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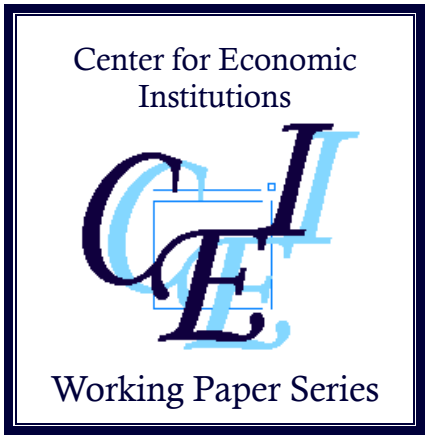

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International Linkages and the Changing Nature of International Business Cycles*

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Abstract

We quantify the effects of changes in international input-output linkages on the nature of business cycles. We build a multi-sector multi-country international business cycle model that matches the input-output structure within and across countries. We find that, in our 23 countries sample with manufacturing and non-manufacturing sectors, changes in the international input-output linkages between 1970 and 2007 causes a 15% drop in output volatility in a median country, but the effects are heterogeneous across countries. Changing international linkages tend to stabilize output in most countries, while leading to a higher risk of a global recession.

JEL classification: E32, F31.

Keywords: International business cycles, trade linkages, volatilities, input-output.

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1 Introduction

Understanding the sources of business cycle volatilities is an important topic in macroeconomics. This paper explores the hypothesis that international linkages have a sizable effect on business cycles. In particular, we quantify the effects of the changing international input-output linkages, including trade intensity and trade partners, on aggregate volatilities of output, consumption, investment, as well as the cross-country transmission of shocks between 1970 and 2007.

To that end, we build a multi-country multi-sector real business cycle model augmented with several features: a weak wealth effect on labor supply, variable capacity utilization, and endogenous variable markup through firms' entry and exit. There are four reasons for our modeling choice. First, a multi-country multi-sector model allows us to map with the the sector-to-sector input-output linkages within and across countries in the data. Second, a multi-country framework can account for the fact that trading relationships between different countries such as the United States and China can have different consequences on domestic economies. Third, we can consider important heterogeneity across sectors, which can be important for the transmission of shocks across countries and business cycle volatilities. In our model, we focus on manufacturing and non-manufacturing sectors, which have substantially different degrees of openness and volatility. Aggregating these sectors into one would make a country too closed, so the transmission of business cycles across countries may be limited. Fourth, the additional features are designed to help the model to generate substantial endogenous transmission of shocks across countries through international trade. Without these features, the model would have a hard time generating endogenous comovements across countries through international trade, so international linkages would play a negligible role in affecting business cycle properties in a standard model by construction. Our baseline analyses assume that each country is driven by independent sector-specific productivity shocks.

In our model, changes in international linkages can both stabilize and destabilize output volatility. The intuition is as follows. Suppose there is an independent positive productivity shock in the domestic economy. Domestic firms try to use more intermediate inputs to increase production. If this country trade more with other countries, it requires more foreign intermediate inputs, which are not supplied as much as domestic intermediate inputs, since foreign productivity does not increase. In other words, the input-output linkages across countries can constrain the production relative to a closed economy. In the demand side, although foreign households and firms try to

import more domestic goods, foreign demand does not increase much as foreign economy is not directly impacted by domestic productivity shocks. This implies that a more open economy can constrain the demand for domestic goods relative to a closed economy. This mechanism suggests that a more open economy can stabilize its output volatility with respect to domestic productivity shocks. However, output volatility in an open economy can also increase. The reason is that in our model, foreign shocks can play an important role in driving business cycle fluctuations, as international trade can transmit shocks across countries. Under some calibration, such as when foreign shocks are more volatile relative to domestic shocks, although the above intuition is still true, a more open country can cause output to fluctuate more than a closed economy. Because of these contrasting forces in the model, the effects of changes in international linkages are a quantitative question.

Our quantitative exercise proceeds in three steps. In the first step, the model is calibrated using data for manufacturing and non-manufacturing sectors in 23 countries and a composite of the rest of the world (ROW). Besides the standard aggregate macroeconomic data, our calibration relies crucially on the detailed World Input-Output (IO) tables from Johnson and Noguera (2017) available between 1970 and 2007 to match the structure of the model completely with the domestic and international input-output structure. In particular, the World IO tables allow us to pin down all of the steady state shares in the model including the shares of domestic and foreign inputs used in productions of consumption and investment goods, and country and sector sizes.

In the second step, we estimate the effects of changing the entire international and domestic input-output linkages on the volatilities of macroeconomic variables. More specifically, we study how much the model-implied output volatility changes when the steady state shares are calibrated based on the changes in all of the elements of the World IO tables over the 1970–2007 period. Since the changes in the entire international and domestic input-output linkages include several changes such as international linkages, relative country sizes and relative sector sizes, the third step is to decompose the total effects found in the second step into the international linkage effects only. To that end, we construct hypothetical World IO tables over the 1970–2007 period where *only* international input-output linkages change. We then compute the changes in the model-implied output volatility based on these hypothetical World IO tables, which gives us the effects of international linkage change on aggregate variables over time. Finally, we compare the effects of international linkages to the effects of changes in relative sector sizes, which have been shown to be important in affecting business cycle volatilities in previous literature in the closed economy

setting.

We find that changes in the entire international and domestic input-output linkages from 1970 to 2007 have sizable effects on aggregate fluctuations across countries. In the baseline calibration, the entire world input-output linkage changes, keeping the size of the shocks constant over time, cause 21% reduction in output volatilities in the median country in our sample, as opposed to about 40% reduction in the data. The decomposition exercise suggests that the international input-output linkages reduce output volatilities by about 15% in a median country in our sample, which is similar in magnitude to the effects of the relative sector size changes.

The changing international input-output linkages have heterogeneous effects across countries. While changes in international input-output linkages decrease output volatilities by 17% in Canada between 1970 and 2007, these input-output changes explain a negligible reduction of output volatilities for the United States (7%) and Japan (3%). In countries such as the United States, the reduction in output volatilities over the last 40 years, so-called the Great Moderation, is attributed to the changes in the relative sector sizes. In particular, the decomposition suggests that 20% reduction in volatility in the United States and 24% in Japan are due to the relative sector size channel, rather than the international input-output linkage channel.

In our robustness exercises, we find that the estimated effects of changing international linkages depend on the channels and the degrees of transmission of shocks across countries in the model. For example, when calibrating a low elasticity of substitution between home and foreign goods, which often increase the degree of shock transmission across countries in standard models, the changes in international linkages lead to a 16% drop in output volatility in the last 40 years in the median country. This result is similar to our baseline estimate. On the other hand, a version of our model without endogenous countercyclical markup, variable capital utilization, and standard wealth effects on labor supply, would suggest that the changing international linkages have negligible effects on output volatility. The reason is that this model, which is essentially a standard international real business cycle model, does not generate much endogenous transmission of shocks through international trade. As a result, this model would suggest that changing international linkages do not have much effects on the aggregate economy. In another robustness check, in which we assume that the uncertainties driving business cycles are confidence shocks, the model generates a larger drop in output volatility in the median country as the baseline. Finally, when shocks are correlated across countries, the changing international linkages tend to cause a smaller drop in output volatility over time compared to the baseline. The intuition for this result is that the

channel through which international linkages reduce output volatility is more muted when shocks are correlated, i.e. both foreign and domestic productivities increase simultaneously.

While changing international linkages tend to reduce business cycle volatilities in many countries, our model indicates that the total changes in IO linkages also increase the influence of foreign shocks in domestic economy for most countries. In particular, we define a "cross-country value added multiplier" to be the ratio of the responses of the foreign value-added output to that of domestic value-added output in response to a domestic shock. The cross-country value added multiplier for U.S. shocks indicates how much output in other countries respond to U.S. shocks relative to the response of U.S. output. Our motivation for computing this multiplier is as follows. Although our decomposition exercise quantitatively assess the historical importance of changing international linkages, the decomposition is about the long run, and it depends on calibrated fixed standard deviations of shocks. A rare large shock in foreign country, such as in the Great Recession, can increase observed volatility with more linkages, even when theoretical long run volatility declines. This multiplier helps us isolate the effects of a unit GDP shock in one country to other countries over time. When we calibrate the model at each point in time using the World IO tables, we find that the multipliers for each country's shocks increase over the last 40 years, suggesting that the influence of foreign shocks has increased. The multipliers for Chinese shocks increase substantially during this time period, reflecting the fact that China becomes a more important economy in the world. This finding suggests that changing IO linkages increase the potential risk of foreign shocks transmitted through international trade, causing a global recession.

We note that our exercise does not attribute the changes in the international linkages to trade costs or trade policy. The changes in the international input-output linkages in our model are modeled as exogenous changes affecting the steady-state shares in intermediate and final goods. As discussed in Obstfeld and Rogoff (2000), the specification of the shares in our model, which is based on standard international business cycle models, is isomorphic to the specification with iceberg trade costs. So one can interpret that the changes in the steady state shares over time in our exercise are driven by trade cost changes. At the same time, there are other reasons that these shares change, including trade policies, preferences, and demand composition. Furthermore, each of these fundamental reasons such as trade costs or trade policies can affect not only the international linkages but also domestic structure such as relative sector sizes in the economy. We do not focus on these fundamental reasons. Instead, we focus on the consequences of international linkage changes on business cycles using a structural model that incorporates minimum departures from standard

international business cycle models. We take the within and across countries input-output linkage changes as given, and isolate the international linkage channel.[1] Finally, there are certainly other explanations of changes in volatilities across countries such as the shock processes, monetary and fiscal policies, we focus on the linkages across countries and quantify the importance of this channel in driving business cycle volatilities.

Related literature Our paper contributes to the literature studying the causes of the decline in volatilities, or the Great Moderation, in the United States and some other countries. For example, Clarida, Gali, and Gertler (2000) propose better monetary policies, Justiniano and Primiceri (2008) estimate that investment-specific technology shocks explain the sharp decline in output volatilities. Jaimovich and Siu (2009) attribute part of the movement in output volatility in G7 countries to the changes in the composition of the labor force. Moro (2012) and Carvalho and Gabaix (2013) show that changes in the manufacturing sector in the United States can explain the decline in output volatilities. Garin, Pries, and Sims (2017) study the relative importance of aggregate and sectoral shocks. Unlike these papers, we explore the international input-output linkage channel as a determinant of aggregate volatilities, which turns out to be substantial in many countries but not in the United States. We view our channel as complementary to other mechanisms in the literature. We also cover a larger number of countries and explore the heterogeneity effects of international input-output linkages as well as the relative sector size changes on aggregate volatilities.

Our paper also relates to the literature exploring the effects of trade openness and volatilities, which has come to different conclusions. While Haddad et al. (2013) and others find that trade openness decreases volatilities, some papers such as Kose, Prasad, and Terrones (2003) find the opposite. Di Giovanni and Levchenko (2009) estimate that trade openness results in an increase in volatilities through sectoral volatilities, with a reduction in volatilities due to comovement using an unbalanced panel data of 28 manufacturing sectors for 61 countries between 1963 and 2003. There are several differences between our paper and these papers. First, we use a structural model to quantify the importance of input-output linkages in driving volatilities across a number of countries, while these papers use reduced-form estimates. Although reduced-form estimation can explore the larger panel of sectors and countries, it does not address the heterogeneous effects of trade on volatilities across countries. Our structural approach takes into account the fact that their inter-

[1] Similarly, we focus on the effects of changes in relative sector sizes, and do not model the causes of these changes, which can include trade costs, structural changes, relative productivity changes, and policies. Therefore, we do not interpret that the sum of the effects of changes in international input-output linkages and relative sector sizes on aggregate volatilities as the impact of international trade cost changes, or other fundamental reasons.

national and domestic structures differ. Besides, we focus on a particular channel of international trade, the input-output linkages, rather than the total effects of international trade, which can work through several different channels. Furthermore, the endogeneity issue is not completely resolved in reduced-form estimates, and the total effects of trade openness on aggregate volatilities are based on specific assumptions such as no spillover across sectors within the country. The closest paper to ours is Caselli et al. (2017), who use a structural trade model and find that reduced trade costs since 1970s increase volatilities for some countries but decrease volatilities for some other countries in their sample. While their structural model is a static trade model to capture trade patterns across countries, our model is a fully dynamic business cycle model with capital accumulation and labor choices, taking into account endogenous transmission of shocks across countries, which is suitable to study business cycle properties. The endogenous transmission mechanism in our model allows for international linkages to play an important role in driving business cycles across countries. Furthermore, we can use our model to analyze the relative importance of international input-output linkage changes and sector sizes in driving business cycles, which is not included in their model.

