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May 2017

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Sveriges Riksbank Working Paper Series

No. 340

May 2017

Abstract

To what extent is the international business cycle affected by the fact that an essential input (oil) is traded on the world market? We quantify the contribution of oil by setting up a model with separate shocks to efficiencies of capital/labor and oil, as well as global shocks to the oil supply. We find that the shocks to the supply and the efficiency of oil both contribute to positive comovements. These two shocks are also relatively transitory, which induces high responses in output and low responses in consumption. As a consequence, the model resolves both the consumption correlation puzzle and the international comovement puzzle.

Keywords: International comovements, business cycles, oil, productivity

JEL: E32; F32; F41; Q43

1 Introduction

In 1992, Backus, Kehoe and Kydland documented that simple models of international real business cycles have difficulties accounting for several features of the data. First, empirical

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cross-country correlations are generally higher for output than for consumption. Existing models, however, typically predict consumption correlations to be much higher than the output correlations. This fact is often referred to as the consumption correlation puzzle or the quantity anomaly.

Second, employment and investment display relatively strong positive cross-country correlations in the data, whereas models predict negative cross-country correlations. This is generally referred to as the international comovement puzzle.

The model prediction of a strong positive cross-country correlation for consumption arises because the existence of almost complete markets enables households across countries to insure themselves against country-specific risk. The international comovement puzzle stems from the fact that efficiency requires investments and employment to increase in the most productive country and be reduced in the least productive country in response to a productivity shock. Cross-country correlations of inputs and output therefore tend to be low. Trading frictions and restricted asset trading can help lower the high consumption correlation but, as documented by Baxter and Crucini (1995), Kollman (1996) and Arvantis and Mikkola (1996), the allocation in an economy where agents only have access to a single, non-contingent bond will only differ from that with complete markets if productivity shocks are very persistent and do not spill over across borders.[1]

In this paper, we analyze the potential importance, for the international business cycle, of the fact that an essential input into production, i.e., oil, is traded on a world market. Specifically, we set up a simple model with two countries that use capital, labor, and oil as inputs to produce a country-specific tradable intermediate good that is needed to produce a final good, and one country that extracts and sells oil.

The model is similar to that in Backus and Crucini (2000), but one important difference is that, whereas Backus and Crucini consider Hicks-neutral productivity shocks, we incorporate factor-specific technology shocks into the model. These non-Hicks-neutral technology shocks are motivated by findings in Hassler, Krusell, and Olovsson (2012) showing that technologies that save on capital/labor and energy typically grow at distinct rates and also have different volatilities.

In addition to the country-specific technology shocks, the model features exogenous shocks to the oil supply. These shocks are global and affect both final-goods-producing countries in the same direction. Exogenous shocks to the oil supply - caused by wars and other exogenous political events - occur regularly and can be substantial as documented

[1] Two papers that find large effects of financial frictions are Heathcote and Perri (2002) and Kehoe and Perri (2002).

by Hamilton (2003) and Kilian (2008).[2] Furthermore, according to Kose, Otrok and Prasad (2012), global factors account for about 30 percent of business cycle fluctuations in industrialized countries. Specifically, they statistically disentangle the effects of global factors, but do not identify what these global factors are. The inclusion of oil allows us to identify a specific source of the global component and quantify its importance. In particular, we want to assess whether shocks to the oil supply can be quantitatively important for the international business cycle given that energy's share of income is only around five percent.[3]

We follow Heathcote and Perri (2002) in identifying the two "countries" as the U.S. and the Rest of the world (ROW). The focus on the U.S. is obvious in our setting; it is, and has for many decades been, by far the world's largest consumer of oil. Between 1980 and 2000, the U.S. share of the world petroleum consumption was just below 30 percent. The large influence that the U.S. economy has had on the oil price has also been empirically documented by Barsky and Kilian (2002) and Hamilton (2003).[4] Moreover, the U.S. is a net importer of oil. Similarly, our definition of ROW only includes countries that are net importers of oil.

The productivity processes are estimated using data from the OECD, FRED, the Penn World Table and the U.S. Energy Information Administration, whereas the process for exogenous oil-supply shocks is estimated using data from Kilian (2008). Kilian's measure of oil-supply shocks has the benefit of being an estimate of true exogenous variation, which makes it ideal when quantifying the effects of oil-supply shocks on macroeconomic variables such as GDP and consumption. Consistent with most empirical findings and the macroeconomic literature with oil as an input, we impose a low (short-run) elasticity of substitution between capital/labor and oil.

The analysis shows that adding oil as an input changes the predictions of the model substantially. Specifically, the model resolves both the consumption correlation puzzle and the international comovement puzzle. It predicts a cross-country correlation of consumption that is lower than that of output, as well as strongly positive cross-country correlations of employment and investment. These findings hold with standard preferences,

[2] Hamilton estimates the exogenous shortfalls in world production for five specific events and finds them to be between 7.2-10.1 percent of world production.

[3] Indeed, the main reason why the input of energy is abstracted from in the vast majority of macroeconomic research is likely the perception that energy's share is too small for energy to have quantitatively important implications for macroeconomic outcomes.

[4] Barsky and Kilian write "The view that oil prices are endogenous with respect to U.S. macroeconomic variables such as real interest rates and real GDP has considerable empirical support". Hamilton writes "Statistically, oil prices certainly are predictable from U.S. macroeconomic developments".

and irrespective of whether productivity shocks are correlated between the countries or not.[5] In fact, even though the model correlations are generally spanned by the data, they are, on average, too high. Hence, despite the fact that energy's share of output is small, the world market for oil can be quantitatively important for the international business cycle.

The results are driven by a combination of the opposing effects of the different shocks. Shocks to the capital/labor productivity have similar effects as standard total-factor-productivity shocks in models without oil, i.e., they produce low or negative cross-country correlations of inputs and output, and a high positive correlation for consumption. Specifically, a positive shock to the capital/labor efficiency in the home country generates a boom in that country. The shock also leads to an improvement in the terms of trade and creates a positive wealth effect in the foreign country. The consumers in the foreign country respond to this wealth shock by increasing consumption and reducing labor supply and investments.

When oil is traded on the world market, there is an additional effect from the shock in the home country in that it leads to an increase in the oil price (that comes from the higher marginal product of oil in the home country). The higher price induces firms in the foreign country to reduce their oil use, and with capital/labor and oil being gross complements, the lower input of oil implies a lower capital/labor productivity in the foreign country. The result is a reduction in hours worked, output and consumption in the foreign country, which implies lower cross-country correlations of all these variables. Hence, with oil, the cross-country correlations of inputs, output and consumption are all lower than without oil.

Shocks to the oil supply are global and have two effects: they affect the capital/labor productivity and they generate wealth effects. The productivity effect induces positive comovements of labor supply, production, and consumption. To what extent these shocks increase the correlation for output relatively more than for consumption depends crucially on to what extent the shocks are persistent. If the oil supply shocks are transitory - as they are estimated to be - then the wealth effect is small. According to the permanent income hypothesis, a large fraction of the extra income generated from the increase in output will then be saved for the future. Consequently, the response in consumption will be smaller than that in output.

