rate and the terms of trade.

The terms of trade is very volatile, even more than in the data. The volatility of the terms of trade relative to output is 3.04 with $\omega = 0.99$, and 4.34 with $\omega = 1.11$, compared to 1.79 in the data. In this sense, our model suggests that high volatility of the international prices *per se* is not a measure of their 'disconnect' from fundamentals. To highlight this point, consider 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). As shown in Table 4, the standard deviation of the import ratio is 4.13 percent in the data. In our benchmark parametrization, it is equal to 2.78 for the smaller ω, but increases to 4.44 percent for the larger ω.[18]

Moreover, with $\omega = 0.99$ the model is consistent with the ranking of variability in international prices observed in the data: the real exchange rate is more volatile than the terms of trade. The difference may be due either to the volatility of deviations from the law of one price (which drives a wedge between the terms of trade and relative prices at consumer levels) or to the volatility of nontradable prices, or a combination of the two. For this reason, the correct ranking of volatility is very hard to replicate using models that abstract from the features above (see Heathcoate and Perri [2002]).

We find that the relative price of nontradables across countries is not the main force driving the high volatility of the model's real exchange rate. Table 3 shows that the volatility of the relative price of nontradables predicted by our model is quite in line with that in the data: depending on

[17] 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.

[18] Remarkably, the data supports 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 for either value of ω.

ω, this volatility is 1.72 and 1.43, against an empirical estimate of 1.73. When we compute the ratio between the standard deviation of the relative price of nontradables across countries, and the standard deviation of the real exchange rate, this ratio is roughly 20 percent. This figure is slightly lower than that estimated by Betts and Kehoe [2001], who find this ratio to be between 35 and 44 percent using a weighted average of U.S. bilateral real exchange rates.[19]

The Backus-Smith correlation The main result of our baseline model shown in Table 3 is that the correlation between relative consumption and the real exchange rate is not only negative, but also quite close to its empirical counterpart. With both $\omega = 0.99$ and $\omega = 1.11$, the correlation generated by the model is equal to -0.55, against our empirical estimate of -0.45. A similar pattern emerges for the terms of trade: its correlation with relative consumption is -0.72 and -0.73 in the model, against an empirical estimate of -0.53.

Since our two values of ω are set so that the model fits the empirical volatility of the real exchange rate, our results show that the price elasticity that is consistent with a realistic volatility in international prices also implies a realistic pattern of risk-sharing.[20] What generates a negative Backus-Smith correlation is the mechanism linking volatility and risk-sharing derived and discussed in Section 2 using a very simple setting under financial autarky. However, the simple model predicts a perfectly negative correlation between relative consumption and the real exchange rate. In our baseline economy with capital accumulation and international borrowing and lending, the same mechanism accounts for the quantitative result of a negative but less than perfect correlation. To see why, note that when international asset trade is limited to uncontingent bonds, the relation between the real exchange rate and marginal utilities of consumption only holds in expected first-differences — the log-linearized Euler equations for the bond yield (abstracting from the time-varying discount factor):

$$E_t\left(\widehat{RER}_{t+1} - \widehat{RER}_t\right) \approx E_t\left[\left(\widehat{U}^*_{c,t+1} - \widehat{U}^*_{c,t}\right) - \left(\widehat{U}_{c,t+1} - \widehat{U}_{c,t}\right)\right]. \qquad (20)$$

To the extent that the tight link between growth rates of variables is inherited by their levels, this expression may seem to run against the Backus-Smith evidence. In a stochastic environment, however, the international bond is traded only after the resolution of uncertainty, and does not

[19]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.

[20]The model can also generate a negative Backus-Smith correlation when we calibrate ω as to match the empirical volatility of the terms of trade (rather than the real exchange rate) relative to volatility of output. Following this approach, we obtain a value of ω equal to 0.96, corresponding to a Backus-Smith correlation equal to -0.24. In this new exercise the predicted volatility of the real exchange rate is about 70 percent of what is found in the data.

provide households with ex-ante insurance against country-specific income shocks — it only makes it possible to reallocate wealth and smooth consumption over time. The *impact effect* of a shock to tradables in a bond economy will thus be roughly the same as under financial autarky, moving relative consumption and the real exchange rate in a direction that will depend on the value of the price elasticity. Under our calibration, the Backus-Smith correlation will therefore be negative on impact, but positive in the aftermath of a shock, when the dynamics of relative consumption and the real exchange rate is determined by the above equation. For this reason, the Backus-Smith correlation in a bond economy will be less negative than under financial autarky.[21] It will also become higher and closer to that implied by complete markets, the weaker the impact response (in absolute value) of the real exchange rate — i.e., the less volatile the real exchange rate and the terms of trade on impact.[22]

International relative prices and business cycles Consider now the rest of the statistics for the baseline economy in Tables 3 and 4. As is well known, most open-economy models — including those allowing for nominal rigidities and monetary shocks — predict a strong and positive link between relative output and real exchange rates. As Stockman [1998] points out, this prediction is at variance with the data: the empirical correlation shown in Table 3 is -0.23. A similar shortcoming concerns the correlation between relative output and the terms of trade, which is negative in the data (and equal to -0.20), while it tends to be positive in quantitative models.