We broadly fit into the broad literature studying business cycle comovement across countries. International business cycle models, starting from Backus, Kehoe, and Kydland (1992), tend to generate weak cross-country correlations of aggregate variables. A more specific problem, pointed out by Kose and Yi (2006), is that standard models fail to generate a positive relationship between output correlations across countries and bilateral trade, dubbing the "trade-comovement" puzzle. Several papers have proposed solutions to this weak comovement problem.[2] In general, the weak comovement problem is related to the classical problem of the closed economy RBC model where only technology shocks can generate the right comovement of aggregate variables and large shift of the labor demand curve. So, frictions addressing this problem can potentially work to increase comovements in the model. We focus on the implications of changing international linkages and business cycle dynamics over time. Since comovement is a problem in the standard model, our baseline model is built on Miyamoto and Nguyen (2017), which studies the dynamic comovement given the identified technology shocks and includes simple departures from the standard models

[2]This literature is large. A few more recent examples include Davis and Huang (2011), Liao and Santacreu (2015), Llosa (2016), de Soyres (2017) and Drozd, Kolbin, and Nosal (2014) generate larger comovement across countries when including more frictions into their models. Other examples include Burstein, Kurz, and Tesar (2008), who calibrate their model with a low elasticity of substitution across countries, representing production sharing, so the relative price movements increase, shifting the labor demand curve, increasing cross-country correlations of output. Kollman (2001) and Huang and Liu (2007) use nominal rigidities generating variable markups to resolve the low comovement across countries.

such as variable capacity utilization, weak wealth effect on labor supply, and variable markup.[3] So as a byproduct, our model can generate more output correlations across countries for each bilateral country pairs.

The rest of the paper is organized as follows. Section 2 documents some features of the input-output linkages and business cycles in 23 countries between 1970 and 2007. We then describes the model built to quantify the role of international linkages in Section 3. The calibration of the model is presented in Section 5. We analyze the shock transmission mechanism in the model to study how international and domestic input-output linkages can affect the behavior of the aggregate economy in Section 4. The main results of the paper are presented in Section 6. We present the results under several different model assumptions in Section 7. Finally, we show that countries are more at risk of a global recession in Section 8. Section 9 concludes.

2 Data

Our data cover 23 countries and a composite ROW between 1970 and 2007. These countries are Australia, Austria, Belgium, Brazil, Canada, China, Germany, Denmark, Spain, Finland, France, UK, Greece, India, Ireland, Italy, Japan, Korea, Mexico, Netherland, Portugal, Sweden, and the United States. The national account data and the sectoral value added data for manufacturing and non-manufacturing sectors are in annual frequency from the United Nation database, while the World IO table between 1970 and 2007 are from Johnson and Noguera (2017). We supplement the annual national account data by quarterly data from the OECD.[4]

Business cycles have changed substantially in many countries over the 1970–2007 period, but the change is heterogenous across countries. We plot in Figure 1 the median 10-year rolling over standard deviations of HP-filtered output, consumption and investment in 23 countries in our samples between 1970 and 2007.[5] The graphs are similar if we use quarterly data. Aggregate volatilities tend to decrease over this period in many countries. Output is about 40% less volatile in the early 2000s than in the early 1970s in the median country.

The changes in business cycle properties are heterogeneous across countries. While for countries like the United States and Canada, output volatilities have declined up to 40% between 1970 and

[3] Johnson (2013) shows that the intermediate input trade in an otherwise standard international real business cycle model does not resolve the weak comovement problem.

[4] Chinese data are taken from the National Bureau of Statistics of China. The World Input Output Database (WIOD) has more sectors and countries, but they go back to 1995 only. Also, its two versions 1995–2011 and 2000–2014 are not compatible with each other, making it impossible for us to extend the data.

[5] The plot is similar if we use the growth rates of output, consumption and investment.

2007, business cycles in Korea or Mexico do not have a clear trend: they go through both high and low volatility periods during the same period.

The input-output linkages within and across countries have also changed substantially, and heterogeneously across countries between 1970 and 2007. Volume of trade increases significantly: total exports and imports in the value added in the manufacturing sector in a median country increase from 80% in 1970 to over 250% in 2007, as plotted in Figure 2.[6] Not only do countries trade more, but they also change their trade partners. For example, as shown in Figure 3, while the United States traded more with Japan than with Mexico and China in terms of total exports and imports share in the manufacturing value added up to 1995, both Mexico and China now have larger trade shares with the United States than Japan. The linkages within countries have also gone through much changes. The use of imported intermediate inputs has increased from 7% of the value added of the manufacturing sector in the United States in 1970 to over 30% in 2007. Furthermore, the importance of each sector in the economy changes over time. As plotted in Figure 4, the share of the manufacturing sector in gross output decreases from 38% to around 31% in median country during this period. However, the pattern is not the same for all countries. While the size of the manufacturing sector tends to decline in many countries such as the United States, where the manufacturing sector as a share of total value added has declined from 24% to 13%, this share has stayed around 20% for Mexico, and increased in Korea to 30%. These changes in the input-output linkages can potentially explain some of the heterogeneous changes in business cycles over time.

3 The Model

This section describes the model used to quantify the effects of international linkages on the changing nature of business cycles across countries. The model is an extension of Backus, Kehoe, and Kydland (1995) with several additional features. First, we build a multi-country and multi-sector model, where countries trade with one another in both intermediate and final goods in each sector. This feature is to capture the input-output linkages within and across countries in the data. Second, we augment the model with variable capacity utilization, and endogenous markup caused by firms' entry and exit. As suggested in Miyamoto and Nguyen (2017), these departures from a standard international real business cycle model allow the model to generate endogenous transmission of

[6] See Appendix Figure A1 for the total imports and exports in gross output.

productivity shocks across countries through international linkages. We model the firms' entry and exit problem, based on Jaimovich and Floetotto (2008), which generates endogenous variations in the number of operating firms, and consequently, markup over the business cycle. Finally, the model also includes investment adjustment costs to avoid the strong resource shifting mechanism in the model after a foreign shock, which can cause domestic investment to fall.

There are $I = 24$ countries. Each country has $S = 2$ sectors. The multi-country set up allows us to account for trading relationships among different countries. If we aggregate all foreign countries into a rest-of-the-world composite, whether the country trades with the United States or China does not matter. Furthermore, the rest-of-the-world aggregate does not distinguish whether a country trades with multiple weakly correlated countries, in which the effects of foreign shocks on domestic economy can be small, or one big country, in which the effects of foreign shocks can be large. Since our goal is to analyze the effects of changing international linkages, we build a multi-country model to account for the entire trade network across countries.

Additionally, we focus on two sectors in each country: manufacturing and non-manufacturing sectors. The reasons to consider two sectors are as follows. First, these two sectors have different degree of openness in terms of trade shares, and different volatilities. While the manufacturing sector is open and volatile, the non-manufacturing sector is almost closed and stable over time. If we aggregate these two sectors into one in the model, the country is less open as a whole, so international trade may play a smaller role for business cycles. In a two-sector model, since only the manufacturing sector is volatile, which matters for business cycles, and it is more open, international linkages can contribute more to business cycle fluctuations. Therefore, we can capture important heterogeneities across sectors by including both manufacturing and non-manufacturing sectors separately.[7] Second, having two sectors allow us to compare the importance of the international linkage changes on business cycle volatilities with that of the changes in the relative sector sizes, which has been emphasized to be important in the literature.

We describe the setup for country i below.

[7] To the extent that there are heterogeneities within each sector, we may still have some aggregation bias. However, the need for long data of the World IO tables constrains us from using a model with more disaggregated sectors.

3.1 Households

Households in country i, subject to a budget constraint, maximize their lifetime expected utility:

$$\max \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t U(C_t(i), H_t(i)) \tag{1}$$

where $C_t(i)$ and $H_t(i)$ denote consumption and hours worked in country i at time t, respectively.

Households face a period by period budget constraint, as follows:

$$C_t(i) + p_I(i) I_t(i) + \varepsilon_t(i) E_t r_{t,t+1} B_{t+1}(i) \leq W_t(i) H_t(i) + R_t^k(i) u_t(i) K_t(i) + \varepsilon_t(i) B_t(i) \tag{2}$$

where $I_t(i)$ is the investment of country i at time t, $B_{t+1}(i)$ is the bond holding of country i in the unit of the ROW goods, $r_{t,t+1}$ is the stochastic discount factor such that $E_t r_{t,t+1} B_{t+1}$ is the period t price of B_{t+1} in period $t+1$, and ε_t is the real exchange rate relative to the ROW, $K_t(i)$ is capital available at time t, $W_t(i)$ and $R_t^k(i)$ are the wage and rental rate of capital, respectively. The evolution of capital follows a standard form as follows:

$$K_{t+1}(i) \leq (1 - \delta(u_t(i))) K_t(i) + I_t(i) \left(1 - S\left(\frac{I_t(i)}{I_{t-1}(i)}\right)\right), \tag{3}$$

where $u_t(i)$ is the variable capital utilization rate, $\delta(u_t(i))$ is the cost associated with variable capital utilization, and $S(.)$ is the investment adjustment cost, respectively. The investment adjustment cost satisfies $S(1) = 0, S'(1) = 0, S''(1) = s > 0$. We assume that the steady state utilization rate $u(i)$ is 1, and the utilization cost function $\delta(u_t(i))$ is convex, and $\delta(1) = \delta_0$, which is the steady-state depreciation rate. We calibrate the inverse elasticity $\delta''(1)/\delta'(1)$.

3.2 Firms

There are S sectors in each country, $s, k \in 1, ..., S$ and $i, j \in 1, ..., I$. Each firm in country i sector s produces a tradable differentiated using capital, labor and a composite intermediate good, which is an aggregate of intermediate goods produced by other countries and sectors. The local industry in each sector s of country i has a limited number of firms, and aggregates individual firms' output into raw output $Q(i, s)$. The raw output $Q(i, s)$ is then aggregated across countries and sectors to produce final consumption, investment and intermediate goods. The details of the production in the economy are described below.

The final composite goods are aggregate of sector final composite goods. Firms producing final composite goods in country i, $F(i)$, combine sectoral final composite goods to be used for consumption and investment in country i:

$$C(i) = \left[\sum_{s=1}^{S} (\omega_{CF}(s,i))^{\frac{1}{\gamma_F}} \underbrace{(f_C(s,i))^{\frac{\gamma_F-1}{\gamma_F}}}_{\text{sectoral final composite good}}\right]^{\frac{\gamma_F}{\gamma_F-1}} \tag{4}$$

$$I(i) = \left[\sum_{s=1}^{S} (\omega_{IF}(s,i))^{\frac{1}{\gamma_F}} \underbrace{(f_I(s,i))^{\frac{\gamma_F-1}{\gamma_F}}}_{\text{sectoral final composite good}}\right]^{\frac{\gamma_F}{\gamma_F-1}} \tag{5}$$

where $\omega_{CF}(s,i)$ and $\omega_{IF}(s,i)$ are the shares of sector s in the final composite consumption and investment goods, respectively, $f(s,i)$ is the sectoral final composite goods, and γ_F is the elasticity of substitution across sectoral final composite goods. Then, the demand for final sectoral composite is given by

$$f_C(s,i) = \left(\frac{P_{Cf}(s,i)}{P(i)}\right)^{-\gamma_F} \omega_{CF}(s,i) C(i), \tag{6}$$

$$f_I(s,i) = \left(\frac{P_{If}(s,i)}{P_I(i)}\right)^{-\gamma_F} \omega_{IF}(s,i) I(i), \tag{7}$$

where $P_I(i)$ is the investment goods price, $P(i)$ is the price level of country i, and $P_f(i,s)$ is price of sector s goods in country i.

Final sectoral firms combine goods of the same sector in both domestic and foreign countries to produce a sectoral final composite consumption good as follows:

$$f_C(s,i) = \left[\sum_{j=1}^{I} (\omega_{Cf}((j,s),i))^{\frac{1}{\gamma_f}} \underbrace{(f((j,s),i))^{\frac{\gamma_f-1}{\gamma_f}}}_{\text{shipment from country } j \text{ to } i}\right]^{\frac{\gamma_f}{\gamma_f-1}}, \tag{8}$$

where $f((j,s),i)$ is the shipment of sector s goods from country j to country i, $\omega_f((j,s),i)$ is the share of $f((j,s),i)$ in sectoral final composite consumption goods, and ω_f is the elasticity of substitution across countries in sector s. Then the demand for the shipment of sector s goods from country j to country i is given by:

$$f_C((j,s),i) = \left(\frac{P_f((j,s),i)}{P_{C,f}((s,i))}\right)^{-\gamma_f} \omega_{C,f}((j,s),i) f_C(s,i), \tag{9}$$

where $P_f((j,s),i)$ is price of shipment of sector s goods from country j to country i. The produc-

tion of sectoral final composite investment goods are analogous to that of sectoral final composite consumption goods.