Shocks to the energy efficiency, finally, have qualitatively similar effects as shocks to

[5] In the literature often referred to as the new open-economy macroeconomics (NOEM), technology shocks are assumed to be uncorrelated across countries.

the oil supply, i.e., they are relatively transitory and induce positive comovements of output, labor supply, investments and consumption. It is, in fact, crucial for the results to consider factor-specific productivity shocks. When these shocks are replaced by the more standard Hicks-neutral productivity shocks, the consumption correlation puzzle reappears in the model.[6]

The model abstracts from many features such as nominal frictions, monopolistic competition, habit formation, etc., and is kept relatively simple in order to focus on a specific mechanism. Given that many New Keynesian models build on a core from real-business-cycle models, however, it is useful to analyze modifications of this core separately as a first step. Nominal frictions and other features can then straightforwardly be introduced as a next step. We carry out a large number of experiments to evaluate the sensitivity of the results and find that the results are quite robust over a large parameter space. We therefore expect our results to survive also in more complicated settings.

This paper is related to a large number of previous studies. Apart from the papers already mentioned, a non-exhaustive list includes the following contributions. Stockman and Tesar (1995) introduces non-traded goods that drive down the cross-country correlation for consumption. Baxter and Farr (2005) shows how variable capital utilization can lead to positive comovements of inputs and also improve on the quantity anomaly. Corsetti, Dedola and Leduc (2008) mainly focuses on mechanisms that can solve the Backus-Smith puzzle - the fact that empirical correlations between consumption and real exchange rates are negative whereas models typically predict them to be highly positive - but they also address the quantity anomaly. Justiniano and Preston (2010) quantifies to what extent an estimated, microfounded and semi-small open economy can reproduce the observed comovements in international business cycles. They find that the cross-country correlation functions implied by the model are close to zero, which contrasts with the empirical evidence. Bodenstein, Erceg and Guerrieri (2011) considers a model with oil and focuses on the trade balance between oil importers and oil exporters. Engel and Wang (2011), finally, focuses on the role of durables in accounting for business cycle statistics on comovements of import and export.

The paper is structured as follows. Section 2 describes the data. Section 3 sets up the model, and the results are then presented in Section 4. A sensitivity analysis is carried out in Section 5. The main assumptions are discussed in Section 6, and Section 7, finally, concludes.

[6]Backus and Crucini (2000) considers only Hicks-neutral productivity shocks and finds them to only have modest effects.

2 Stylized facts

This section documents the facts. Most of these facts have been presented before, but we also provide data for oil use, which has not received much previous attention in this context.[7]

We follow the tradition of using quarterly data. Since some of our series are relatively short, however, we also present data and model results for an annual frequency.

The data for these computations are taken from OECD's Quarterly National Accounts, FRED and the Energy Information Administration. More details about the data are provided in Appendix A.

All variables are logged and detrended with the HP filter.[8] Tables 1 and 2 present the quarterly statistics for eighteen OECD countries, and the annual statistics are presented in Tables 7-8 in Appendix A.

The results are similar to those from earlier studies: output is more volatile than consumption and employment, but less volatile than investments. Oil use is highly volatile, but slightly less so in the annual than in the quarterly data.[9] The mean correlations of the considered variables with output are around 0.70, except for oil use that is lower.

The international correlations are displayed in Table 2. Specifically, the table shows correlations of variables in each country with the same variables in the United States. With only a few exceptions, all correlations are positive.

Consistent with previous findings, the cross-country correlations for consumption tend to be smaller than those for output, and the cross-country correlations for employment and investments largely positive.[10] Also, oil use displays a positive cross-country correlation. This is also true for the annual data, as is shown in Table 8 in Appendix A.

3 The model

We now consider a model similar to that in Backus and Crucini (2000). Following the tradition in the macroeconomic literature with oil, we focus on oil as the sole energy

[7] For previous studies without oil see, for instance, Backus, Kehoe and Kydland (1992, 1993) and Ambler, Cardia, and Zimmermann (2004).

[8] A smoothing parameter of 1600 is used to produce cyclical components for the quarterly macroeconomic variables .

[9] See Table 7 in Appendix A.

[10] Ambler, Cardia, and Zimmermann (2004) looks at 190 pairwise correlations between 20 industrialized countries, and test hypotheses concerning their correlations. Even though their numbers differ somewhat from ours, their findings are much in line with those presented in Tables 7-8.

Table 1: Cyclical properties in sixteen developed countries (based on quarterly data)

	Volatility					Correlation with output			
	std in %	Relative std							
	y	c	l	o	i	c	l	o	i
Austria	1.07	0.82	0.82	5.00	2.17	0.54	0.77	0.02	0.57
Belgium	0.99	0.69	0.57	7.22	3.67	0.58	0.65	0.01	0.65
Denmark	1.42	1.16	1.10	4.00	4.06	0.70	0.57	0.25	0.73
Finland	2.15	0.83	0.52	2.65	2.58	0.82	0.72	0.12	0.87
France	0.94	0.83	0.82	5.43	2.65	0.68	0.84	0.08	0.90
Germany	1.44	0.55	0.75	2.80	2.15	0.51	0.86	-0.02	0.85
Greece	2.30	0.94	0.69	3.48	3.27	0.68	0.46	0.24	0.58
Ireland	2.88	0.74	0.91	2.31	3.17	0.54	0.69	0.15	0.53
Italy	1.17	1.01	0.70	5.03	2.52	0.67	0.77	0.18	0.80
Japan	1.39	0.71	0.37	6.30	2.16	0.69	0.78	0.19	0.78
Netherlands	1.28	0.86	0.91	2.45	3.10	0.73	0.72	0.26	0.74
Portugal	1.60	1.21	0.73	3.61	3.67	0.87	0.41	0.28	0.86
Spain	1.30	1.13	1.12	2.91	3.29	0.89	0.70	0.38	0.85
Sweden	1.62	0.83	0.76	5.05	3.02	0.59	0.78	0.01	0.82
United Kingdom	1.31	1.09	0.55	3.10	3.35	0.85	0.75	0.07	0.81
United States	1.29	0.79	1.22	1.74	2.91	0.87	0.90	0.51	0.93
Average	1.51	0.89	0.78	3.94	2.98	0.70	0.71	0.17	0.77

The time frequency is quarterly. y is output, c is consumption, l is employment, o is oil use, and i is investment. All variables are in logarithms and have been detrended with the HP filter. Source: OECD statistics database, the FRED database, and the Energy Information Administration.

input.[11,12] This specific assumption is discussed further in Section 6.2.

As mentioned in the Introduction, the model abstracts from many features such as nominal frictions, monopolistic competition, habit formation, etc., and is kept relatively simple in order to focus on a specific mechanism. The world consists of three countries: h (home), f (foreign), and e (energy). In countries $i \in \{h, f\}$, intermediate-goods-producing firms employ capital (K_i), labor (L_i), and oil (O_i) to produce an intermediary (X_i). These intermediaries are then traded between countries h and f, and are also used as payments for the oil that h and f buy from e. Final-goods-producing firms in all countries use the intermediates to produce the non-traded final goods. Neither capital nor labor is assumed to be internationally mobile.