Our baseline economy yields contrasting results on this issue. The correlation between relative output and the real exchange rate (the terms of trade) is high and positive — equal to 0.78 and 0.90 respectively — with $\omega = 1.11$, but becomes strongly negative with $\omega = 0.99$. This is because, with the lower ω, positive productivity shocks in the tradable sector appreciate the terms of trade and the real exchange rate — a result that we will discuss in greater detail below. We observe here that this very mechanism also accounts for the ability of the model to match the observed positive correlation between international relative prices and net exports, also shown at the bottom of the table.

In Table 4, we see that the cross-country correlation of output in the model (0.45 and 0.43

[21] Interestingly, the model can also replicate the Backus-Smith correlation 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. In our economy this correlation *ex-post* is -0.46 (-0.61) when ω equals 0.99 (1.11).

[22] The same mechanism holds in an economy in which the consumption share of nontradables is set to zero, so that they are used only in distribution, and their production function is not subject to thechnology shocks. In this case, we find that the Backus-Smith correlation is around -0.90.

depending on ω) is very close to that in the data (0.49), and higher than that of consumption. The cross-correlation of consumption is lower than in the data (0.14 and 0.11, against 0.32), while the cross-correlations of investment and employment are higher— Backus, Kehoe and Kydland [1995] dub this empirical incongruity the 'quantity anomaly'. However, our model does relatively better in this dimension than the standard real business cycle model. It is well known that this class of models predicts that consumption should be more correlated across countries than output, and that the correlation across countries of investment and employment is negative.— even when they assume incomplete markets, with a real bond as the only internationally traded asset (see Heathcote and Perri [2002]).

Finally, a minor discrepancy between the benchmark model and the data is that — relative to output — consumption, investment, and employment are slightly less volatile than in data; net exports are about half as volatile in the model as in the data (0.29/0.40 against 0.63). However, note that our results with $\omega = 0.99$ account for countercyclical net exports. Their correlation with GDP is -0.53 in the model, and -0.51 in the data.

The Arrow-Debreu Economy The fourth column of Tables 3 and 4 reports results for an economy with a complete set of Arrow-Debreu securities. Since in such an economy the volatility of the real exchange rate is to a large extent independent of the price elasticity of imports, we only show numerical results for the lower value of ω — basically replicating the parameterization in Stockman and Tesar [1995], who also examine an economy with complete markets. As 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. Moreover, the volatility of the real exchange rate, the terms of trade, the import ratio and net exports is several times lower than that in the data.

Nevertheless, this model generates a negative correlation between the real exchange rate and relative output, in line with the observed one. This is because a productivity gain in the Home tradable sector raises relative output, worsens the Home terms of trade, but appreciates the real exchange rate — the real appreciation reflecting a higher relative price of nontradables and a fall in relative consumption in the period following the shock, 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.

4.2 Sensitivity analysis

We now assess the sensitivity of our results to (a) removing the distribution sector from our baseline economy, (b) removing cross-country spillovers from the process driving productivity shocks, and (c) using different specifications of investment. We also check whether the Backus-Smith correlation could be explained by a Balassa-Samuelson effect of productivity shocks on consumption and the real exchange rate. Results from these exercises are shown in Tables 3 and 4.

Changing the distribution margin and the elasticity of substitution When we abstract from distributive trade and set $\eta = 0$, the two values of ω for which the relative volatility of the real exchange rate in the model is the same as in the data are 0.33 and 0.41*,* a good deal lower than in our benchmark economy. As discussed in Section 4, the need to combine tradables with retailing in our baseline economy makes the price elasticity of imports lower than the value implied by the preference parameter ω. Without retailing, for the model to fit the volatility of the exchange rate, we need to assume a relatively lower elasticity of substitution between Home and Foreign goods.

With a lower elasticity of substitution but no retailing, the model still performs remarkably well with respect to the Backus-Smith anomaly: the correlation between the real exchange rate and relative consumption is negative and equal to -0.37 (-0.77) for $\omega = 0.33$ (0.41). The underlying mechanism has already been thoroughly discussed 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 to real exchange-rate fluctuations much more than in our 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 much higher fraction than in the data. Moreover, the relative price of nontradables is more than twice as volatile as in our baseline model with distribution (3.67 and 2.28 against 1.72 and 1.43 depending on ω), as well as in the data (1.73). These results confirm that introducing a distribution sector improves the performance of the model independently of contributing to lower the trade elasticities.