Following Jaimovich and Floetotto (2008), there is a continuum of local industries of measure one, which is aggregated to a raw sectoral output in each country. This assumption means that individual firms can affect prices at the local industry prices but not in the aggregate, which simplifies the model. In particular, the raw sectoral output $Q(i,s)$ is given by:

$$Q\left(i,s\right)=\left[\int_{0}^{1}L\left(i,s|l\right)^{\frac{\gamma_{Q}-1}{\gamma_{Q}}}dl\right]^{\frac{\gamma_{Q}}{\gamma_{Q}-1}}, \tag{10}$$

where $L(i,s|l)$ is the output of local raw industry l in country i and sector s and γ_Q is the elasticity of substitution across different local sectors. In each local industry l of sector s in country i, there are a limited number of firms $N_f(i,s|l)$, so the local output is an aggregate of each individual firm f's output $q(i,s|l,f)$ as follows:

$$L\left(i,s|l\right)=N_{f}\left(i,s|l\right)^{-\frac{1}{\gamma_{L}-1}}\left[\sum_{k=1}^{N_{f}}q\left(i,s|l,f\right)^{\frac{\gamma_{L}-1}{\gamma_{L}}}\right]^{\frac{\gamma_{L}}{\gamma_{L}-1}}, \tag{11}$$

where γ_L is the elasticity of substitution across firms. Entry and exit of firms in the raw sector l occurs such that the zero profit condition holds in every period in each sector. These firms combine intermediate input $M(k,(i,s))$ and capital, labor to make raw sectoral output with productivity $A(i,s)$ as follows:

$$q\left(i,s|l,f\right)=\left[\begin{array}{c}\omega_{q}\left(i,s\right)^{\frac{1}{\gamma_{q}}}\left(A\left(i,s\right)K\left(i,s|l,f\right)^{\alpha}H\left(i,s|l,f\right)^{1-\alpha}\right)^{\frac{\gamma_{q}-1}{\gamma_{q}}}\\+\left(1-\omega_{q}\left(i,s\right)\right)^{\frac{1}{\gamma_{q}}}\left(M\left(i,s|l,f\right)\right)^{\frac{\gamma_{q}-1}{\gamma_{q}}}\end{array}\right]^{\frac{\gamma_{q}}{\gamma_{q}-1}}-\phi\left(i,s\right) \tag{12}$$

where $\omega_q(i,s)$ is the parameter related to the share of value added in the raw output production, γ_q is the elasticity of substitution between intermediate and value added goods and $\phi(i,s)$ is the fixed cost.[8]

The intermediate input $M(.)$ is combined in two stages. First, intermediate goods, $m((j,k),(i,s))$ from different origins are combined with an elasticity of substitution ω_m to a sector k intermediate

[8]We model productivity A to be combined with domestic labor and capital goods, instead of the aggregator of capital, labor and intermediate inputs, because the latter specification can cause volatility of value added to change mechanically when the value added shares in the data change over time.

goods to be used in country i in sector s, $m(i,s|f)$. Therefore, $m(k,(i,s))$ is given by:

$$m\left(k,(i,s)\right)=\left[\sum_{j=1}^{I}\left(\omega_m\left(\left(j,k\right),\left(i,s\right)\right)\right)^{\frac{1}{\gamma_m}}\underbrace{\left(m\left(\left(j,k\right),\left(i,s\right)\right)\right)^{\frac{\gamma_m-1}{\gamma_m}}}_{\text{from country } j \text{ sector } k \text{ to country } i \text{ sector } s}\right]^{\frac{\gamma_m}{\gamma_m-1}}, \tag{13}$$

where $\omega\left(\left(j,k\right),\left(i,s\right)\right)$ is the share of intermediate goods from sector k in country j to sector s in country i. Second, these sectoral specific intermediate goods $m(k,(i,s))$ are aggregated across sector to be used in each sector s in country i, $M(i,s)$, as follows:

$$M\left(i,s\right)=\left[\sum_{k=1}^{S}\left(\omega_M\left(k,(i,s)\right)\right)^{\frac{1}{\gamma_M}}\left(m\left(k,(i,s)\right)\right)^{\frac{\gamma_M-1}{\gamma_M}}\right]^{\frac{\gamma_M}{\gamma_M-1}}, \tag{14}$$

where γ_M is the elasticity of substitution across different sectors and $\omega_M(k,(i,s))$ is the share of the sectoral intermediate goods.

3.3 Resource Constraints and Definitions

Finally, the resource constraint in each country dictates that the output in sector s in each country i has to satisfy the following conditions:

$$n\left(i\right)Q\left(i,s\right)=\sum_{j=1}^{I}n\left(j\right)\left[f_C\left(\left(i,s\right),j\right)+f_I\left(\left(i,s\right),j\right)\right]+\sum_{j=1}^{I}\sum_{k=1}^{S}n\left(j\right)m\left(\left(i,s\right),\left(j,k\right)\right) \tag{15}$$

and

$$\sum_{i=1}^{I}n(i)B_{t+1}\left(i\right)=0, \tag{16}$$

where $n(i)$ is the size of country i. Additionally, $\sum_{s=1}^{S}H(i,s)=H(i)$ and $\sum_{s=1}^{S}K(i,s)=u(i)K(i)$.[9]

Since the model includes gross output $Q(i,s)$, we define real value added output as follows. In each sector in each country, the real value added output is equal to gross output subtracting intermediate input usage evaluated at the steady state prices, i.e.:

$$RVA(i,s)=P_{Q,ss}\left(i,s\right)Q\left(i,s\right)-P_{M,ss}\left(i,s\right)M\left(i,s\right) \tag{17}$$

The aggregate value added output in each country is the weighted sum of sectoral real value added.

[9] We follow Atalay (2017) and assume this simple specification of perfect mobility of labor inputs across sectors, as he finds that aggregate economic activities are not sensitive to the elasticity of substitution of labor inputs across sectors.

Throughout the paper, we use output or VA to denote real value added output, and GO for gross output.

3.4 Productivity Process

We close the model with the description of the productivity processes. The productivity in each sector in each country follows an AR(1) process with persistence $\rho(i,s)$:

$$\ln A_t(i,s) = \rho(i,s) \ln A_{t-1}(i,s) + \varepsilon_t(i,s), \tag{18}$$

where $\varepsilon(i,s)$ has a standard deviation $\sigma(i,s)$, mean 0. In the baseline model, we assume no cross-country productivity correlations, or sectoral productivity correlations. There are several reasons for us to assume no correlation across countries in the baseline. First, the available productivity data, similar to Johnson (2013), exhibit almost no correlation across countries. As discussed in Engel and Wang (2011), empirical findings in the existing literature often suggest small cross-country spillover of productivity shocks.[10] Second, our focus is to quantify the effects of the international linkage channel *alone* without correlations or spillover of shocks on business cycle properties. Third, we allow cross-country correlations of productivity shocks in the robustness check to examine how this assumption affects our results.

4 Model Predictions

Before quantitatively assessing the role of changing international input-output linkages on business cycles, we discuss the mechanism in the model through which changes in input-output linkages can affect aggregate volatilities across countries in this section. To build intuition, we consider a two-country two-sector version of the model: the size of country 1 is $1/10^{th}$ of country 2, analogous to the relative sizes of Canada and the United States. The two sectors are the manufacturing (sector 1) and non-manufacturing sectors (sector 2). The differences between sector 1 and sector 2 are as follows: First, sector 1 is open while sector 2 is almost closed. Second, the final demand for consumption in sector 1 is 0.72, while it is 0.75 in sector 2. These shares are close to the average shares of final demand for investment in manufacturing and non-manufacturing sectors in the data. Third, the standard deviation of productivity shocks in sector 1 in each country is five

[10] Miyamoto and Nguyen (2017) find that the correlations of our identified productivity shocks, as well as utilization-adjusted productivity data, between the United States and Canada is near zero in the short run.

times larger than that in sector 2, reflecting the fact that manufacturing sector is more volatile than non-manufacturing sector. The persistence of the productivity shock processes in both sectors in each country, ρ, is 0. The following analyses assume that productivity shocks are independent across countries and sectors.

We first show that international input-output linkages transmit shocks across countries in the model. Figure 5 plots the impulse responses of both country 1 and 2 to a positive productivity shock in sector 1 of country 2. Country 2 goes through a boom: the value-added output, consumption and investment increase substantially. The increase in output in sector 1 in country 2 is larger than sector 2 in the same country. The reason is that while there is an exogenous increase in productivity in sector 1, the value-added output in sector 2 increases only due to the transmission within the model: an increase in production in sector 1 leads to higher demand for sector 2's goods, which in turn generates more hours worked in sector 2, causing its value-added output to increase. Since productivity does not change in country 1, its value-added output only increases because hours and capital utilization increase in the short run. Intuitively, as productivity increases output in country 2, goods in country 2 become more abundant, causing the terms of trade in country 1 to appreciate. Since domestic goods become more valuable in country 1, more firms enter into the economy, so markups decline. Together with a higher capital utilization, firms in country 1 increases their labor demand substantially. With our calibration of the wealth effect on labor supply, households in country 1 do not decrease their labor supply while increasing consumption. In equilibrium, hours in country 1 increase, so the value-added output in country 1 comoves strongly with that country 2, as shown in Figure 5. The risk sharing mechanism in the model causes consumption to increase in country 1: given the appreciation of the terms of trade, households are richer and can enjoy higher consumption. Similarly, investment increases in our model due to an increase in hours worked, i.e. with our features, the incentives to shift investment to a more productive country are not large compared to the standard Backus, Kehoe, and Kydland (1995) model. In Appendix Figure A3, we show that the response of country 1's value-added output is much weaker in the plain vanilla international real business cycle model without all or each of our additional features.

The analyses above imply that due to the transmission of shocks through international input-output linkages, output fluctuations in each country are driven not only by domestic shocks, but also by foreign shocks. Therefore, changes in international input-output linkages can affect both output volatility and cross-country correlation in country 1. We plot in Figure 6 the standard deviation of the value-added output in country 1 as we vary the shares of import and export in

output for sector 1. In the left panel of the figure, we assume symmetric shocks, and in the right panel, the standard deviations of the shocks in country 2 are twice as large as in country 1. There are two opposite forces driving output volatility. First, openness can be stabilizing output: as country 1 trades more with country 2, output becomes less volatile, as the contribution of domestic shocks declines. Intuitively, when country 1 is hit with a good productivity shock, it can increase output. However, as country 1 needs to use intermediate inputs from country 2, which has become relatively more expensive due to its scarcity, country 1 cannot increase output as much as without the imported intermediate inputs. On the demand side, country 1 has demand from country 2, but the increase in demand from country 2 is not as large as the demand from country 1 had it been closed. The reason is that country 2 is richer given the appreciation of the terms of trade, but it is not as rich as country 1 with an increase in productivity. So, more openness tends to stabilize output volatility. Second, output can be more destabilized when a country becomes more open, as foreign shocks become an important driver of country 1's output. In this simple calibration exercise, depending on the volatility of foreign shocks relative to that of domestic shocks, output in country 1 may become more volatile when it is open than when closed. When the productivity shocks in both countries are symmetric, as in the left panel of 6, the stabilizing effect is stronger, so the standard deviation of output in country 1 falls as it becomes more open. However, when foreign shocks are sufficiently volatile, output can become more volatile than when there is no trade linkage between the two countries, as demonstrated in the right panel of Figure 6. More generally, if foreign shocks are not volatile, or there are many trading partners with uncorrelated shocks across trade partners, the stabilizing effects can be more important, driving down domestic output fluctuations. This example demonstrates that international input-output linkages do not always lower output volatilities. Rather, its effects on output volatilities depend on how important foreign shocks are relative to domestic shocks, as well as the relative volatilities of the shock processes, the number of trading partners and the entire network. So the question on the effects of international input-output linkages is quantitative. We next calibrate the model using the World IO tables and business cycle moments later to investigate this question.

We note that another source of variations over time in the World IO tables is the relative sector sizes, which have been found in previous literature such as Carvalho and Gabaix (2013) to be important in explaining output volatility over time. In our model, this changing feature of the data can also have an effect on business cycle properetires.[11] To see this, we examine the standard

[11]Note that when the relative sizes of sector 1 to sector 2 decrease, holding all else constant, including the shares

deviation of the value-added output when varying the relative sizes of sector 1 and sector 2 in both countries in the two-country model. As sector 2 becomes larger relative to sector 1, the standard deviation of output in country 1 becomes smaller. The reason is that output in country 1 includes outputs in both sector 1 and sector 2. When sector 1 becomes relatively less important in the economy, its contribution to output falls, so output becomes less volatile. Therefore, as plotted in Appendix Figure A4, the decline in the size of sector 1 relative to sector 2 decreases the standard deviation of output monotonically.

We next present our quantitative exercise using data for 23 countries between 1970 and 2007.

5 Model Parameterization

This section describes the calibration strategy for our model. Given the data availability in the World IO tables, we calibrate our model to the manufacturing and non-manufacturing sectors in 23 countries and the ROW between 1970 and 2007. We discuss how we set parameters that are common across countries, then explain how we set individual country's shock processes.

Common parameters Table 1 summarizes the calibrated values for common parameters across countries in our baseline. The model is calibrated for annual data. The discount factor is set to be 0.96, so the implied steady state annual interest rate is about 4%. As standard in the literature, we set the labor share parameter, α, to be 0.36. The depreciation rate at the steady state is 10% a year. The parameter related to the inverse of the intertemporal elasticity of substitution, σ, is set to be 2, which is along the line of Backus, Kehoe, and Kydland (1995) and others in the international business cycle literature. The parameter related to the inverse of Frisch labor supply, ν, is set to be 1, following previous papers such as Kimball and Shapiro (2008) and Bilbiie (2009). There is a lack of consensus on the wealth elasticity of labor supply, so we set it to be 0.1, which suggests a low wealth effect on labor supply and is in the lower range in the literature.[12] We check the robustness of the results with respect to this parameter.

There is a wide range of estimates for the elasticities of substitution across sectors and countries: the international macroeconomic literature estimates of the elasticity of substitution across countries are typically around 1, e.g. Backus, Kehoe, and Kydland (1995) setting this parameter

of imported intermediate and final goods, country 1 is less open in the aggregate.