[11] See, for example, Kim and Loungani (1992), Rotemberg and Woodford (1996), Backus and Crucini (2000), Bodenstein, Erceg and Guerrieri (2011), and Olovsson (2016).

[12] The results in the paper are likely robust to instead considering a fossil-fuel composite that consists of natural gas and coal in addition to oil, since usage and prices of these fuels are positively correlated with oil use. The correlation between the oil price and a fossil-fuel-composite price is 0.87 for the period 1949-2009.

Table 2: International comovements

	Contemporaneous cross correlations with same U.S. variable				
	y	c	l	o	i
Austria	0.37	0.14	0.77	0.22	0.45
Belgium	0.51	-0.02	0.55	0.24	0.41
Denmark	0.59	0.52	0.59	0.37	0.50
Finland	0.49	0.31	0.70	0.46	0.26
France	0.40	0.15	0.75	0.31	0.30
Germany	0.37	0.23	0.79	0.06	0.42
Greece	0.12	-0.17	0.02	0.21	-0.12
Ireland	0.30	0.59	0.77	0.13	0.24
Italy	0.52	0.23	0.66	0.40	0.14
Japan	0.38	0.04	0.71	0.28	0.38
Netherlands	0.55	0.34	0.47	0.19	0.36
Portugal	-0.01	-0.08	0.18	0.10	-0.35
Spain	0.23	0.31	0.65	0.27	0.14
Sweden	0.60	0.31	0.66	0.27	0.43
United Kingdom	0.61	0.61	0.79	0.26	0.50
Average	0.40	0.23	0.60	0.25	0.27

The time frequency is quarterly. y is output, c is consumption, l is employment, o is oil use, and i is investment. All variables are in logarithms and have been detrended with the HP filter. Source: OECD statistics database, the FRED database, and the Energy Information Administration.

We will use index i to denote countries in their role as intermediate-goods producers, i.e., $i \in \{h, f\}$, and index j to refer to countries in their role as final-goods producers, i.e., $j \in \{h, f, e\}$. Uppercase letters are consistently used to denote aggregate variables within each country, whereas lowercase letters are used to denote individual per-capita variables. The model is now described formally.

Perfectly competitive intermediate-goods-producing firms in countries $i \in \{h, f\}$ produce intermediates X_i according to the following production function

$$X_i \equiv F(A_i, B_i, K_i, L_i, O_i) = \left[(1-\gamma)\left(A_i K_i^{\alpha} L_i^{1-\alpha}\right)^{\frac{\varepsilon-1}{\varepsilon}} + \gamma (B_i O_i)^{\frac{\varepsilon-1}{\varepsilon}}\right]^{\frac{\varepsilon}{\varepsilon-1}}, \qquad (1)$$

where $A_i \equiv \exp(Z_{A,i})$ and $B_i \equiv \exp(Z_{B,i})$ respectively denote the (detrended) productivity levels of capital/labor and oil, and ε is the elasticity of substitution between capital/labor and oil.[13] The production function in (1) ensures that the relative shares of capital and labor inherit their properties from the usual Cobb-Douglas form used in

[13] We consider a stationary model and abstract from long-run growth.

growth studies.[14]

Note that, whereas standard Cobb-Douglas production functions typically feature Hicks-neutral shocks, i.e., shocks that affect all inputs in the same way, (1) features factor-specific technology shocks.[15] As we will see, these non-Hicks-neutral shocks have important implications for the international business cycle. The processes for $Z_{A,j}$ and $Z_{B,j}$ obey the following laws of motion:

$$\begin{bmatrix} Z'_{m,h} \\ Z'_{m,f} \end{bmatrix} = \Xi_m \begin{bmatrix} Z_{m,h} \\ Z_{m,f} \end{bmatrix} + \begin{bmatrix} \chi'_{m,h} \\ \chi'_{m,f} \end{bmatrix} \text{ for } m \in \{A, B\}, \tag{2}$$

where Ξ_m are matrices of constant coefficients and $\chi'_{m,h}$ and $\chi'_{m,f}$ are normally distributed with mean zero. The off-diagonal elements in Ξ_m capture spill-overs, i.e., the extent to which the next period's shock to the productivity factor m in one country depends on the current shock to productivity factor m in the other country. Based on findings for the U.S., we assume that there are no spill-overs from A to B, either within or between countries.[16]

Final-goods-producing firms in country $j \in \{h, f, e\}$ are perfectly competitive. These firms produce final goods using intermediate goods as inputs according to the following constant returns to scale technology

$$Y_j = G_j(X_{h,j}, X_{f,j}) = Z_{y,j} \left[\eta_j X_{h,j}^{\frac{\sigma-1}{\sigma}} + (1 - \eta_j) X_{f,j}^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}}, \tag{3}$$

where σ is the elasticity of substitution between the intermediates from different countries and $Z_{y,j}$ is a constant productivity level. The parameters η_j give the bias towards intermediates from the own country relative to intermediates in the other country. Following Heathcote and Perri (2002), final goods are used for consumption and investment but are not traded between countries.

The households in countries h, f, and e derive utility from consumption of the final

[14] A similar function is used in Hassler, Krusell and Olovsson (2012), Stern and Kander (2012), and Gars and Olovsson (2015).

[15] The model is set up so that A and B can decrease from one period to another. It is, however, straightforward to add positive trends to the productivity processes to make it less likely that productivity levels actually decrease. After a transformation that makes the growth model stationary over time, the transformed production function can be shown to be identical to (1). See also Hassler, Krusell and Olovsson (2016) for a more elaborate description of a version of the model with growth.

[16] The correlation between the shocks to A and B within the U.S. is close to zero at -0.10.

good with preferences given by the following utility function

$$u(c_j, 1-l_j) = \frac{\left(c_j^{1-\mu}(1-l_j)^{\mu}\right)^{1-\phi} - 1}{1-\phi}, \quad \text{for } j \in \{h, f, e\}, \tag{4}$$

where l_j denotes hours worked and $1 - l_j$ is leisure.[17] Households in country $i \in \{h, f\}$ own the capital stock (K_i) of that country. They can also trade in a single non-contingent bond that exists in zero net supply. Denoting bond holdings in country f by S_f, bond holdings in country h are then given by $S_h = -S_f$.

3.1 The oil-producing country

Country e extracts and sells oil to countries h and f on a competitive world market. It is, for simplicity, assumed that the supply of oil in e just follows an exogenous process. This assumption is standard in the literature and is, for instance, found in Bodenstein, Erceg and Guerrieri (2011), Arezki, Ramey, and Sheng (2017), and Olovsson (2016). It is motivated by the fact that oil-producing countries seem to respond slowly to demand shocks due to adjustment costs and uncertainty about the oil market.[18,19]

The next period's supply of oil is then given by

$$O' = \varphi + \exp(Z_o'), \tag{5}$$

where φ is a parameter and Z_o is a shock to the supply of oil. This shock is assumed to follow the process

$$Z_o' = \rho_{z_o} Z_o + \chi_o,$$

with χ_o being independent and normally distributed with mean zero and variance given by σ_{χ_o}. Note that the next period's oil supply is a function of the current shock, χ_o. This specification implies that agents get information about the future oil supply one period

[17] The utility function in country e is effectively irrelevant since households in e never make any decisions where the utility function matters.