Balassa-Samuelson effects An interesting issue is whether the Backus-Smith anomaly could be accounted for by a Balassa-Samuelson effect, linking exchange-rate fluctuations to movements in the relative price of nontradables. The idea is as follows. Consider a model in which domestic and foreign tradables are highly substitutable. A positive productivity shock to the tradable sector should appreciate the real exchange rate (terms of trade movements are tiny), *and* drive up domestic relative to foreign consumption. Is the Backus-Smith correlation driven mainly by this effect?

To address this issue, we abstract from distributive trade $\eta = 0$ and assume a rather high value of ω, equal to 10 — so as to make tradables more homogeneous across countries and reduce the role of the terms of trade in exchange-rate fluctuations (results are the same for higher ω). With such a high elasticity of substitution, the correlation between the real exchange rate and relative output becomes very negative (-0.72), but the corresponding correlation with relative consumption remains close to one, i.e. as high as 0.92. In addition, both the real exchange rate and the terms of trade are a great deal less volatile than output (0.95 and 0.20), while their cross-correlation is substantially lower than in the data (0.13).

Absence of Spillovers As shown in Table 2, the process driving productivity that we estimate and use in our model displays substantial cross-country spillovers. How much of our results can be attributed to the magnitude of such spillovers? It turns out that removing them altogether in our numerical exercises does not substantially affect our main conclusions. Adopting the productivity process without spillovers, we again calibrate our economy such that the real exchange rate is as volatile as in the data, obtaining $\omega = 0.93$ and $\omega = 1.16$. The Backus-Smith correlation remains close to the one in our baseline economy: -0.64 and -0.39. However, one significant implication of removing spillovers is that consumption becomes negatively correlated across countries for $\omega = 0.93$.

Changing the investment specification In our baseline economy investment is carried out solely in domestically produced tradable goods. In our last exercise, we allow for a more general specification in which investment is a composite good comprising both Home and Foreign tradables. We assume that investment goods are 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. As in our baseline calibration, we set a_{H} and a_{F} such that imports (which now also include investment) are 5 percent of aggregate output in steady state. We continue to assume that distribution services are required only to bring tradables to consumers. In Tables 3 and 4 results are shown under the heading "CES Investment."

With the more general CES specification for investment, the values of ω needed to reproduce the volatility of the real exchange rate relative to that of output are smaller than under our benchmark calibration. This is because investment goods can now be imported from abroad, and investment does not use distribution services. Thus, any given price elasticity of imports corresponds to a lower elasticity of substitution relative to our baseline specification. Nonetheless, 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 in our previous experiments, their correlation remains well below unity. When $\omega = 0.57$, the model predicts a slightly negative correlation of -0.08.

Finally, we report results for an economy without capital accumulation (shown under the heading "No Capital" in the tables). Excluding capital does not substantially change the match of the model with the data along most dimensions. However, for $\omega = 0.97$,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).

4.3 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.

Our experiments consist of shocking the exogenous process for sectoral productivity once by 1 percent at date 0, when both countries are at their symmetric, deterministic steady state, and let productivity be driven by the estimated autoregressive process in (15). Figure 2 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 2 report impulse responses for $\omega = 0.99$ and $\omega = 1.11$, respectively.[23]

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]).[24] The notable feature of

[23] Although not reported in the charts, all variables ultimately return to their steady-state values following this one-time shock, because of the endogeneity of the discount factor. As we mentioned previously, the slow convergence is due to the low value of the parameter ψ required to match the steady state real interest rate.

[24] 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.. $\omega \to \infty$, so that there are no terms of trade fluctuations (see e.g., Stockman and Dellas [1989] and Tesar [1993]). With this specification,

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. Note that net exports increase following the rise in productivity, which is consistent with the depreciations of the real exchange rate and the terms of trade.

The response of the economy to an innovation in the productivity of the domestic traded sector is widely different when $\omega = 0.99$. In this case, relative output still rises, but the real exchange rate and the terms of trade now appreciate. Recalls 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 a terms-of-trade appreciation in equilibrium 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. Finally, the positive productivity shock triggers a fall in net exports, which can account for its well-known negative counter-cyclical movements.

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.

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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. Note, however, that these models obviously leave unexplained the terms of trade behavior.

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

In this section we study the comovements between the real exchange rate, the terms of trade, and relative consumption in response to productivity changes in the U.S. economy. Given our focus on time series evidence, we use VAR methods, extending work by Galí [1999] and Christiano, Eichenbaum and Vigfusson [2003] — 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 in a closed-economy framework the effects of technology shocks identified using long-run restrictions. This literature uses the basic 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.[25] However, since Galí [1999], several contributions have pointed out that these methods yield results that may be sensitive to assumptions about the particular VAR specification, e.g. the number and kind of variables included and the time series of properties of the variables. In this vein, Christiano, Eichenbaum and Vigfusson [2003] show that the findings in Galí [1999] are turned around when variables like per capita hours worked are treated as a trend stationary process rather than as a difference stationary process, as does the latter author.