[12]The Greenwood, Hercowitz, and Huffman (1988) preferences correspond to the wealth elasticity of labor supply to be 0, and the standard KPR preferences corresponds to 1.

to be 1.5, while the estimates in the trade literature range from 6 to 15. In the baseline, we set the elasticities of substitution across both final and intermediate goods in different sectors and countries to be 1, i.e. $\gamma_C = \gamma_I = \gamma_f = \gamma_F = \gamma_Q = \gamma_M = \gamma_m = 1$.[13]. This implies that the composite intermediate input is Cobb-Douglas in inputs from different countries. We also set γ_q, the elasticity of substitution between value added and intermediate goods, to be 1, so the production function is Cobb-Douglas in value added and the composite intermediate input. Since these elasticities of substitution can be important for the strength of the transmission mechanism of shocks across countries, we consider other values in the robustness check.

The elasticity of substitution across firms in the raw sector, γ_L is set to be 20 and steady state markup to be 1.2 to generate the elasticity of markup about 0.12 as used in Jaimovich and Floetotto (2008). This value guarantees that the number of firms within a sector is larger than 0. Following Jaimovich and Rebelo (2009), we set the inverse of capital utilization elasticity, $\frac{\delta''}{\delta'}$, to be 0.05. The investment adjustment cost is set to target the median relative standard deviation of investment to that of output and the autocorrelations of investment, value-added output, and consumption between 1970 and 2007. Since the utilization elasticity, investment adjustment cost, and markup parameters can be important for the endogenous transmission mechanism of productivity shocks across countries, we examine how our results change when these parameters change in the robustness check.

Productivity process We calibrate the shock processes for each country as follows. In the baseline, we assume that productivity shocks are uncorrelated across countries and there is no spillover, so that all the comovements across countries are driven by the endogenous mechanism. In order to calibrate the productivity processes, we have to set several steady state input-output shares in the model. Let ω be a vector of all the steady state shares, such as the intermediate and value added in production, the shares of foreign and domestic goods in final consumption, investment and intermediate goods for all countries. The steady state ω can be computed using data on gross output, value added of each sector in each country, and bilateral final and intermediate goods shipments. These data are available from the World IO table. Along with the resource constraints, we are able to set the steady state shares so as to match the relative sector sizes in

[13] Johnson (2013) also set the baseline elasticities across intermediate goods to be 1, though he chooses the elasticities across final goods to be 2. Burstein, Kurz, and Tesar (2008) assigns the elasticity of substitution between home and foreign goods to be small to account for production sharing across countries. Recently, Boehm, Flaaen, and Pandalai-Nayar (2017) estimates that the elasticity of substitution to be near zero. We consider a low elasticity as these papers in the robustness check.

the data. We use the World IO table averaged between 1984 and 1993.[14] The idea is that we use the midpoint of the sample, and average over 10 years to eliminate the effects of business cycles on the elements of the World IO tables. We also calibrate country and sector sizes, $n(i)$, and the shares of intermediate and value added in gross output to match the relative gross sector output sizes across countries completely in the same time frame. Since the World IO table does not have information on the shares of manufacturing and non-manufacturing goods used in consumption and investment separately, we set these shares to equal the average between 1995 and 2007 reported in the World Input Output Database. We then set the productivity shock persistence to be 0 in both manufacturing and non-manufacturing sectors, which is similar to Johnson (2013). Given other parameters, the autocorrelations of output implied by the model are closed to those in the data. To calibrate the standard deviations of the shocks, we target the model-implied standard deviations to be the same as the standard deviations of the value-added output between 1970 and 2007 for each sector in each country.[15] We solve the model using the first order perturbation method.

6 The Effects of Changing Input-Output Linkages on Aggregate Volatilities

This section presents the estimated effects of changes in the international input-output linkages on output volatilities of 23 countries between 1970 and 2007. We proceed in two steps. First, we study the effects of changing input-output linkages *both* across and within countries. More specifically, we compute how much the model-implied output volatility changes when the steady state shares are calibrated based on the changes in all of the elements of the World IO tables over the 1970?2007 period. Second, we decompose the effects in the first step into several channels, focusing on the international input-output linkages and comparing that with the relative sector size changes.

To estimate the effects of both international and domestic input-output linkage changes, denote $\omega(year)$ the steady state in each $year$, associated with the World IO table at each point in time. To avoid the possibility that changes in the shares in the World IO table each year are driven by specific events or business cycles, we set $\omega(year)$ to match the 11-year centered moving average in the data. For example, $\omega(1990)$ is the steady state shares associated with the average of the

[14] The results do not change significantly if we use the first 10 or the last 10 years in the calibration for the shock processes.

[15] Labor productivity data for some countries are available. However, since the model includes both variable capital utilization and variable markup, we cannot use labor productivity only to back out productivity shock processes.

World IO tables between 1985 and 1995. We solve the model to calculate the model-implied output standard deviation, σ^Y_{year}, for each $\omega(year)$. Then, the effects of both international and domestic IO linkage changes are the changes in standard deviations of output when all $\omega(year)$ vary over time according to the World IO tables, for example, $\sigma^Y_{1992} - \sigma^Y_{1990}$ is the effect of World IO changes between 1990 and 1992.

In the decomposition exercise, our goal is to isolate the changes in the international linkages across countries from other changes such as the sector sizes, the value added shares, as well as the sectoral composition of inputs. Conceptually, this amounts to calculate the cumulative changes in the model-implied standard deviations when we vary $\omega(year)$ over time according to the World IO tables with only changes in the values of the bilateral shipments across sectors across countries. Similarly, to compute the effects of the changes in relative sector sizes, one wants to fix everything in the World IO table except for the relative sector sizes.

In practice, the World IO table each year have constraints that the sum of the column, which includes the intermediate inputs and sectoral value added, to be equal to the sectoral gross output, and that the sum of the intermediate in each row, together with the final demand, to be equal to the sectoral gross output. Therefore, we cannot impose that only the values of the bilateral shipments across sectors and countries are at a new level of year T while keeping the rest in year $T-1$. Therefore, our procedure for international linkage changes proceeds as follows: We normalize the values of the bilateral shipment in intermediate inputs in each column of the World IO table by the corresponding column's gross output, called the technical coefficients.[16] We construct a hypothetical World IO table in year T, denoted by $\widetilde{WIOT}$, using information in both year T and year $T-1$. First, for each sector s in country i, we keep the levels of the gross output and value added, and the shares in gross output of the intermediate inputs from each sector to be at the levels of the World IO table in year $T-1$. Second, the shares of the intermediate inputs from all countries j in gross output within each sector are updated to year T. This step reflects the change in international linkages in the intermediate goods trade in each sector. Third, the constraints in the World IO table pin down the final demand in each sector in each country, which is the difference between gross output and total intermediate goods demand in each row. Fourth, we use the shares of foreign relative to domestic final demand in each sector in year T to construct the new final demand in each sector in year T. This step reflects the change in international linkages of final goods trade in each sector. This hypothetical World IO table lets us calibrate $\omega(T)$, then we solve

[16] We use the convention in the literature of Leontief analysis, see Miller and Blair (2009) for more details.

the model and calculate the cumulative change in the output standard deviation over time as above. Denote $\widetilde{\sigma}^Y$ is the standard deviation of output implied by the model with hypothetical World IO table. Then, $\sum_{h=0}^{T}\left(\widetilde{\sigma}^Y_{1970+h+1}-\sigma^Y_{1970+h}\right)$ is the change in the standard deviation of output between 1970 and $1970+T+1$ caused by international linkage changes. Note that comparing 1970 with 1980 with the assumed counterfactual changes in the World IO table based on 1970 is different from the accumulated effect of changes in each year. To avoid the dependence of the result on a particular reference year, we take the cumulative changes, which makes it easier to compare any pair of years.[17]

To compute the effects of relative sector size changes, we isolate the changes in relative sector sizes keeping all the linkages such as the shares of demand and intermediate inputs at the previous year's level. To that end, for each year T, we construct $\widetilde{WIOT}$ as follows. First, we fix the total gross output in each country in year $T-1$. Second, using the shares of each sector in total gross output at the new levels in year T, we compute the new sectoral gross output for the hypothetical World IO table in year T. Third, we keep all the technical coefficients at the levels in year $T-1$, so we can calculate the bilateral shipment in each sector in each country using the new gross output level. Fourth, final demand for each country is computed as the differences between gross output and intermediate input on each row. Finally, final demand for each sector is the total final demand scaled by the shares of each country demand for each good, fixed at the level in year $T-1$. Once we construct the hypothetical World IO table, we calibrate $\omega(T)$ and compute the standard deviation as above.

We note that our approach assumes that agents do not anticipate the changes in the steady state ω. The other extreme is to assume perfect foresight, but this assumption can be unrealistic in our long sample period. Agents may, in reality, form some anticipation over the changes, but modeling agents' expectations at each point in time is beyond the scope of our paper. Besides, our paper examines business cycles using filtered data, so the slow moving effects of the share changes are filtered out although the steady state changes are not filtered. We focus on the trend of the standard deviation of output, so our assumption may not affect our results too much.

We present the results of these decomposition exercises in the sections below.

[17] There are certainly other decomposition ways. We discuss in details the baseline decomposition and compare it with other ways of decompositions in Appendix Section B.

6.1 The Effects of World Input-Output Linkages

We first discuss the effects of both international and domestic input-output linkages over time on aggregate volatilities in 23 countries between 1970 and 2007. The upper left panel of Figure 7 plots the model-implied standard deviations of output, consumption, investment between 1970 and 2007 taken at median across countries, compared to the corresponding 10-year rolling over standard deviations in the data. The model captures the downward trend of the volatilities in output at the median. Quantitatively, the changes in the world input-output linkages generate a drop in volatilities of about 21% in output. over the period between 1970 and 2007, which is a significant fraction of the decline in the data (about 40% in output). The model does not generate higher frequency changes in volatilities as in the data. One reason is that we compute the theoretical standard deviations, which does not take into account small sample uncertainties.[18]

While the changes in world input-output linkages imply a decrease in aggregate volatilities in the last 40 years at median, the effects are heterogeneous across countries. Volatilities of output are predicted to decline substantially, up to 30%, in Austria, Belgium, Japan, and about 20% in the United States, but the effects are small, by less than 10%, in Korea, the Netherlands, Ireland and France. We plot three countries: Canada, the United States, and Mexico in Figure 8. The model attributes 30% decline in output standard deviations in Canada and the United States between 1970 and 2007 to changes in the world input-output linkages, but only about 10% decline in volatilities for Mexico.

Overall, our baseline model suggests that when economies are driven by uncorrelated productivity shocks, changes in world input-output linkages have heterogeneous effects in our sample between 1970 and 2007: while it causes aggregate volatilities to drop substantially for some countries, it effects are limited in some other countries.

6.2 The Effects of International Input-Output Linkages

The upper right panel of Figure 7 plots the effects of changing international input-output linkages on output volatilities over time together with the effects of world input-output linkages at median. International input-output linkages have a sizable effect on the economies: of the 21% drop in output volatilities caused by changes in the World IO tables, about 15% is due to international input-output linkages at median.

[18] In general, the standard deviations are not precisely estimated as we do not have many data points.

While for most countries in our sample, changes in the international input-output linkages lead to a drop in output volatility between 1970 and 2007, the magnitude are heterogeneous across different countries, as plotted in Figure 8. While changes in international input-output linkages cause an over 20% decrease in Mexican output volatility, and about 17% in Canada between 1970 and 2007, the linkages only explains about 6% of the United States' drop in volatility. A possible reason for the heterogeneous effects of international linkages on these countries is their openness to trade and trade partners. Canada is the most open country out of the four countries: Canada's export and import over output increases from about 20% up to 30% in this time frame, most of which come from the manufacturing sector. Mexico also becomes more open: its export and imports ratio over output increase from 10% to 25%, and Mexico's main trade partners are Canada and the United States, so they benefit from increasing trade over time. The United States is more open in 2007 than in 1970, but the shares of imports and exports in output are small, so the impact of changing international input-output linkages is negligible.[19]

In general, our decomposition suggests that there is a negative relationship between changes in openness and the reduction in output volatility over the 1970–2007 period. As plotted in the left panel of Figure 9, the more open in terms of total trade shares over value added the country becomes, the larger the drop in output volatility is due to the international linkage channel. Although our simple model analysis above shows that changes in output volatility depend not only on how open the country is, but also on the volatility of foreign shocks, our quantitative results suggest that most countries in our sample benefit from changing international linkages over the last 37 years, and more so for countries that have become more open.

6.3 The Effects of Relative Sector Sizes

The lower left panel of Figure 7 plots the effects of changing relative sector sizes on output standard deviations at median. The drop in output volatilities generated by changing relative sector sizes over the entire 1970–2007 period is small, explaining about 4.5% of the decline in the standard deviation of output at median. As suggested in Figure 8, changes in the relative sector sizes are important to explain the Great Moderation in the United States, but not for all other countries. In fact, the model attributes about 20% drop in output volatilities in the United States to the decline in the manufacturing sector, while the effects of the international linkage changes are negligible. In contrast, the changes in the manufacturing sector in Mexico actually increase output volatilities in

[19] All countries are plotted in Appendix Figure A5.

this country, by a small amount (3%). Although the changing relative sector sizes help to reduce Canadian output volatility, it is more modest than the United States (7%). Why does our model imply that relative sector size changes are important for the United States but not for Mexico? The reason is that in the data, U.S. manufacturing sector becomes much smaller over time: its share in total value added drops from 22% to 17%, and in total gross output drops from 40% to 20%. The manufacturing sector is more volatile than the non-manufacturing sector, so aggregate output volatility drops. The fact that our model contributes a significant fraction of output drop in the United States to the reduced importance of the manufacturing sector is consistent with other papers such as Carvalho and Gabaix (2013). For Canada, although the contribution of the manufacturing sector in aggregate economy also drops in Canada, it is much less compared to the United States: the shares of Canadian manufacturing sector gross output in total gross output decreases from 31% to 25% only, so the model attributes some of the drop in Canadian output standard deviation to this fact, but not as much as in the United States. In Mexico, the shares of the manufacturing sector in gross output are fairly stable over time, so the contribution of the changes in the relative sector sizes are negligible. We plot in the Figure 9 a scatter plot of the changes in the manufacturing sector shares in between 1970 and 2007 and the cumulative changes in the standard deviations of output over this period in our decomposition. As before, the share of manufacturing sector in total value added in each year is a 11-year centered moving average to avoid specific events affecting the shares. There is a clear negative relationship between the manufacturing sector share changes and the changes in the output volatilities: a country experiencing a larger decline in the manufacturing sector shares tend to have a larger reduction in output volatility due to changes in the relative sector sizes. This result suggests that our model and decomposition exercise are sensible.