[18] Kilian (2009) argues that the unresponsive oil supply is consistent with evidence from interviews with Saudi officials in the early 1980s and with the fact that state-owned Saudi oil company producers only produce forecasts for demand once a year. We discuss the oil supply further in Section 6.

[19] We also abstract from the possibility to store oil above ground. Most of the stored oil in the U.S. is held by the Strategic Petroleum Reserve and is rarely used in practice. The remaining inventories of oil in the U.S. are relatively small. As shown by Olovsson (2016), the possibility to store oil does not rule out large swings in the oil price or that oil-related shocks can have quantitatively important effects on output, consumption, labor supply and investments.

in advance.[20] Also,for simplicity, we abstract from savings and investment decisions in country e.

3.2 A model without oil

The model described above is the benchmark economy in the paper. To evaluate the quantitative importance of oil, we also present results for a model without oil. The production of intermediates, X_i, are then produced according to the more standard production function

$$X_i \equiv F\left(A_i^{no\_oil}, K_i, L_i\right) = A_i^{no\_oil} K_i^{\alpha} L_i^{1-\alpha}, \tag{6}$$

where $A_i^{no\_oil} \equiv \exp\left(Z_{A,i}^{no\_oil}\right)$ and $Z_{A,i}^{no\_oil}$ follows

$$\begin{bmatrix} \left(Z_h^{no\_oil}\right)' \\ \left(Z_f^{no\_oil}\right)' \end{bmatrix} = \Xi_{Z^{no\_oil}} \begin{bmatrix} Z_h^{no\_oil} \\ Z_f^{no\_oil} \end{bmatrix} + \begin{bmatrix} \left(\chi_h^{no\_oil}\right)' \\ \left(\chi_f^{no\_oil}\right)' \end{bmatrix}.$$

As above, χ_h' and χ_f' are normally distributed with mean zero.

3.3 Competitive equilibrium

A competitive equilibrium consists of state-dependent prices and quantities such that all agents maximize their respective objectives while taking all prices as given. The vector of aggregate state variables is given by

$$\Phi \equiv (A_h, A_f, B_h, B_f, K_h, K_f, O, S_h).$$

Equilibrium prices include prices of the intermediates, $p_{h,j}(\Phi)$, and, $p_{f,j}(\Phi)$, for $j \in \{h, f, e\}$ expressed in terms of domestic final goods; wages $w_i(\Phi)$ and rental rates of capital $r_i(\Phi)$ in country $i \in \{h, f\}$ in terms of the domestic intermediate; oil price $p_O(\Phi)$, in terms of intermediate X_h; and bond price $q(\Phi)$ in terms of intermediate X_h.[21]

[20] The assumption is broadly consistent with the setting in Olovsson (2016), but it is not important for the results whether the oil supply in period t reacts to the shock in period t or $t-1$.

[21] The denomination of the bond follows Heathcote and Perri (2002).

3.3.1 Intermediate and final-goods-producing firms

The representative intermediate-producing firm in country $i \in \{h, f\}$ solves the following profit-maximization problem

$$\max_{K_i, L_i, O_i} F\left(A_i, B_i, K_i, L_i, O_i\right) - r_i K_i - w_i L_i - \frac{p_{h,i}}{p_{i,i}} p_O O_i. \tag{7}$$

The profit-maximization problem faced by the final-goods-producing firms in country $j \in \{h, f, e\}$ is then given by

$$\max_{X_{h,j}, X_{f,j}} G_j(X_{h,j}, X_{f,j}) - p_{h,j} X_{h,j} - p_{f,j} X_{f,j}. \tag{8}$$

The first-order conditions to (7) and (8) are displayed in Appendix A.3.

3.3.2 Consumers

Households in country $i \in \{h, f\}$ maximize utility by solving the Bellman equation

$$V_i(k_i, s_i; \Phi) = \max_{c_i, l_i, k_i', s_i'} u(c_i, l_i) + \beta \mathbb{E}\left[V_i\left(k_i', s_i'; \Phi'\right) | \Phi\right],$$

subject to their respective budget constraint

$$\begin{aligned} c_i + k_i' + p_{h,i}(\Phi) q(\Phi) s_i' &= p_{i,i}(\Phi)\left[r_i(\Phi) k_i + w_i(\Phi) l_i\right] \\ &\quad + (1-\delta) k_i + p_{h,i}(\Phi) s_i. \end{aligned} \tag{9}$$

Again, the resulting first-order conditions to (9) are laid out in A.3.

In country e, the representative household just consumes the domestically produced final good while respecting the budget constraint[22]

$$C_e = p_{h,e} p_O O. \tag{10}$$

3.3.3 Market clearing

Denoting the size of the population in country $i \in \{h, f\}$ by $\bar{L}_i$, the aggregate equilibrium quantities of bond holdings, capital and labor supply are respectively given by

[22] Note that there is no need to consider per-capita consumption here.

$$
\begin{aligned}
S_i &= \bar{L}_i s_i, \\
K_i &= \bar{L}_i k_i \text{ and} \\
L_i &= \bar{L}_i l_i.
\end{aligned}
$$

Market-clearing in the oil market, the bond market, and the markets for intermediates respectively require the following conditions to hold:

$$O_h + O_f = O, \tag{11}$$

$$S_h = -S_f, \tag{12}$$

and

$$X_i = \sum_{j \in \{h,f,e\}} X_{i,j} \text{ for } i \in \{h, f\}. \tag{13}$$

Since trade in intermediates is frictionless by assumption, the law of one price must hold. This implies that the relative price of the intermediates must be the same in all countries:

$$\frac{p_{h,h}}{p_{f,h}} = \frac{p_{h,f}}{p_{f,f}} = \frac{p_{h,e}}{p_{f,e}}. \tag{14}$$

Finally, the resource constraints in country e and country $j \in \{h, f\}$ are respectively given by

$$Y_e = C_e, \tag{15}$$

and

$$Y_j + (1 - \delta)K_j = C_j + K_j'. \tag{16}$$

We now have all the required equilibrium conditions to solve for prices and decision rules. There are, in total, 22 quantities: O_i, l_i, X_i, Y_j, $X_{i,j}$, c_j, k_i' and s_i' for $i \in \{h, f\}$ and $j \in \{h, f, e\}$. There are also 12 prices: $p_{i,j}$, r_i, w_i, q and p_O for $i \in \{h, f\}$ and $j \in \{h, f, e\}$. In total, there are 35 conditions given by equations (1), (3), (9)-(16), (23)-(29), and 34 unknowns. One resource constraint is, however, redundant.