Following these insights, we thus examine the effects of technology shocks to the U.S. manufacturing sector (our proxy for traded goods), identified with long run restrictions, on the real exchange rate, the terms of trade, net exports and relative consumption and output, while carrying out several robustness checks. As 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. Moreover, the use of TFP provides a further check on the identification strategy, as it amounts to controlling for long-run effects on labor productivity brought about by changes in the long-run capital labor ratio.[26] Leaving to the data

[25]See Shapiro and Watson [1988], Francis and Ramey [2003] and Chang and Hong [2002], among others. Some open-economy papers, following Blanchard 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.

[26]For instance, Uhlig [2003] argues that a unit root in labor productivity may results not only from the standard RBC shock to TFP, but also from permanent shocks to the capital-income tax. .

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

$$\begin{bmatrix} \Delta x_t \\ \Delta y_t \end{bmatrix} = \begin{bmatrix} C^{xz}(L) & C^{xm}(L) \\ C^{yz}(L) & C^{ym}(L) \end{bmatrix} \begin{bmatrix} \Delta \varepsilon_t^z \\ \Delta \varepsilon_t^m \end{bmatrix}. \tag{21}$$

Here x_t denotes the variable that is assumed to be affected in the long run only by permanent technology shocks: 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, both measured in deviation from labor productivity in an aggregate of other OECD countries. In the quarterly specification y_t is a 5x1 vector of variables, including (the log of) U.S. aggregate GDP and consumption relative to that of a composite of other OECD countries, the U.S. ratio of net export over GDP, (the log of) the U.S. real effective (trade-weighted) exchange rate, and (the log of) the terms of trade (computed as the non-energy imports deflator over the exports deflator). In the annual specification, in order to save degrees of freedom y_t is 3x1. The first two components of the quarterly specification are always included, while the last three are included one by one.[27]

$C(L)$ 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.[28] 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 benchmark specification is the assumption that all the other variables also have a unit root; this assumption is not rejected by the data over our sample. However, following the suggestions in Christiano, Eichenbaum and Vigfusson [2003], we also estimated specifications of the VAR with those variables, like the real exchange rate, for which the unit root null is not rejected only marginally, in levels. Our main findings below, that a technology improvement leads to a persistent terms-of-trade deterioration and real exchange-rate depreciation, are basically unaltered.[29]

[27] We also estimated specifications of the model including more U.S. and international variables, like investment, real wages and hours worked, and different definitions of the terms of trade. Since very similar results to those discussed in the text are obtained, they are not included to save on space. They are available from the authors upon request.

[28] 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.

[29] These results are not included in the paper to save on space, but they are available upon request.

Figure 3 shows the effects of the identified technology shocks on the levels of productivity, relative consumption, the real exchange rate, and the terms of trade. 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).[30]

The first column in Figure 3 shows the impulse responses using Galí's identification scheme, with x_t equal to (relative) U.S. manufacturing labor productivity. 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. Net exports fall following the positive productivity shock, which is consistent with the predictions of the model with appreciations of the real exchange rate and the terms of trade.

The second column in Figure 3 reports the effects of a technology shock identified as the only shock that permanently affects TFP in U.S. manufacturing. Our findings are broadly robust across different long-run identification schemes. In the annual data 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.[31] As with quarterly data, the rise in productivity leads to a fall in net exports.

Finally, we also checked whether these results were robust to using a different identification scheme, namely, assuming that a technology shock is the contemporaneous innovation to relative labor productivity in U.S. manufacturing, while keeping the same order of the variables as in (21) but in levels rather than first-differences. This identification scheme is closer in spirit to the assumption implicit in our calibration that labor productivity is basically an exogenous process. Again, the results were very similar to those obtained above so that we do not report them here for the sake of brevity.

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

[30] The standard error bands were computed using a bootstrap Monte Carlo procedure with 5000 replications. We thank Yongsung Chang for graciously providing us with his bootstrapping codes.

[31] 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.

following changes in (relative) labor productivity in 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, as well as the fall in net exports 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 the price elasticity.[32] 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.[33]

6 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 to 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, large terms of trade movements are much less effective in providing insurance against production risk and are 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

[32] It is worth stressing that our results for the U.S. — a very large, very rich and relatively closed economy — may not generalize to smaller and more open countries. If anything our theoretical model suggests that in equilibrium wealth effects are weaker for smaller and more open economies.