To summarize, our model suggests that at median, relative sector size channel is less important than the international input-output linkages, but this result is heterogeneous across countries.

6.4 Other Macroeconomic Variables

We plot in Figure 10 the decomposition exercise for consumption and investment at median as well as the 25–75 percentile in our sample. The total changes in the World IO linkages cause about 25% drop in the volatility of consumption at median. The percentile bands suggest that all countries benefit from changes in the World IO linkages as consumption volatility drops. Similar to output, the international linkages have a sizable effect, explaining about 20% drop in consumption volatility at median, while the relative size channel is more muted, explaining around 5% at median.

The total World IO changes have smaller effects on investment than consumption: it generates a drop of about 13% in investment volatility over the 1970–2007 period at median. Furthermore, not all countries benefit from the changes, as the upper 90 percentile band shows an increase in volatility of investment. Our decomposition suggests that both international linkage changes and relative sector size changes have modest effects on investment: at median, each channel explains less than 10% of the volatility.

7 Inspecting the Mechanism

We perform several robustness check to understand how our results depend on the model mechanism. Our findings indicate the importance of the transmission channels and mechanisms in the model. The results of each of the robustness exercises are plotted in Figure 11.

First, when the endogenous transmission mechanism through international trade is small, the international linkage changes have negligible effects on business cycle volatilities over time. To show that, we consider a version of the plain vanilla international real business cycle models by shutting down the following features in the baseline model: capital utilization and variable markup, and calibrating larger wealth effect on labor supply. We keep the baseline calibration of this model, for example, the shock processes are the same as the baseline. As plotted in the second panel of Figure 11, the contribution of international linkages to changes in output volatilities is much smaller than the baseline: the effects in the median country is almost nil, while the contribution of relative sector sizes does not change. The reason is that, as discussed in Miyamoto and Nguyen (2017), foreign shocks do not explain much of the movements in labor inputs in the plain vanilla international RBC model. Labor input in the plain vanilla international real business cycle model is primarily driven by domestic TFP changes, as the terms of trade effects are modest. Therefore, the international real business cycle model generates small endogenous transmission of shocks across countries through international trade, so changes in international linkage have negligible effects on business cycle volatilities over time in most countries.

Second, when we lower the elasticity of substitution across countries, the effects of international linkage changes over the sample period are similar to the baseline. A low elasticity of substitution, as shown in prior work such as Burstein, Kurz, and Tesar (2008), can increase the comovement of output across countries endogenously. The intuition is that lower elasticity of substitution magnifies the effects of the terms of trade changes to labor inputs in the production, helping output in domestic

country to increase more after a foreign productivity shocks. In this case, we keep all the calibrated parameters the same as the baseline and change only the elasticity of substitution across home and foreign goods to be 0.1. We find that the contribution of international linkages to changes in volatilities in this case is only slightly larger than the baseline. This result is sensible given that the baseline model already generates strong endogenous transmission through international trade.

Third, when shocks are correlated across countries exogenously, changes in international linkages reduce output volatility by a smaller amount than the baseline. Specifically, we allow the possibility that there are exogenous cross-country correlations of each sector's productivities. More specifically, we use Kalman smoother to smooth out the shocks that replicate exactly each country's sectoral output. We set the correlations of the shocks by computing the correlations of the smoothed shocks. In this case, the contribution of international linkages to the decline in output variations over time to be about 8% at median, which is smaller than the baseline results of 15%. Intuitively, when there is a positive productivity shock in the domestic economy, productivity also increases in the foreign economies, making it cheaper for domestic economy to use intermediate input to increase production, compared to the baseline without any correlated shocks. Besides, the demand from foreign country is also larger than the baseline. As a result, output volatility does not decrease as much as the baseline when there are more international linkages.

Finally, we examine how our results depend on the transmission channel in the model. Specifically, we consider a case when the main driving force in the economy is a demand shock. To that end, we model a "confidence shock" which works like a demand shock. The last panel of Figure 11 shows the decomposition result of the international linkage changes over the last 40 years. At median, the international linkage changes lead to a 22% drop in volatility of output, which is larger than the baseline decomposition when productivity shocks are the driving force of business cycles. The 25–75 percentile bands also indicate that the baseline is in the lower range of this case.

8 Potential Risk

While our decomposition exercise shows that changing international input-output linkages tend to stabilize output in many countries in the last 40 years, it is based on the calibrated fixed shock processes. The decomposition is also about the long run, so even when theoretical long run volatility declines, in the short run, a rare large shock such as one in the Great Recession can increase the observed volatility given more input-output linkages. This section is to isolate the effects of a unit

GDP shock in one country to another, i.e. the spillover effects of shocks across countries, over time. We find that the spillover effects of idiosyncratic country-specific shocks have increased, leading to more potential risk of a global recession.

To that end, we define a "cross-country value added multiplier" that can capture the effects of a country-specific shocks on output in other countries. The cross-country value added multiplier for a US shock in the manufacturing sector for country X cumulative at horizon H, denoted by $M^H_{US,X}$, is calculated as follows:

$$M^H_{US,X} = \frac{\sum_{h=1}^{H} \frac{\partial VA_{X,h}}{\partial A_{US,1}}}{\sum_{h=1}^{H} \frac{\partial VA_{US,h}}{\partial A_{US,1}}}, \tag{19}$$

where $\frac{\partial VA_{X,h}}{\partial A_{US,1}}$ and $\frac{\partial VA_{US,h}}{\partial A_{US,1}}$ are the impulse responses of the value added of country X and the US in horizon h to a US manufacturing sector shock, respectively. $M^H_{US,X}$ is the percentage change in the value added in country X when US value added goes up by 1%, due to a US shock, so $M^H_{US,X}$ can be interpreted as the degree of shocks transmitted across countries.

To understand how the degree of transmission changes over time, we calculate the multiplier cumulative for 10 years at each point in time using the World IO table, corresponding to each $\omega(year)$.[20] Figure 12 plots the multipliers over time for US, Chinese, Japanese, and German shocks at median and the 25-75 percentiles. There is a clear tendency that the multipliers for these countries' shocks become larger over time. The multipliers for US shocks increase from about 0.1 to 0.14 at median. The multipliers for German shocks also increase substantially from 0.1 to 0.2 at median. The magnitudes of the multipliers suggest that the United States, Germany and Japan have large spillover effects to other countries in 1970, and even more so in 2007. The multipliers for Chinese shocks are smaller in magnitude, but has increased substantially over time, suggesting the increasing importance of China in the world economy. The overall upward trending of the multipliers implies that with the changing linkages within and across countries, the spillover effects of country-specific shocks increase over time. Therefore, although changes in linkages contribute to stabilize output volatility in the long run, a global recession like during the 2007-2009 period is more likely now than ever before.

[20] The effects die out quickly within a few years, so the multiplier cumulative at other horizons is similar to the one reported here.

9 Conclusion

We quantify the effects of changing international input-output linkages on aggregate volatilities in a structural model of 23 countries between 1970 and 2007. We find that while international input-output linkages lead to about 11% reduction in output volatilities at median across 23 countries in our sample in the last 40 years, its effects are heterogenous across countries. Furthermore, the changing international input-output linkage channel is less important than the changing relative sector sizes in reducing output volatilities in a number of countries including the United States, Japan, Great Britain and France. Importantly, our analyses suggest that the spillover effects of country-specific shocks have increased substantially over time due to the changing linkages within and across countries, raising the possibility of a global recession.

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Tables and Figures

Table 1: Calibrated Parameters

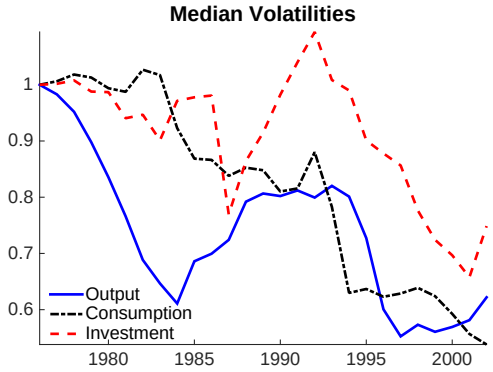
Parameter	Value	
β	0.96	Discount factor
α	0.36	Labor share parameter
δ	0.1	Depreciation rate
σ	2	Inverse of IES
ν	1	Inverse of Frisch labor supply
κ	0.1	Wealth effect parameter
$\frac{\delta_u''}{\delta_u'}$	0.05	Inverse utilization elasticity
γ_F	1	ES between sectoral goods
γ_f	1	ES between home and foreign goods
ϵ_{markup}	0.12	Elasticity of markup
s	0.1	Investment adjustment cost
ρ_A	0	Shock persistence

Table 2: Second Moments

	Data	Model
Standard deviations		
Output	1.3	1.5
Consumption	1.2	1.0
Investment	3.8	3.3
Manufacturing real value added	2.7	2.7
Non-manufacturing real value added	1.4	1.4
Autocorrelation		
Output	0.32	0.26
Consumption	0.35	0.23
Investment	0.39	0.47
Manufacturing real value added	0.25	0.12
Non-manufacturing real value added	0.32	0.3

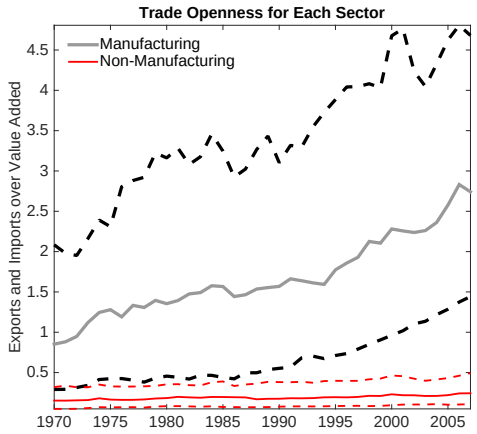
Notes: The second moments reported in both the model and the data are taken as median across countries using HP filtered data between 1971 and 2007.

Figure 1: Median volatilities and cross-country correlations of output, consumption and investment between 1970 and 2007



Notes: The median 10-year rolling over standard deviations of the HP-filtered of output, consumption and investment in 23 countries between 1970 and 2007. We normalize the standard deviations in 1975 as 1 for each country, then we take median across 23 countries.

Figure 2: Trade Openness in Manufacturing and Non-Manufacturing sectors between 1970 and 2007



Notes: We plot the median across 23 countries, 25-75 percentile for each sector. Trade openness is defined as total exports and imports divided by the value added in each sector.

Figure 3: US major trade partners in the manufacturing sector between 1970 and 2007

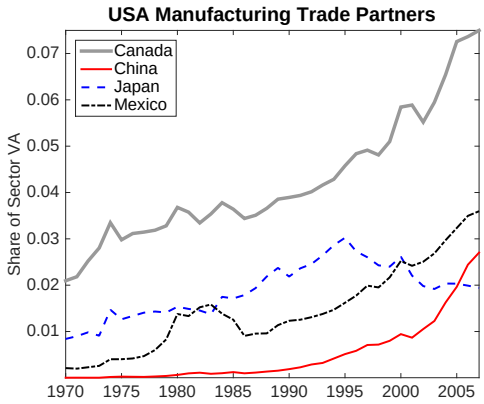
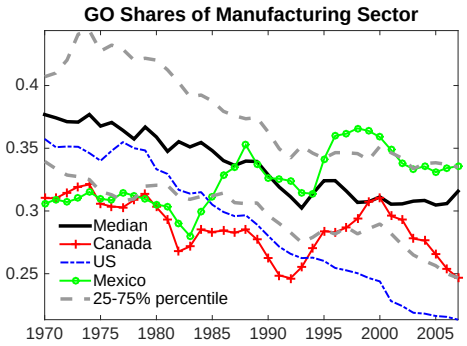
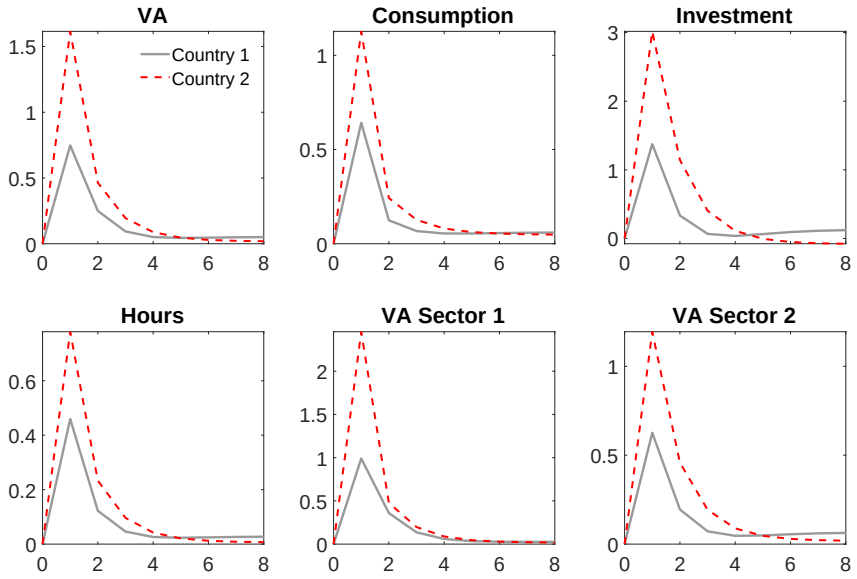