We will occasionally refer to the terms of trade, defined as the price of imports into country h relative to the price of exports from country h. Formally, the terms of trade, τ_h, is given by

$$\tau_h = \frac{p_{f,h}}{p_{h,h}}. \tag{17}$$

3.4 Calibration

We follow Heathcote and Perri (2002) and Bodenstein, Erceg and Guerrieri (2011) in identifying country h as the United States and country f as the ROW. The U.S. is a net importer of oil and, as mentioned in the Introduction, our interest in the U.S. comes from the fact that it, by far, is the world's largest consumer of oil.[23] Between 1980 and 2000, the U.S. share of world petroleum consumption was just below 30 percent. No other individual country was even close to that number during or after that period. The large influence that the U.S. has had on the oil price has also been empirically documented by Barsky and Kilian (2002) and Hamilton (2003) (see footnote 4). The reason for defining country f as the ROW is that bilateral trade between the U.S. and any other country is only a fraction of GDP.[24] Our definition of the ROW follows that in Heathcote and Perri (2002), except that we only include countries that are net importers of oil.

We normalize the size of the labor force in country h to one and set the labor force in country f, $\bar{L}_f$, so that the home country accounts for one-third of world GDP. This is basically the average over the period 1960-2010.[25] The size of the population in the oil-producing country, $\bar{L}_e$, is without loss of generality normalized to one. Average total factor productivity in the U.S. is also normalized to one, and average productivity in ROW, $Z_{y,f}$, is set to around 0.8.[26]

This part of the calibration is a bit of a compromise. It implies that country h consumes around 30 percent of the oil in the world, which is somewhat higher than in the data; it was 27 percent in 1980 and the average over the period 1980-2000 was 26 percent according to the U.S. Energy Information Administration.[27] Increasing $Z_{y,i}$ to reduce the share of oil that is consumed by the United States, however, increases GDP in the ROW above the target level. The results are robust to relatively large changes in $\bar{L}_f$ as discussed in Section 5.

The rest of the model is calibrated as follows.

[23] The fraction of imported oil relative to the total amount of oil used in the U.S. was 0.62 (computed based on EIA data on use and imports of petroleum products) in 2009.

[24] This is true also for the trade between the U.S. and the European Union, i.e., the case considered by Backus, Kehoe, and Kydland (1992).

[25] Source: the World Bank (http://data.worldbank.org/indicator/NY.GDP.MKTP.CD).

[26] Total factor productivity in the ROW relative to in the United States was 0.83 in 2013. This value is computed using data from the Penn World Table 9.0 and the ROW value constitutes a GDP-weighted average.

[27] Since then, its share has come down somewhat further as China has steadily increased its share of total petroleum. A future analysis should take the reduced influence of the U.S. and the increased influence of China into account.

3.4.1 Preference and production parameters

Results are presented for both an annual and a quarterly version of the model. The discount factor is set to 0.96 in the annual model, and to 0.99 in the quarterly. These values are standard in the macroeconomic literature. The utility weight on leisure is set to $\mu = 0.636$, which implies that the representative agent dedicates roughly 1/3 of her time to work. The coefficient of relative risk aversion, ϕ, is set to 2 as is standard in the literature on international business cycles.

There are three production parameters for intermediate goods: α, γ, ε. The parameter α is set to $\alpha = 0.32$ to generate a capital share of income of 0.30. The weight on energy in production, γ, is set to 0.05. The depreciation rate is set to 0.0862 in the annual model and to 0.0235 in the quarterly to match a capital/output ratio between two and three.

The elasticity of substitution between capital/labor and fossil energy, ε, has been analyzed in a large number of studies and all short-run estimates are found to be low. Early empirical investigations are Hudson and Jorgenson (1974) and Berndt and Wood (1975), both of which find energy to be complementary to capital. Griffin and Gregory (1976), instead, uses pooled international data to capture the long-run relationships between capital and energy. The paper finds that in the long run, capital and energy are substitutes.[28] Hassler, Krusell, and Olovsson (2012) considers a production function similar to (1) and allows the short-run elasticity to differ from the long-run elasticity. The short-run elasticity is governed by the parameter, ε, whereas the possibility to substitute in the long run is affected by endogenous investments into the *levels* of A and B. They then estimate the one-year elasticity of substitution between capital/labor and fossil energy and finds it to be close to zero and in fact not statistically significantly different from zero. Since the production function used by Hassler, Krusell and Olovsson is similar to (1), and all studies find capital and fossil energy to be short-run complements, ε is set to 0.09 to match a a standard deviation for the oil price of around 15 percent.[29] The value of 0.09 is, in fact, the same as in Backus and Crucini (2000).[30]

The implications of the elasticity of substitution between the traded goods, σ, is discussed in detail in Pakko (1997), Arvantis and Mikola (1996), and Heathcote and Perri (2002). Since our model has several similarities to that in Heathcote and Perri, we

[28] Koetse et al. (2008) carries out a meta-regression analysis on empirical estimates of capital-energy substitution and concludes that the demand for energy-saving capital is affected by energy-price increases, but that it generally takes some time before demand reacts.

[29] See Olovsson (2016).

[30] A low elasticity of substitution is also employed in Rotemberg and Woodford (1996).

take their estimate and set $\sigma = 0.90$ in the benchmark calibration, but we also report results for a large interval of this parameter.[31]

Parameters η_i $i \in \{h, f\}$ determine the degree of home bias in the composition of domestically produced final goods in the each country. We set η_h to 0.90 to match an export share around 0.12 for the United States.[32] Parameter, η_f, is then set to 0.97, which delivers an export share around 0.08 for the ROW.[33] Country e does not have bias towards h or f, so $\eta_e = 0.5$.

The supply of oil is determined by the parameter, φ. This value is set to match oil's share of income. Bodenstein, Erceg and Gurrieri (2011) sets the oil share to 4.2 percent in the U.S. and 8.2 percent in the ROW. Backus and Crucini (2000) matches the energy cost-to-value-added of 10 percent in the United States. We set φ to target an energy share about 5 percent in both countries.

3.4.2 Estimation of the shock-process parameters

Hassler, Krusell and Olovsson (2012) shows that the level of the technologies that save on capital/labor and oil, respectively, can be computed from the following two equations:

$$\log A_{i,t} = \log y_{i,t} - \log\left(k_{i,t}^{\alpha} l_{i,t}^{1-\alpha}\right) + \frac{\varepsilon}{\varepsilon-1}\log\left(\frac{w_{i,t} l_{i,t}}{y_{i,t}}\right) - \frac{\varepsilon}{\varepsilon-1}\log\left((1-\alpha)(1-\gamma)\right) \quad (18)$$

and

$$\log B_{i,t} = \log(y_{i,t}) - \log o_{i,t} + \frac{\varepsilon}{\varepsilon-1}\log\left(\frac{p_{o_{i,t}} o_{i,t}}{y_{i,t}}\right) - \frac{\varepsilon}{\varepsilon-1}\log\gamma, \quad (19)$$

where $i \in \{h, f\}$.[34] We compute the stationary properties for $Z_{A,h} = \log(A_h)$, $Z_{A,f} = \log(A_f)$, $Z_{B,h} = \log(B_h)$ and $Z_{B,f} = \log(B_f)$ from (18) and (19) by removing a linear trend from each series. Specifically, the random shocks $\chi_{m,h}$, $\chi_{m,f}$ (for $m = A, B$) are

[31] The benchmark value for the elasticity is also in line with the estimates in Stockman and Tesar (1995) and Corsetti, Dedola and Leduc (2008), but it is lower than typical micro-estimates of the elasticity.