[33] In our analysis we link the terms of trade appreciation in response to productivity shocks to price elasticities. One of us has followed a different approach, exploring whether terms of trade appreciation could follow the introduction of new export varieties due to technological improvements (Corsetti Martin and Pesenti [2004]). Preliminary results suggest a negative answer.

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 improves 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. 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 would prove extremely helpful.

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A Data Sources

This appendix describes the data used in this paper. The complete dataset is available from the authors upon request and covers the period 1970 to 2001, unless otherwise stated.

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 an aggregate of OECD countries (Canada, Japan, EU-15) obtained from the OECD STAN sectoral database.

U.S. GDP, consumption and investment are annual chain-weighted 1996 dollar NIPA series from the BEA. World GDP, consumption and investment are annual constant 1995 PPP dollar series for Japan, Canada and EU-15 from the OECD Quarterly National Accounts. The U.S. labor input is the "Index of total hours in the non-farm business sector" from the BLS, while world labor input is aggregate employment for Japan, Canada and EU-15 from the OECD.

The series for U.S. imports and exports at current and constant prices are annual 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 vis-à-vis the main U.S. trading partners; 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. The relative price of nontradables in terms of tradables is computed as the ratio of the services CPI over the commodities CPI. Again all this are annual series.

In the estimation of the VAR models for the series on world labor productivity (quarterly) and total factor productivity (annual) we use the ratio between aggregate GDP and labor input for Japan, Canada and EU-15, and the index of TFP in the aggregate OECD countries from the OECD, respectively. In the quarterly VAR, the series for GDP, consumption, net exports, real exchange rate and terms of trade are the quarterly counterpart of the annual series described above.

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
Median[b]	-0.30	-0.27	-0.27	-0.21
	(-0.12,-0.56)	(0.12,-0.54)	(-0.11,-0.41)	(0.02,-0.55)

[a]Consumption and bilateral and effective real exchange rates are annual series from the OECD Main Economic Indicators dataset, from 1973 to 2001. [b]In parenthesis the cross-sectional 68 percent confidence interval.

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	$\frac{1}{1-\rho} = \{0.99, 1.11\}$
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	$\eta = 1.09$
Labor Share in Tradables	$\xi = 0.61$
Labor Share in Nontradables	$\zeta = 0.56$
Depreciation Rate	$\delta = 0.10$

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]