Figure 4: Relative sector sizes between 1970 and 2007: Manufacturing sector shares in total gross output



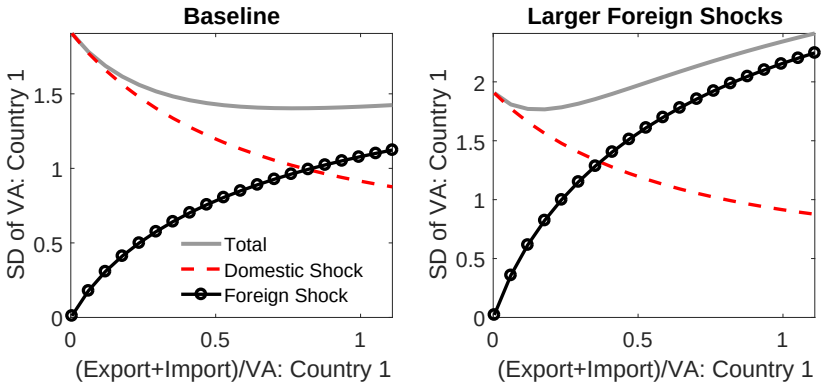
Notes: We plot the median across 23 countries, 25-75 percentile and three countries: Canada, the United States, and Mexico.

Figure 5: Model Behavior: Transmission of shocks across countries



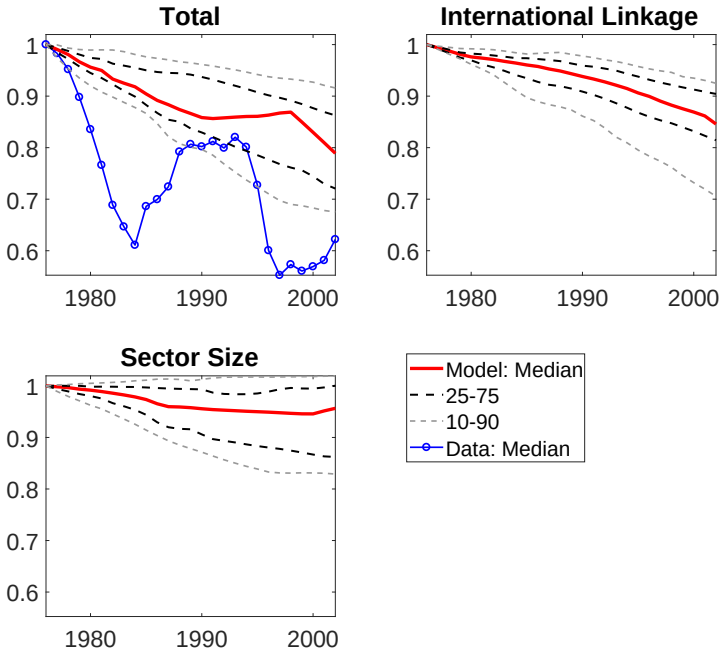
Notes: The impulse responses in country 1 and 2 to a positive TFP shock in country 2 sector 1 simulated in a 2-country model experiment. VA denotes value added in each country or sector.

Figure 6: Model Implication: Relationship between international linkages and output volatility and cross-country correlations



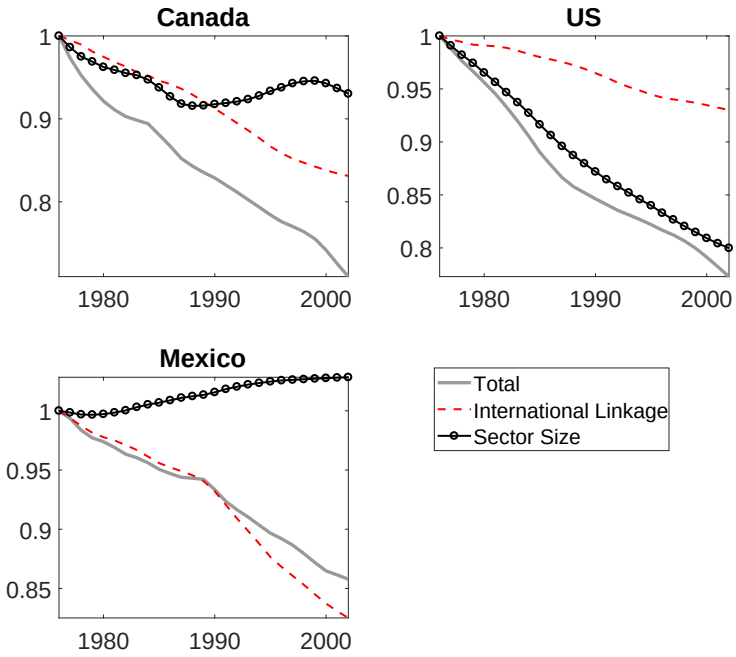
Notes: We plot the standard deviation of output as we vary the shares of imports and exports in sector 1 value added, when the countries are driven by all shocks (Total), only foreign shocks, and only domestic shocks in our baseline model for two countries.

Figure 7: World Input-Output Changes and Output Volatilities



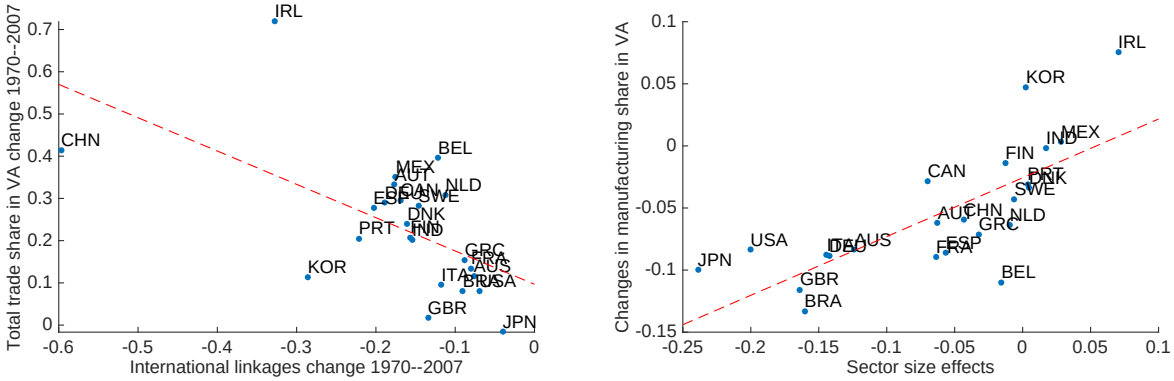
Notes: The left figure plots the standard deviations of output, consumption and investment at median as the world input-output changes from 1970 to 2007. The right figure plots the 10-year rolling over standard deviations of output, consumption and investment at median for 23 countries using annual data between 1970 and 2007.

Figure 8: Heterogeneous Effects of International Input-Output Linkage Change on Output Volatilities



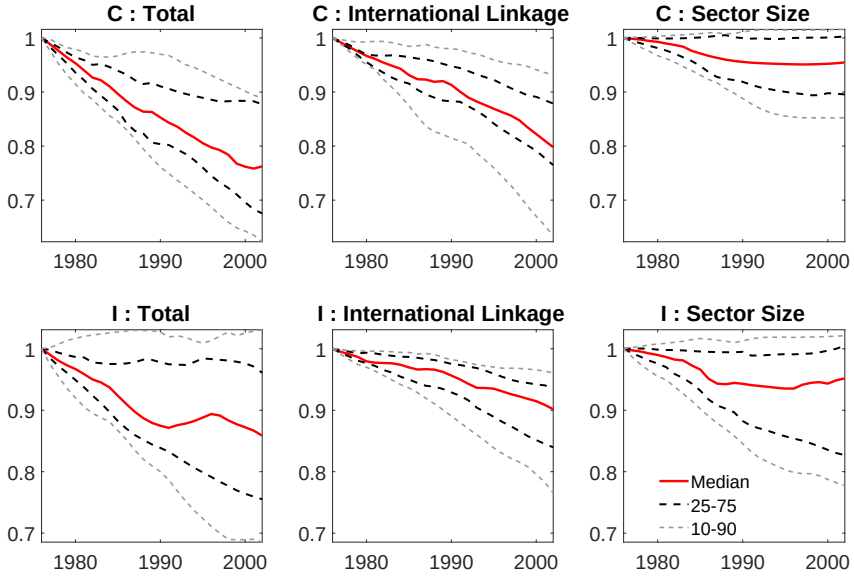
Notes: We plot the total effects of world input-output changes (Total) on standard deviation of output as the grey line. The black line with plus signs plots the change in the standard deviation of output when only the international input-output linkages change. The red dashed line plots the change in the standard deviation of output when only the relative sector size changes. The red line is the linear least squared fit.

Figure 9: International Linkage Effects vs. Changes in Openness, and Relative Sector Size Effects vs. Changes in Manufacturing Sector Share in Value Added



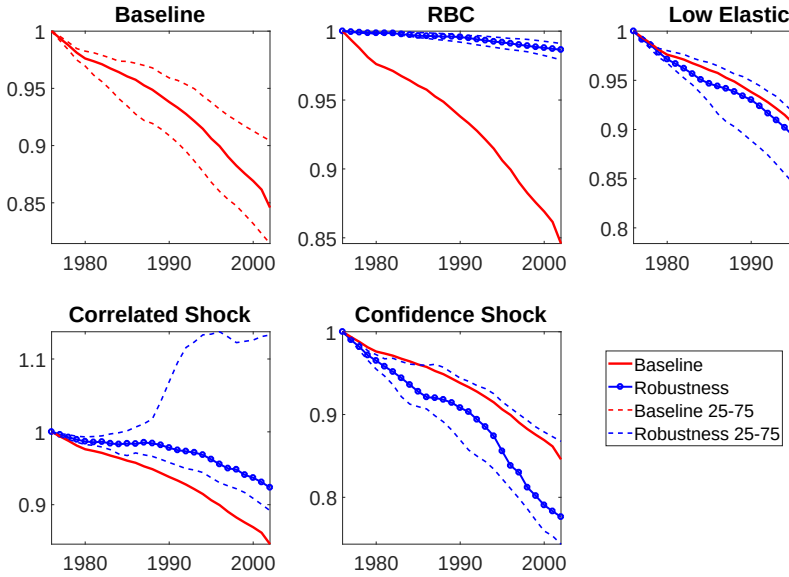
Notes: On the left, we plot the scatter plot of the effects of the international linkages over the 1970–2007 period in our decomposition for each country, against the changes in trade shares in value added in the same period. On the right, we plot the scatter plot of the total effects of the relative sector size changes over the 1970–2007 period in our decomposition for each country, against the changes in manufacturing shares in value added in the same period. The shares in the data are 10-year centered moving average.

Figure 10: Other Variables



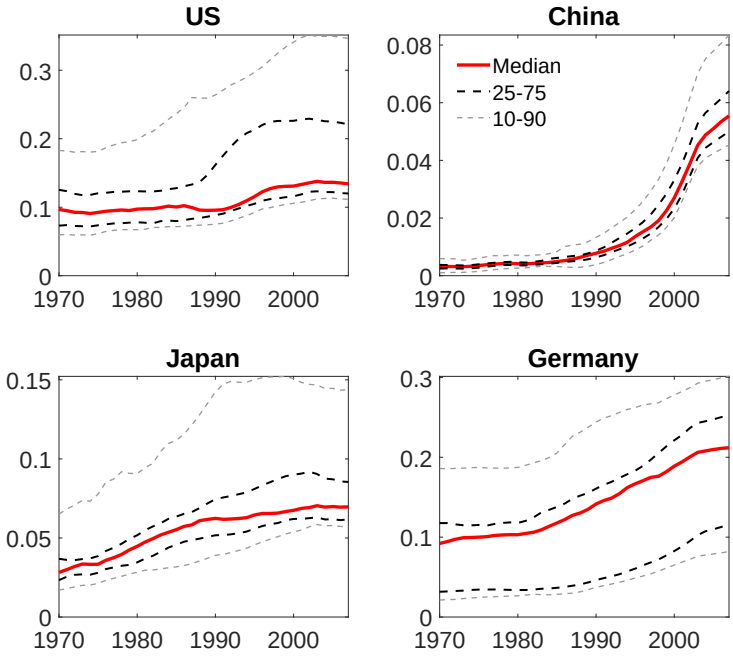
Notes: The first row is the decomposition for consumption and the second row is for investment. Each plot shows the median and the percentile bands.