[32] This implies a trade share that includes oil below 15 percent, which is consistent with the data.

[33] The empirical shares were computed using data on U.S. and World GDP and on U.S. import and export shares. U.S. and World GDP were taken from the World Bank. U.S. imports and exports as shares of GDP were taken from OECD Data. The import and export shares of the rest of the world are the export and import shares of the U.S. respectively multiplied by $\frac{GDP_{US}}{GDP_{ROW}} = \frac{GDP_{US}}{GDP_{World}-GDP_{US}}$. The export share for the U.S. was 0.12 in 2016, and the corresponding share for the ROW was 0.05. Hence, the latter share is slightly too high in the model.

[34] The energy price is assumed to be the same in all considered countries. This is only restrictive if taxes vary substantially from year to year. Similarly, using the price of refined instead of crude oil will only make a difference if the cost of refining the oil differs substantially from period to period.

computed as the residuals to the estimated system. Matrices Ξ_A and Ξ_B can then simply be estimated using OLS.[35] The stationary properties for $Z_{A,i}^{no\_oil} = \log\left(A_i^{no\_oil}\right)$ is estimated by removing a linear trend from an equation similar to (18) with the difference that the term $(\varepsilon/(\varepsilon-1))\log\left(\frac{w_{i,t}l_{i,t}}{y_{i,t}}\right)$ is excluded and γ is set to zero.

We follow the standard assumption in the literature and impose symmetry on the autoregressive components. This is done by setting up a symmetric matrix, $\tilde{\Xi}_m$, that has the same as eigenvalues as Ξ_m.

For the quarterly model, the estimated symmetric matrices are given by[36]

$$\tilde{\Xi}_A = \begin{bmatrix} 0.97 & 0.029 \\ 0.029 & 0.97 \end{bmatrix}, \tilde{\Xi}_B = \begin{bmatrix} 0.73 & 0.14 \\ 0.14 & 0.73 \end{bmatrix}, \text{ and } \tilde{\Xi}_{Z^{no\_oil}} = \begin{bmatrix} 0.97 & 0.028 \\ 0.028 & 0.97 \end{bmatrix}. \quad (20)$$

The standard deviations of χ_A and χ_B are, respectively, 0.005 and 0.02. The estimated correlation between $\chi'_{A,h}$ and $\chi'_{A,f}$ is 0.23 and between $\chi'_{B,h}$ and $\chi'_{B,f}$ 0.40. These correlations are imposed in the benchmark calibration, but results are also reported for shocks that are uncorrelated across the two countries since this is a common assumption in the NOEM literature.[37]

For the annual model, the estimated symmetric matrices are given by

$$\tilde{\Xi}_A = \begin{bmatrix} 0.87 & 0.070 \\ 0.070 & 0.87 \end{bmatrix}, \tilde{\Xi}_B = \begin{bmatrix} 0.65 & -0.19 \\ -0.19 & 0.65 \end{bmatrix}, \text{ and } \tilde{\Xi}_{Z^{no\_oil}} = \begin{bmatrix} 0.87 & 0.065 \\ 0.065 & 0.87 \end{bmatrix}. \quad (21)$$

The standard deviations of χ_A and χ_B are now, respectively, 0.01 and 0.02. The estimated correlation between $\chi_{A,h}$ and $\chi_{A,f}$ is 0.32 and that between $\chi_{B,h}$ and $\chi_{B,f}$ is 0.55. Note that matrices $\tilde{\Xi}_A$ and $\tilde{\Xi}_{Z^{no\_oil}}$ are close to identical in both the annual and the quarterly models. Note also that there are some differences between the quarterly and the annual processes. In particular, spill-overs of the energy-saving shocks are positive on the quarterly horizon, but strongly negative on the annual horizon.

We now turn to the process for the exogenous shocks to the oil supply. We compute the properties of the process for exogenous shocks to the oil supply with data from Kilian (2008). Specifically, Kilian computes a monthly index for exogenous oil production shocks

[35] Sometimes SUR estimation is used instead, but since the right-hand side variables for productivity factor m are the same for both countries, OLS and SUR would give the same result.

[36] The asymmetric matrices are presented in Appendix A.4.

[37] Justiniano and Preston (2010) estimates the model-implied cross-correlation functions between the Canada and the U.S. to be essentially zero. Bergin (2003) finds almost all shocks to have correlations below 0.10. Miyamoto and Nguyen (2017) estimates the correlation between permanent Canadian and U.S. technology shocks and finds it to be negative and insignificant at -0.07.

by generating counterfactual production levels for several countries. The data covers the period from the first quarter in 1971 to the third quarter in 2004 and it includes both positive and negative shocks. Kilian's measure has the benefit of being an estimate of true exogenous variation in the oil supply, which makes it ideal when quantifying the effects of oil-supply shocks on macroeconomic variables such as GDP and consumption. The standard deviation for the exogenous shocks is 0.017 over the annual horizon and 0.012 over the quarterly. These exogenous shocks are serially uncorrelated, as is also pointed out by Kilian. We thus impose the oil shocks to have zero autocorrelation in the benchmark calibration, but also discuss the implications of higher levels of autocorrelation.[38]

The model is solved by linearizing it around its steady state and then simulating it using Dynare.

4 Results

The results from the model simulations of the benchmark economy alongside the model economy without oil are now presented in Tables 3-4.

In both tables, Panels A and B show that the models both with and without oil perform relatively similar when it comes to volatilities and domestic correlations, even though there also are some differences. In particular, the economy without oil produces a volatility for output that is too low relative to the data, which is less of a problem in the model with oil.

The important differences are instead found in panel C. The model with oil can, in fact, resolve both the quantity anomaly and the international comovement puzzle: consumption is less correlated across countries than output, and both inputs and investment display strong positive cross-country correlations. This is true irrespective of whether productivity shocks are correlated between the countries. In fact, even though the cross-country correlations in the model are spanned by the data (with the exception of quarterly investments), these correlations are, on average, too high relative to the data. The model, thus, suggests that it is more of a puzzle why these correlations are not higher than they are.[39] A potentially mitigating factor could be to allow the oil supply to be somewhat elastic.

[38] Hamilton (2003) also computes measures of exogenous short-falls in oil production, but this measure is less useful for our purposes, since it only covers five specific events.

[39] Perri and Quadrini (2011) argue that the empirical cross-country correlations are substantially higher after the most recent financial crisis.