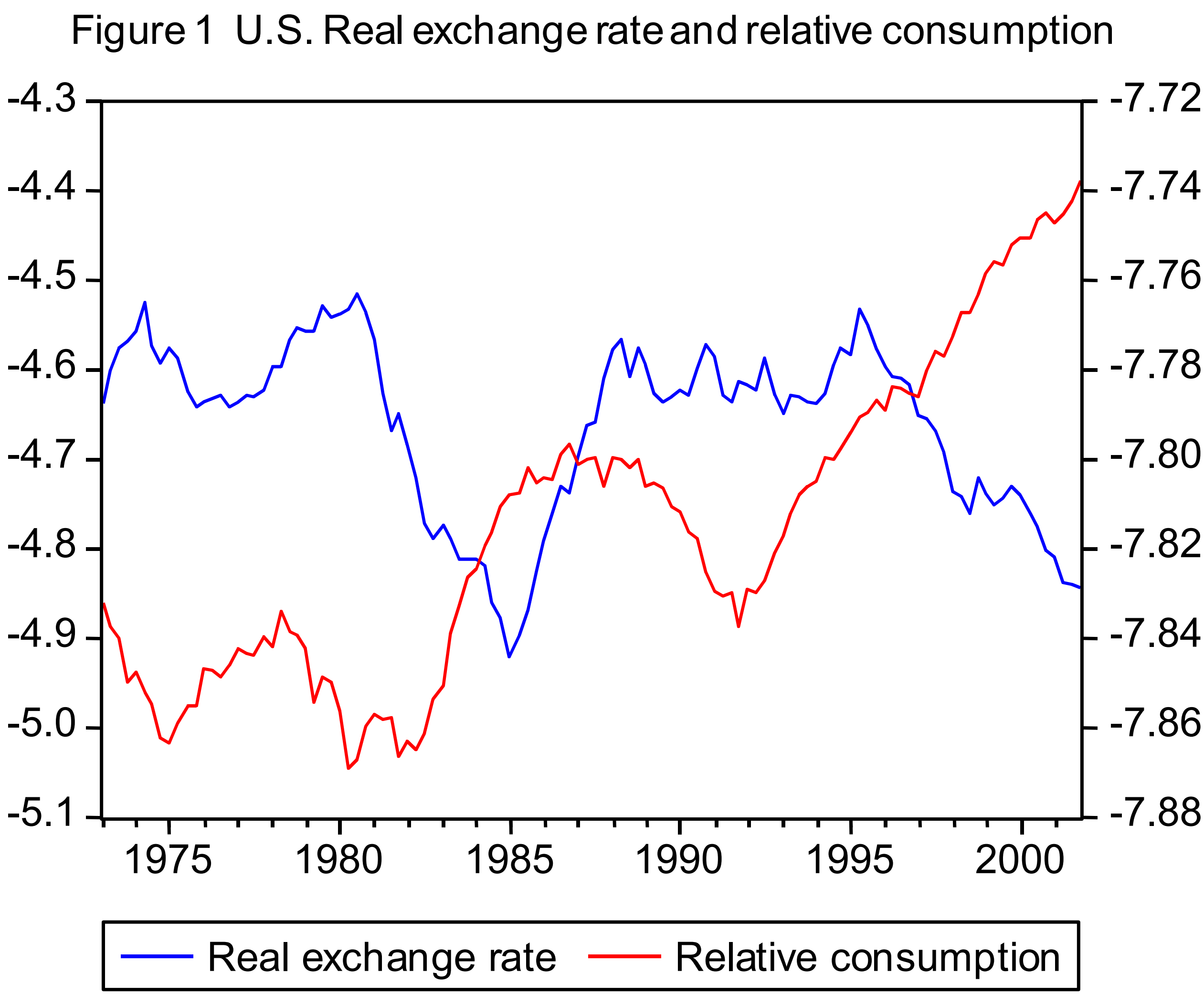
Statistics	Data	Benchmark Economy		Variations on the benchmark economy: Arrow-Debreu Economy	No Spillover		CES Investment		No Capital		No Distribution		
		$\omega = 0.99$	$\omega = 1.11$	$\omega = 0.99$	$\omega = 0.93$	$\omega = 1.16$	$\omega = 0.40$	$\omega = 0.57$	$\omega = 0.97$	$\omega = 1.05$	$\omega = 0.33$	$\omega = 0.41$	$\omega = 10$
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	0.95
Terms of trade	1.79	3.04	4.34	0.61	3.23	4.16	2.49	4.36	3.79	4.13	2.74	4.77	0.20
absolute													
Relative price of nontradables	1.73	1.72	1.43	1.24	1.64	1.51	1.47	1.10	1.23	1.23	3.67	2.28	2.59
Cross-correlations													
Between real exchange rate and													
Relative GDPs	-0.23	-0.97	0.78	-0.48	-0.98	0.70	-0.88	0.80	-0.57	0.82	-0.82	0.82	-0.72
Relative consumptions	-0.45	-0.55	-0.55	0.98	-0.64	-0.39	0.31	-0.08	-0.77	0.66	-0.37	-0.77	0.92
Net exports	0.39	0.95	0.95	-0.73	0.94	0.94	0.88	0.96	0.99	0.99	0.99	0.99	0.23
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	0.13
Between terms of trade and													
Relative GDPs	-0.20	-0.91	0.90	0.82	-0.82	0.87	-0.89	0.83	-0.33	0.93	-0.81	0.85	0.41
Relative consumptions	-0.53	-0.72	-0.73	0.03	-0.81	-0.61	0.21	-0.20	-0.57	0.82	-0.46	-0.86	0.46
Net exports	0.43	0.99	0.99	0.74	0.99	0.99	0.92	0.99	0.97	0.99	0.99	0.99	0.99

[a] $\omega = \frac{1}{1-\rho}$ denotes the elasticity of substitution between Home and Foreign traded goods. The data reported under the heading "Data" are those of the U.S. vis-à-vis the rest of the OECD countries.