Figure 11: Inspecting the Mechanism



Notes: Each figure plots the median and the percentile bands (in blue) along with the baseline median (red). We consider the model without any additional features (RBC), the model with low elasticity of substitution across home and foreign goods (Low Elasticity), the model with productivity shocks correlated across countries (Correlated Shock), and the model's main driving force is a confidence shock (Confidence Shock).

Figure 12: The Cross-Country Value Added Multipliers over Time



Notes: Each plot shows the median and the percentile bands of the multipliers for US shocks, Chinese shocks, Japanese shocks and German shocks.

A Data Appendix

A.1 World input-output table

The data are taken from Johnson and Noguera (2017). We choose 23 countries and aggregate the rest of the countries to ROW. The data span from 1970 to 2009. The original data include 4 sectors, we aggregate them into 2 sectors: manufacturing and non-manufacturing (agriculture, services, non-manufacturing industrial production).

A.2 Real aggregate data

Output, consumption, investment and real value added of manufacturing and non manufacturing sectors come from the United Nation National accounts Main aggregate database. The data are available from 1970 to 2013 for most countries: https://unstats.un.org/unsd/snaama/dnlList.asp. They have sectoral breakdown: agriculture, hunting etc., mining, manufacturing utilities, manufacturing, construction, wholesale, retail trade etc., Transport storage, other activities and total value added. All of the data are in both real and nominal terms.

We aggregate the real value added for non manufacturing sector as follows: we take a weighted sum of the growth rates of the real value added of all sectors other than manufacturing, where the weight is the share of the nominal value added of that sector in total nominal value added of non-manufacturing sectors. We then recover the time series for the non manufacturing sector for each country.

For the ROW, we aggregate all countries available data in a similar manner: the growth rate of the real value added of each sector is the weighted sum of the growth rates of the real value added of each sector in all countries available outside of the 23 countries. We then recover the time series for the real value added for each sector, then follow the same procedure to get the real value added for manufacturing and non manufacturing sectors.

Chinese data come from National Bureau of Statistics of China (http://data.stats.gov.cn/english/easyquery.htm?cn=A01). Manufacturing data are in the Industrial sector, and non-manufacturing data are the aggregate of the rest of the sectors.

B Decomposition

Table A1 describes a general World IO table where M is IS by IS, V is IS by 1, Q is IS by 1,and F is IS by I.

Table A1: General world IO table

	Intermediate	Final	Gross Output
Intermediate	M	F	Q
Value added	V'		
Gross Output	$Q^{'}$		

In the rest of the section, the elements of matrix are denoted with sector and country indices, similar to the main paper. For example, $Q(i,s)$ is a gross output in country i and sector s, $M((i,s),(j,k))$ is intermediate input from country i sector s to country j sector k. We simplify some of the notations compared to the paper, for example, drop $n(i)$. Define technical coefficients A as

$$A \equiv M\widehat{Q}^{-1},$$

where a hat symbol denotes a diagonalized vector, i.e. $\widehat{Q} \equiv diag(Q)$. Denote a matrix of ones with size m by n as $J_{(m,n)}$. We then define the total final demand for sectoral output in each country as

$$F^J = FJ_{(I,1)}.$$

Then, the matrix of shares of final demand in each country, f, is given by

$$f = \left(\widehat{F}^J\right)^{-1} F.$$

In the baseline decomposition, we use the standard demand-driven (Leontief) model interpretation of the IO table. Namely, we use the technical coefficients A for the decomposition. Later, we compare this procedure with the supply-side (Ghosh) model interpretation of the IO table, which means we use the allocation coefficients $B = \widehat{Q}^{-1}M$ for the decomposition. In the rest of the section, our procedure proceeds as follows: Given the IO table at $t = 0$, we compute the elements of a counterfactual IO table at time $t = 1$. We denote this counterfactual IO table at time $t = 1$ with a tilde.

B.1 Sector Size

The goal of isolating the sector size channel is to change the relative size of gross output in each country based on the relative size at $t = 1$ but keep the technical coefficients A at $t = 0$. Our approach is as follows:

1. Define total gross output in country i at time t as $Q_t(i) \equiv \sum_s Q_t(i,s)$. Using total gross output at $t = 0$, $Q_{t=0}(i)$, we compute $\widetilde{Q}(i,s)$ based on sectoral shares at $t = 1$.

$$\widetilde{Q}(i,s) = \frac{Q_{t=1}(i,s)}{Q_{t=1}(i)} Q_{t=0}(i).$$

2. Using technical coefficients $A_{t=0}$, we compute $\widetilde{M}$:

$$\widetilde{M} = A_{t=0}\widehat{\widetilde{Q}}.$$

   Then, $\widetilde{V}$ is computed as the difference between gross output and total intermediate inputs:

$$\widetilde{V}' = \widetilde{Q}' - J'_{(IS,1)}\widetilde{M}.$$

3. We compute total final demand for each goods as the difference between gross output and total intermediate demand in each row:

$$\widetilde{F}^J = \widetilde{Q} - \widetilde{M}J_{(IS,1)}.$$

4. We compute final demand $\widetilde{F}$ using the shares of each country demand for each goods at $t = 0$:

$$\widetilde{F} = \widehat{\widetilde{F}}^J f_{t=0}.$$

B.2 International Linkages

The goal of this decomposition is to construct a hypothetical IO table with only changes in the foreign intermediate input shares based on the shares at $t = 1$. We fix the value added shares and the relative sectoral input shares, so as to isolate the effects of international linkage channel. We change the shares of foreign final demand based on the final demand composition at $t = 1$, which reflects the changes in international linkages through foreign demand. Specifically,

1. We do not change the gross output and value added levels at $t = 0$. Namely, we have $\widetilde{Q} = Q_{t=0}$ and $\widetilde{V} = V_{t=0}$. Thus, the value added shares $v' \equiv V'\widehat{Q}^{-1}$ are fixed.

2. We fix the relative shares of sectoral intermediate inputs $\sum_i A_{t=0}\left((i,n),(j,k)\right)$ for each column at $t = 0$. Additionally, with $A_{t=1}$, we can create $\widetilde{A}$. Specifically, we compute

$$\widetilde{A}\left((m,n),(j,k)\right) = \sum_i A_{t=0}\left((i,n),(j,k)\right) \times \underbrace{\frac{A_{t=1}\left((m,n),(j,k)\right)}{\sum_i A_{t=1}\left((i,n),(j,k)\right)}}_{\text{Share of country } m \text{ inputs in sector } n} .$$
$$\text{Share of sector } n \text{ inputs}$$

3. Given $\widetilde{A}$, we recover $\widetilde{M} = \widetilde{A}\widetilde{\widehat{Q}}$.

4. We compute total final demand for each good as the difference between gross output and total intermediate demand in each row:

$$\widetilde{F}^J = \widetilde{Q} - \widetilde{M}J_{(IS,1)}.$$

5. We compute the final demand $\widetilde{F}$ using the shares of each country's demand for each goods at $t = 1$, which reflects the change in the shares of foreign final demand:

$$\widetilde{F} = \widetilde{\widehat{F}}^J f_{t=1}.$$

B.3 Country Size

The country size decomposition is similar to the sector size decomposition. Instead of changing the relative sector sizes, we change the relative sizes of total gross output in each country based on gross output at $t = 1$. Define total gross output in the world as $Q_t \equiv \sum_i Q_t(i)$. We compute $\widetilde{Q}(i,s)$ as follows.

$$\widetilde{Q}(i,s) = \frac{Q_{t=0}(i,s)}{Q_{t=0}(i)} \frac{Q_{t=1}(i)}{Q_{t=1}} Q_{t=0}.$$

The remaining procedure is the same as the sector size decomposition.

B.4 Robustness

B.4.1 Supply-Side Model Interpretation of the IO table

Here, we use the supply-side model interpretation of the IO table. In particular, we use the allocation coefficients, $B = \widehat{Q}^{-1}M$, and $C = \widehat{Q}^{-1}F$ for the decomposition.

Sector Size: Case 2 The procedure is similar to the baseline demand-driven model case. More specifically,

1. We compute $\widetilde{Q}(i,s)$ based on sectoral shares at $t=1$:

$$\widetilde{Q}(i,s) = \frac{Q_{t=1}(i,s)}{Q_{t=1}(i)} Q_{t=0}(i).$$

2. Using the allocation coefficients $B_{t=0}$, we compute $\widetilde{M}$:

$$\widetilde{M} = \widehat{\widetilde{Q}} B_{t=0}.$$

   Then, $\widetilde{V}$ is computed as the difference between gross output and total intermediate inputs.

$$\widetilde{V}' = \widetilde{Q}' - J'_{(IS,1)} \widetilde{M}.$$

3. Using the share of final demand over gross output for each good C, final demand is computed as $\widetilde{F} = \widehat{\widetilde{Q}} C_{t=0}$.

Country Size: Case 2 We define $\widetilde{Q}(i,s)$ as $\widetilde{Q}(i,s) = \frac{Q_{t=0}(i,s)}{Q_{t=0}(i)} \frac{Q_{t=1}(i)}{Q_{t=1}} Q_{t=0}$. The remaining procedure is the same as sector size decomposition of the supply-side model.

International Linkage: Case 2 We fix the intermediate demand shares and final demand shares over gross output.

1. We do not change gross output level so $\widetilde{Q} = Q_{t=0}$.

2. We fix the shares of sectoral intermediate demand $\sum_i B_{t=0}((j,k),(i,n))$ in each row at $t=0$. We create $\widetilde{B}$ using $B_{t=1}$ and this restriction. Specifically, we compute

$$\widetilde{B}((j,k),(m,n)) = \sum_i \underbrace{B_{t=0}((j,k),(i,n))}_{\text{Share of sector } n \text{ inputs}} \times \underbrace{\frac{B_{t=1}((j,k),(m,n))}{\sum_i B_{t=1}((j,k),(i,n))}}_{\text{Share of country } m \text{ demand in sector } n}.$$

3. Given $\widetilde{B}$, we recover $\widetilde{M} = \widehat{\widetilde{Q}} \widetilde{B}$.

4. Value added $\widetilde{V}$ is computed as the difference between gross output and total intermediate

inputs:

$$\widetilde{V}' = \widetilde{Q}' - J'_{(IS,1)}\widetilde{M}.$$

5. The total final demand for each good is the value at $t = 0$:

$$\widetilde{F}^J = \widetilde{F}^J_{t=0}.$$

6. We compute final demand $\widetilde{F}$ using the shares of each country demand for each goods at $t = 1$. This step reflects the change in the shares of foreign final demand:

$$\widetilde{F} = \widehat{\widetilde{F}}^J f_{t=1}.$$

B.4.2 Other cases

We additionally examine three more ways to decompose the international linkage channel.

International Linkage: Case 3 Compared with the baseline international likage channel, we change value added shares based on $v_{t=1}$. Thus, we have

$$\begin{aligned} \widetilde{Q} &= Q_{t=0} \\ \widetilde{V} &= \widehat{\widetilde{Q}} v_{t=1}. \end{aligned}$$

We still fix the relative shares of sectoral intermediate inputs in each column at $t = 0$. We create $\widetilde{A}$ using $A_{t=1}$ and this restriction. Specifically, we compute

$$\widetilde{A}\left((m,n),(j,k)\right) = \underbrace{\sum_i \sum_s A_{t=1}\left((i,s),(j,k)\right)}_{\text{Intermediate input share}} \times \underbrace{\frac{\sum_i A_{t=0}\left((i,n),(j,k)\right)}{\sum_i \sum_s A_{t=0}\left((i,s),(j,k)\right)}}_{\text{Share of sector } n \text{ inputs}} \times \underbrace{\frac{A_{t=1}\left((m,n),(j,k)\right)}{\sum_i A_{t=1}\left((i,n),(j,k)\right)}}_{\text{Share of country } m \text{ inputs in sector } n}$$

The rest is the same as baseline.

International Linkage: Case 4 We change both value added shares and relative shares of sectoral intermediate inputs. Thus, we have

$$\begin{aligned}\widetilde{Q} &= Q_{t=0} \\ \widetilde{V} &= \widehat{\widetilde{Q}} v_{t=1} \\ \widetilde{M} &= A_{t=1} \widehat{\widetilde{Q}}\end{aligned}$$

The rest is the same as baseline.

International Linkage: Case 5 We change value added shares and the foreign intermediate input shares but we keep domestic intermediate input shares. Namely,

$$\begin{aligned}\widetilde{Q} &= Q_{t=0} \\ \widetilde{V} &= \widehat{\widetilde{Q}} v_{t=1}\end{aligned}$$

$$\widetilde{A}\left((j,n),(j,k)\right) = A_{t=1}\left((j,n),(j,k)\right) \text{ for any } n,j,k$$

The rest of $\widetilde{A}$ is

$$\widetilde{A}\left((m,n),(j,k)\right) = \underbrace{\left(1-\widetilde{v}\left(j,k\right)-\sum_{n} A_{t=1}\left((j,n),(j,k)\right)\right)}_{\text{Share of foreign intermediate inputs}} \times \frac{A_{t=1}\left((m,n),(j,k)\right)}{\sum_{i\neq j} A_{t=1}\left((i,n),(j,k)\right)}$$

for $m \neq j$. The rest is the same as baseline.

C Two Country Model Case

This appendix details the setup and calibration of the model with two countries and two sectors in the paper. The World IO table for 2 countries and 2 sectors (S1 and S2) is given in Table A2.