Table 3: Data and model results for quarterly time periods

	std. dev in %	std.dev/std. dev of y in %			
(A) Volatilities					
	y	c	l	o	i
Data U.S.	1.29	0.79	1.22	1.74	2.91
Model with oil	1.65	0.33	0.35	1.08	2.58
Model without oil	0.77	0.52	0.34	-	3.01
(B) Correlation with output					
		c	l	o	i
Data U.S.		0.87	0.90	0.51	0.93
Model with oil		0.81	0.98	0.53	0.98
Model without oil		0.92	0.97	-	0.97
(C) International correlations	y_h, y_f	c_h, c_f	l_h, l_f	o_h, o_f	i_h, i_f
Data (Average)	0.40	0.23	0.60	0.25	0.27
Model with oil, $corr\left(\chi_{m,h}, \chi_{m,f}\right) > 0$	0.66	0.45	0.77	0.18	0.71
Model with oil, $corr\left(\chi_{m,h}, \chi_{m,f}\right) = 0$	0.54	0.35	0.67	-0.15	0.60
Model without oil, $corr\left(\chi_{m,h}, \chi_{m,f}\right) > 0$	-0.01	0.63	-0.52	-	-0.44
Model without oil, $corr\left(\chi_{m,h}, \chi_{m,f}\right) = 0$	-0.22	0.48	-0.66	-	-0.61

All variables are in logarithms and have been detrended with the HP filter. The time frequency is quarterly. y is output, c is consumption, l is hours worked, o is oily, and, i is investments. $corr\left(\chi_{m,h}, \chi_{m,f}\right) = 0$ implies uncorrelated shocks across countries, whereas $corr\left(\chi_{m,h}, \chi_{m,f}\right) > 0$ allows for positively correlated shocks (for $m = A, B$).

In the model without oil, in contrast, both the quantity anomaly and the international comovement puzzle reappear. The cross-country consumption correlation is substantially higher than that for output, and cross-country correlations of factor use and output are substantially lower than those observed in the data. In fact, with only one exception, the cross-country correlations for output, labor supply, and investment are all negative in the model without oil.

Table 9 in Appendix A.5 decomposes the relative importance of the different shocks. It shows that only two shocks (either A and B or A and O) are enough for resolving both the quantity anomaly and the international comovement puzzle. The table also shows that the more standard approach with Hicks-neutral productivity shocks fails to generate a cross-country correlation for consumption that is lower than that for output.

We conclude that factor-specific technology shocks and exogenous shocks to the oil supply are both quantitatively important in accounting for the observed features of the international business cycles.

Table 4: Data and model results for annual time periods

	std. dev in %	std.dev/std. dev of y in %			
(A) Volatilities					
	y	c	l	o	i
Data U.S.	1.36	0.64	1.12	1.58	3.31
Model with oil	1.27	0.25	0.35	1.37	4.08
Model without oil	0.77	0.34	0.39	-	2.94
(B) Correlation with output					
		c	l	o	i
Data U.S.		0.86	0.89	0.73	0.91
Model with oil		0.85	0.99	0.78	0.99
Model without oil		0.95	0.99	-	1.00
(C) International correlations	y_h, y_f	c_h, c_f	l_h, l_f	o_h, o_f	i_h, i_f
Data (Average)	0.48	0.20	0.50	0.34	0.36
Model with oil, $corr\left(\chi_{m,h}, \chi_{m,f}\right) > 0$	0.48	0.39	0.56	0.64	0.71
Model with oil, $corr\left(\chi_{m,h}, \chi_{m,f}\right) = 0$	0.16	0.05	0.44	0.58	0.23
Model without oil, $corr\left(\chi_{m,h}, \chi_{m,f}\right) > 0$	0.13	0.51	-0.04	-	-0.11
Model without oil, $corr\left(\chi_{m,h}, \chi_{m,f}\right) = 0$	-0.12	0.29	-0.28	-	-0.34

All variables are in logarithms and have been detrended with the HP filter. The time frequency is annual. y is output, c is consumption, l is hours worked, o is oily, and, i is investments. $corr\left(\chi_{m,h}, \chi_{m,f}\right) = 0$ implies uncorrelated shocks across countries, whereas $corr\left(\chi_{m,h}, \chi_{m,f}\right) > 0$ allows for positively correlated shocks (for $m = A, B$).

4.1 Impulse responses to the different shocks

This section provides intuition for the main mechanism by looking at impulse responses for the different shocks. Recall that there are three different types of shocks in the model: shocks to the supply of oil, shocks to capital/labor productivity, and shocks to the energy-saving productivity.

The top graphs in Figure 1 display the effects of a one-time, unexpected one-standard-deviation increase in the supply of oil. As expected, this has positive effects in both countries. Output, consumption, and all inputs increase when the supply jumps. In particular, investments, output and oil use all react quite strongly to the oil supply shock. Even though the lines for consumption are somewhat hard to see in the figure, the responses of consumption are close to zero and well below the lines for output. We discuss this property in more detail in Section 4.2.

The middle graphs plot responses to a one-time, unexpected one-standard-deviation increase of the capital/labor efficiency in country h. This shock is conceptually similar

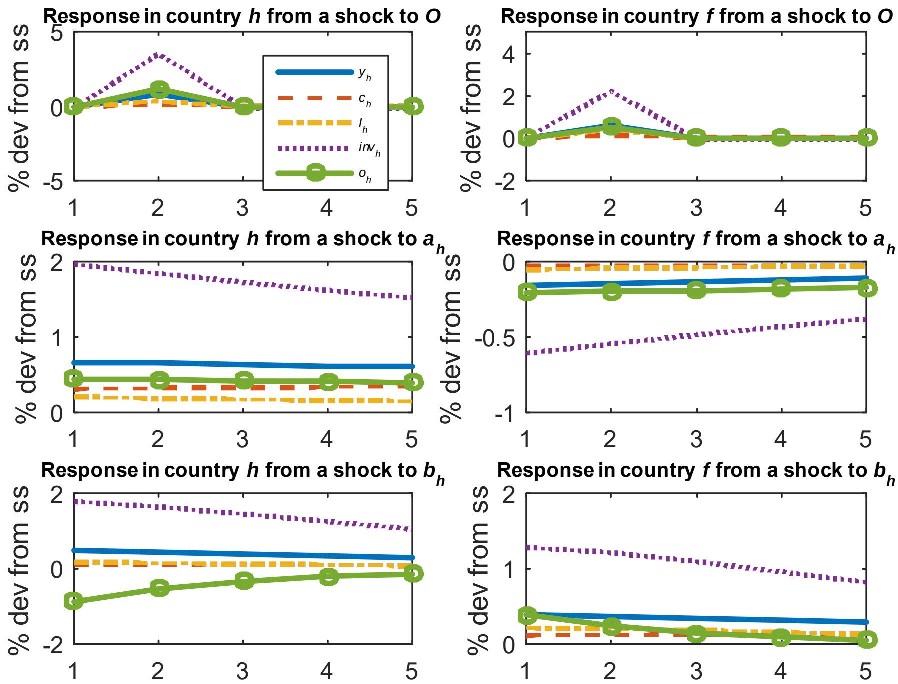

Figure 1: International transmission of shocks. The top graphs display responses of inputs, output and consumption in each country to a one-time, unexpected one-standard-deviation increase in the supply of oil. The middle graphs plot the same variables for a one-time, unexpected one-standard-deviation increase in the capital/labor productivity in country h. The bottom graphs, finally, show responses to a one-time, unexpected one-standard-deviation increase in the energy efficiency in country h.

to the standard total-factor-productivity shock and, consequently, it creates a boom in the home country: labor supply, oil use, output and consumption all increase on impact. Also, as in the standard model, this shock has negative effects on labor supply, oil use, investments and output in country f.