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

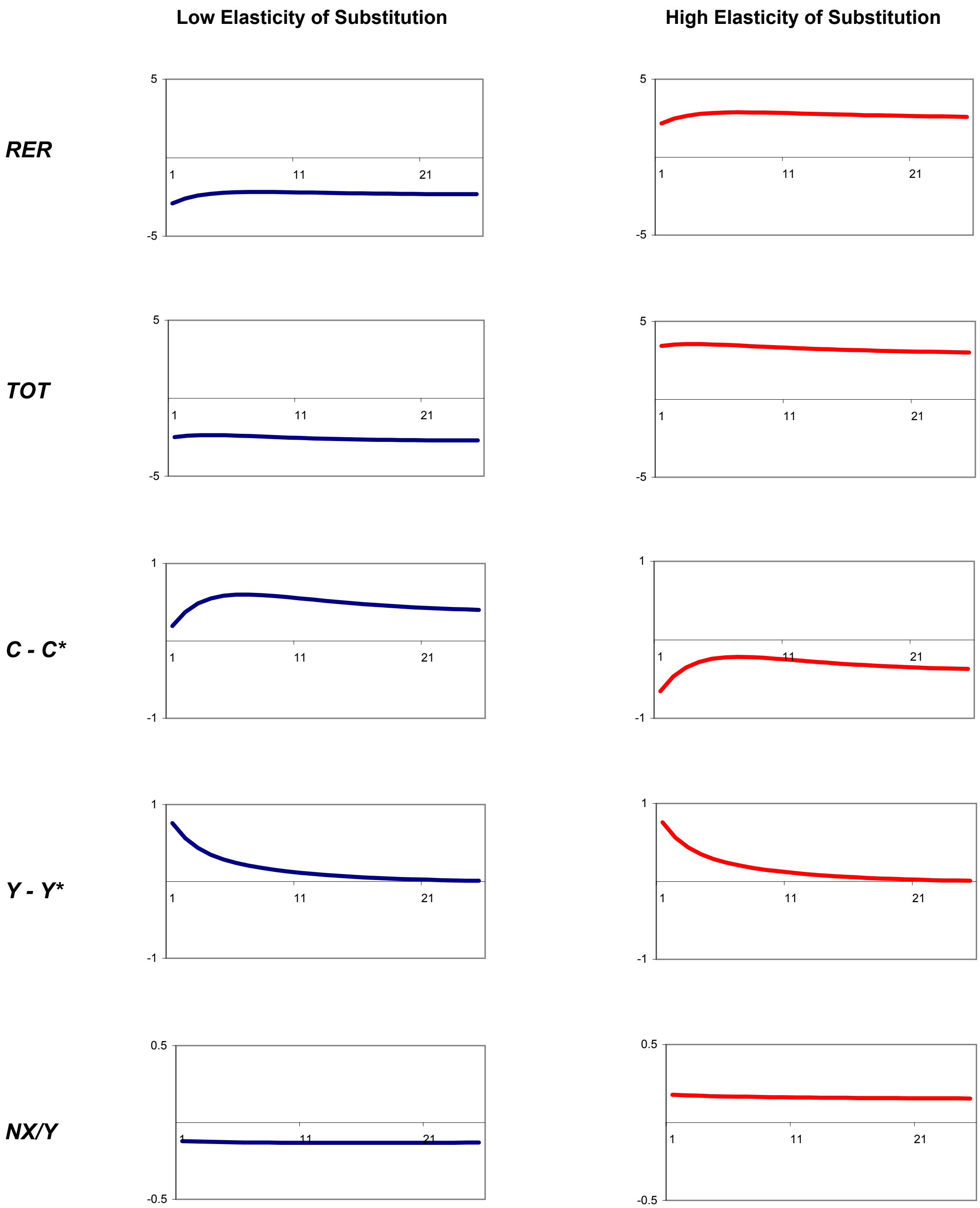
Statistics	Data	Benchmark Economy		Variations on the benchmark economy: Arrow-Debreu Economy	No Spillover		CES Investment		No Capital		No Distribution		
		$\omega = 0.99$	$\omega = 1.11$	$\omega = 0.99$	$\omega = 0.93$	$\omega = 1.16$	$\omega = 0.40$	$\omega = 0.57$	$\omega = 0.97$	$\omega = 1.05$	$\omega = 0.33$	$\omega = 0.41$	$\omega = 10$
Standard deviation relative to GDP													
Consumption	0.92	0.64	0.56	0.55	0.64	0.49	0.56	0.55	1.09	0.92	0.53	0.70	0.52
Investment	4.25	3.88	3.87	3.88	3.74	3.73	4.38	3.69	—	—	3.89	3.91	3.91
Employment	1.09	0.67	0.68	0.67	0.63	0.64	0.69	0.62	0.12	0.10	0.67	0.68	0.69
absolute													
Import ratio	4.13	2.78	4.44	0.54	2.74	4.45	0.92	2.17	2.25	2.69	1.67	3.66	3.81
Net exports over GDP	0.63	0.29	0.40	0.04	0.30	0.38	0.04	0.08	0.25	0.21	0.28	0.42	0.26
Cross-correlations													
Between foreign and domestic													
GDP	0.49	0.45	0.43	0.45	0.44	0.42	0.43	0.53	0.49	0.50	0.46	0.43	0.34
Consumption	0.32	0.14	0.11	0.48	-0.17	0.13	0.36	0.63	0.28	0.71	0.42	-0.17	0.46
Investment	0.08	0.48	0.45	0.47	0.48	0.46	0.16	0.64	—	—	0.46	0.43	0.33
Employment	0.32	0.47	0.41	0.46	0.49	0.43	0.37	0.74	-0.52	-0.30	0.48	0.42	0.27
Between net exports and GDP	-0.51	-0.53	0.58	0.58	-0.51	0.58	-0.62	0.56	-0.36	0.56	-0.61	0.61	0.25

[a] $\omega = \dfrac{1}{1-\rho}$ denotes the elasticity of substitution between Home and Foreign traded goods. The data reported under the heading "Data" are those of the U.S. vis-à-vis the rest of the OECD countries.