We calibrate the parameters as follows. Let w_1 be the share of sector 1 input for sector 1 production common for both countries, and w_2 be the share of sector 2 input for sector 2 production common for both countries. We set the value added share to be half of the gross output in all sectors and countries. The relative sector size of sector 2 to sector 1, B is set to be 2 in both countries. The relative country size of the United States, A is 10. We set α_2 close to zero, 0.001, so that sector

Table A2: World IO table for 2 countries 2 sectors

		Country 1 Sector 1	Country 1 Sector 2	Country 2 Sector 1	Country 2 Sector 2	Country 1 Final	Country 2 Final
Country 1	S1	$w_1(1-\alpha_1)$	$(1-w_2)(1-\alpha_2)B$	$w_1\alpha_1$	$(1-w_2)\alpha_2 B$	$1-w_1\alpha_1$	$w_1\alpha_1$
Country 1	S2	$(1-w_1)(1-\alpha_1)$	$w_2(1-\alpha_2)B$	$(1-w_1)\alpha_1$	$w_2\alpha_2 B$	$(1-\alpha_2)B$	$\alpha_2 B$
Country 2	S1	$w_1\alpha_1$	$(1-w_2)\alpha_2 B$	$w_1(A-\alpha_1)$		$w_1\alpha_1$	$A-w_1\alpha_1$
Country 2	S2	$(1-w_1)\alpha_1$	$w_2\alpha_2 B$	$(1-w_1)(A-\alpha_1)$	$w_2(A-\alpha_2)B$	$\alpha_2 B$	$(A-\alpha_2)B$
VA		1	B	A	AB		
GO		2	2B	2A	2AB		

2 is essentially closed for simplicity. We do not change the openness for sector 2 in the exercise. We set the openness parameter for sector 1 α_1 to be 0.5. In summary, the calibrated parameters are: $w_1 = 0.75, w_2 = 0.875, B = 2, A = 10, \alpha_2 = 0.001$.

The exercise in the paper, which is to calculate the volatility of the value added in country 1 when varying the openness of sector 1, is as follows: We vary α_1 to change the openness of sector 1. A higher value of α_1 means that sector 1 in Canada imports more goods for production, and there is more final demand from the United States. As there are only two countries, we assume the same thing happens for sector 1 in the United States. The openness for Canada is computed as

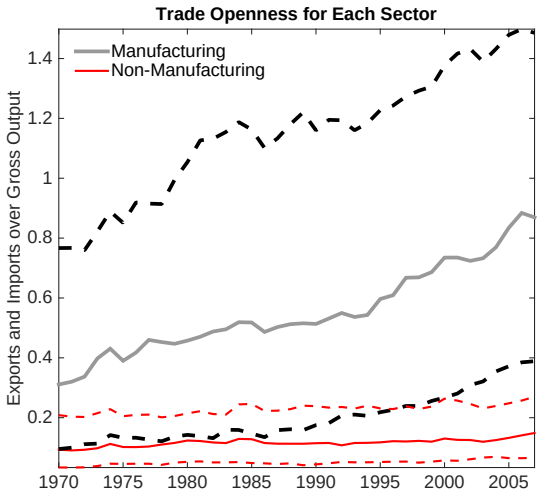
$$\frac{\text{Export+Import}}{\text{VA}} = \frac{2\left[(1+w_1)\alpha_1 + 2\alpha_2 B\right]}{1+B},$$

which is increasing in α_1. Other parameters follow the calibration above. The standard deviations of the productivity shocks in sector 1 and 2 are $(1, 0.2)$ for both countries.

To create the figure that shows the impact of the relative sector size changes, we vary B. We restrict w_2 to satisfy that $w_2 = \frac{B-(1-w_1)}{B}$, which keeps the sum of columns and rows in the IO table consistent with each other.

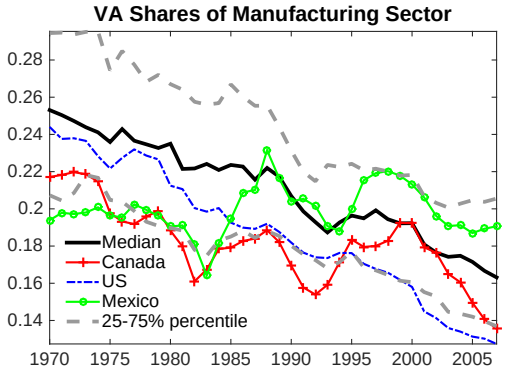
For Online Publication: Additional Tables and Figures

Figure A1: Trade Openness in Manufacturing and Non-Manufacturing sectors between 1970 and 2007



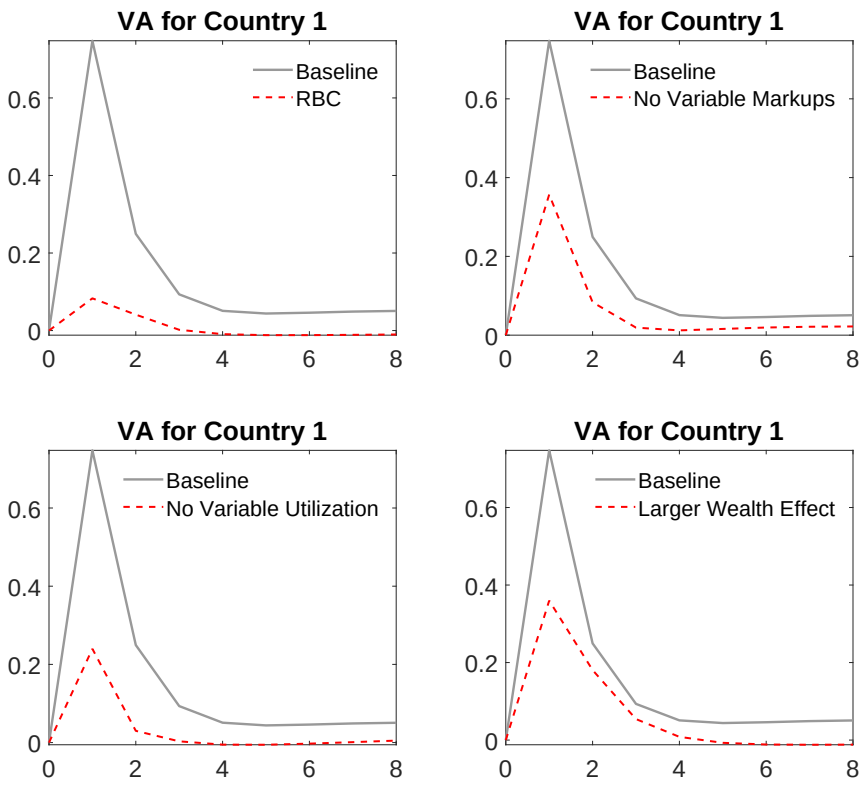
Notes: We plot the median across 23 countries, 25-75 percentile for each sector. Trade openness is defined as total exports and imports divided by the gross output in each sector.

Figure A2: Relative sector sizes between 1970 and 2007: Manufacturing sector shares in total value added



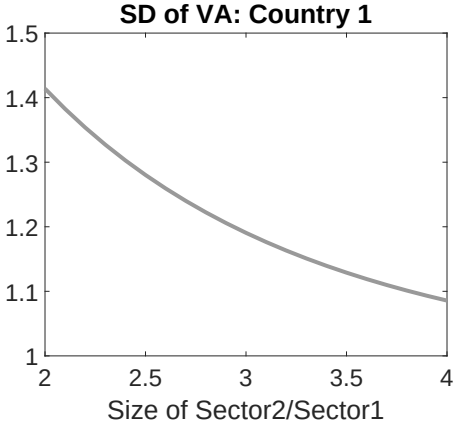
Notes: We plot the median across 23 countries, 25-75 percentile and three countries: the United States, Mexico and Canada.

Figure A3: Model Behavior: Transmission of shocks across countries without our features



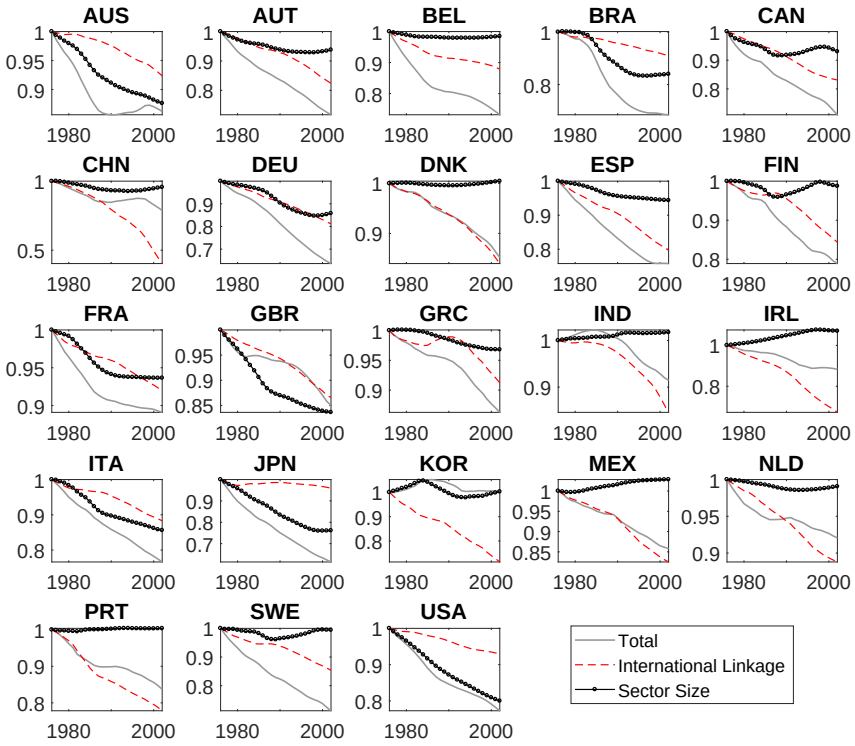
Notes: The impulse responses in country 1 and 2 to a positive TFP shock in country 2 sector 1 simulated in a 2-country model experiment. VA denotes value added in each country or sector.

Figure A4: Model Implication: Relationship between relative sector sizes and output volatility and cross-country correlations



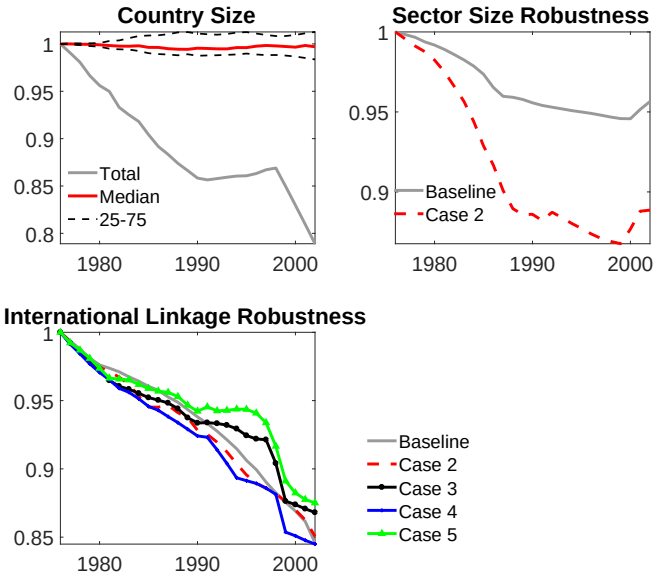
Notes: Figure A4 plots the standard deviation of output as we vary the relative sizes of sector 1 to sector 2.

Figure A5: Heterogeneous Effects of International Input-Output Linkage Change on Output Volatilities in All Countries



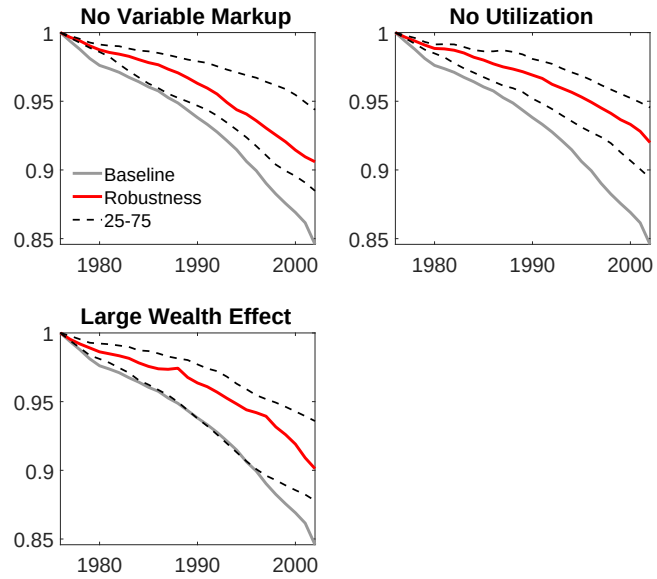
Notes: We plot the total effects of world input-output changes (Total) on standard deviation of output as the grey line. The black line with plus signs plots the change in the standard deviation of output when only the international input-output linkages change. The red dashed line plots the change in the standard deviation of output when only the relative sector size changes.

Figure A6: Other Decompositions



Notes: We plot the decomposition to show the effects of country size changes (Country Size), and the other decomposition method for relative sector size and international linkage changes, as discussed in the Decomposition Appendix B.

Figure A7: Robustness for Decomposition In Different Model Specifications



Notes: We plot the international linkage decomposition on output at median and the 25-75 percentile bands along with the baseline results for different model specifications: when the model has no variable markup, no variable capital utilization, or large wealth effect on labor supply.