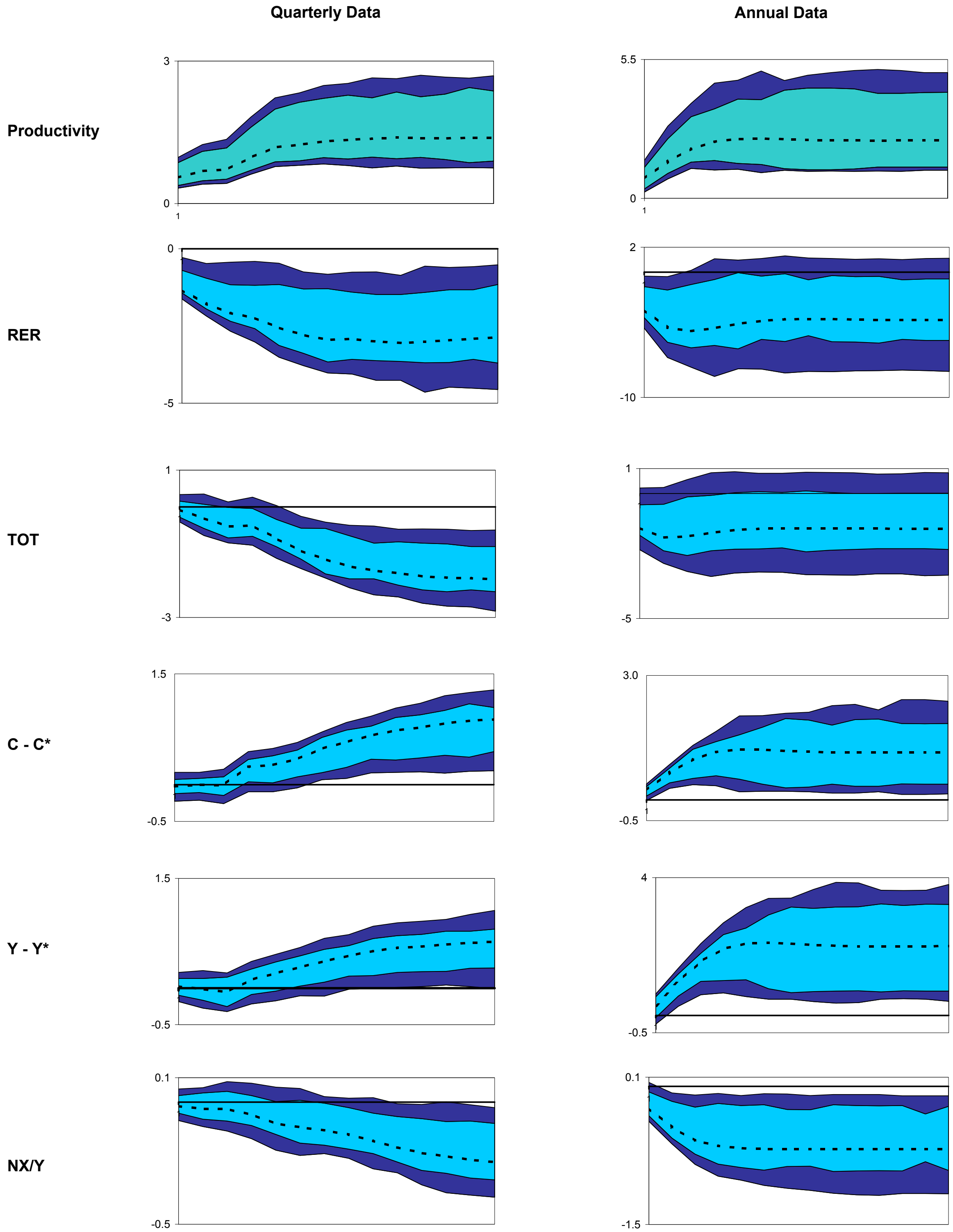
The real exchange rate is eP*/P, where the nominal exchange rate e is the U.S. dollar price of a basket of OECD currencies, P* is an aggregate of OECD CPIs, and P is the U.S. CPI. See the Appendix for the sources.

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



All series are in percent.

Figure 3
Impulse Responses to a Technology Shock in the Traded-Goods Sector



The first column describes the responses from a 6-variable VAR, using quarterly data. The variables are labor productivity, the real exchange rate, the terms of trade, relative consumtpion, relative output, and net exports. The second column shows the responses from a 4-variable VAR, using annual data. The variables are TFP, relative consumption, relative output, and, alternatively, the real exchange rate, the terms of trade, and net exports. All series are in percent.