The bottom graphs, finally, display responses to a one-time, unexpected one-standard-deviation increase in the energy efficiency in country h. This shock also generates a boom in country h: labor supply, oil use, output, consumption, and investment all increase on impact. An important difference relative to the capital/labor productivity shock, however, is that shocks to the energy-efficiency imply positive comovements of labor supply, investments, and output. The reason is that the shock lowers the marginal product of oil in country h. The world market price for oil then falls, which makes it possible for country f to buy relatively more oil. This effectively increases the marginal product of capital/labor in that country. Labor supply and oil use both increase on impact, leading to higher output and investments in country f as well. Shocks to B, thus, generate negative comovement of oil use. Note also that the responses in consumption are smaller in both countries than the responses in output after a shock to the energy efficiency (the lines for consumption are somewhat hard to see, but both lines for consumption are close to zero).

The impulse responses show that an increase in A_h leads to an increase in the labor supply in country h, whereas an increase in B_h leads to a decrease in the oil use in country h. In Appendix A.6, we provide a partial-equilibrium argument for why this holds for realistic parameter values.

The conclusion is that oil-related shocks are fundamentally different from standard shocks to the capital/labor technology. First, shocks to B and O both induce positive spill-overs between the countries and, therefore, lead to positively correlated business cycles, whereas the standard shock implies negatively correlated cycles. Second, shocks to O and B are less persistent and therefore generate smaller responses in consumption than output, which helps solve the consumption correlation puzzle.

Figure 4 in Appendix A.7 shows impulse responses for the oil price. It shows that positive shocks to the capital/labor efficiency generate long-lasting increases in the oil price, whereas shocks to the supply just generate temporary dips in the price. Shocks to energy efficiency generate a decrease in the oil price that lasts longer than for supply shocks but shorter than for shocks to capital/labor efficiency.

4.2 The effects of oil as an input

Section 4.1 explained why oil in production can make inputs and output positively correlated across countries (because two of the three shocks generate positive comovements). It also showed that shocks to O and B generate smaller responses in consumption than output. This section explains in more detail how the model with oil changes the predictions relative to those from a model without oil.

Consider, first, shocks to A in the model without oil. A positive productivity shock in country h generates a boom in that country and more intermediates are produced in h. With home bias in final-goods production, efficiency requires that more inputs of both types should be used in country h. To the extent that financial markets are sufficiently complete, less intermediates of both types are then used in country f, which results in a drop in output. At the same time, the higher price of intermediates of type f (due to its lower relative supply) makes it possible for households in f to increase their consumption and reduce their investments.[40] Hence, in the model without oil, a country-specific productivity shock leads to negatively correlated output levels and positively correlated consumption levels. This is illustrated by the dashed lines in Figure 2.

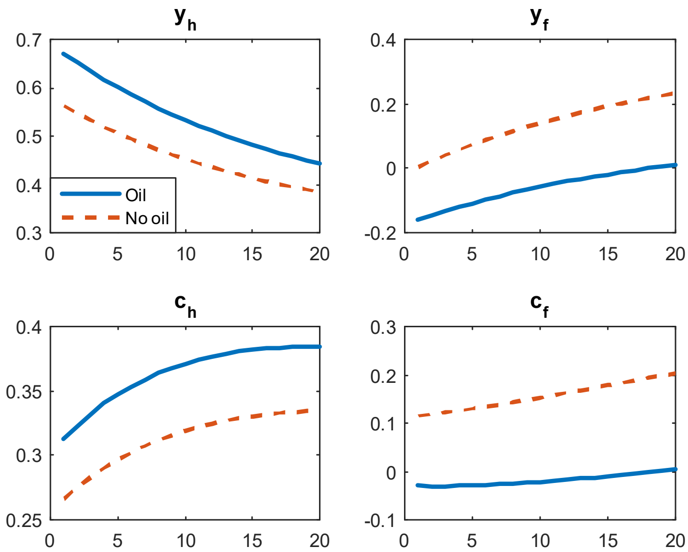

Figure 2: Impulse responses of output and consumption after a shock to the capital/labor productivity in country h.

In the model with oil, country f still experiences a positive wealth effect following a shock to the capital/labor productivity which, again, leads to an improvement in the terms of trade. Now, however, there is an important offsetting effect that reduces the high cross-country correlation for consumption. Specifically, the shock in h increases the marginal product of oil in that country. The consequence is a higher demand for oil by country h as well as a higher oil price. The higher price reduces the demand for oil in f and, with capital/labor and oil being gross complements, lower inputs of oil effectively imply a lower capital/labor productivity in country f. Hence, the positive productivity shock in h now also drives down the capital/labor productivity in country f.

Households react to this specific negative effect as they would to a shock that decreases A_f, i.e., they work and consume less. The result is an even larger drop in GDP in f. As can be seen in Figure 2, both output and consumption become less correlated across the two countries when oil is used.

[40]The improvement in the terms of trade is highly persistent. This is because production and investment in country h increase relatively more in response to the productivity shock than the same variables in country f.

Consider now the effects of shocks to O. These shocks are global and affect both countries symmetrically. An increase in O has two effects: it increases labor productivity (since oil and capital/labor are gross complements) and it constitutes a wealth effect. The effect on productivity leads to higher levels of labor supply, production, and consumption in both countries.

To what extent the oil-related shocks increase the correlation for output relatively more than for consumption depends crucially on the extent to which they are persistent. If shocks to O and B, are relatively transitory - as in the benchmark calibration - then the wealth effect associated with each of these shocks is small. According to the permanent-income hypothesis, a large fraction of the extra income generated from the increase in output will be saved for the future. Consequently, the response in consumption will be smaller than the effect on output.

If, instead, shocks to O and B would be highly persistent, the response in consumption would potentially be higher than in output because the wealth effect could dominate the effect on productivity. Agents would then not have to save as much each period because the oil supply would remain high for a long time.

Denoting the steady-state value of variable x by $\widehat{x}$, the importance of persistence is illustrated in (22), which displays parts of the decision rules for deviations from the steady state for consumption, output, and investment for different values of the autocorrelation (ρ_o) of the shocks to the oil supply (χ_o).

$$\begin{bmatrix} c_{m,t}/\widehat{c}_m \\ y_{m,t}/\widehat{y}_m \\ i_{m,t}/\widehat{i}_m \end{bmatrix} = \begin{bmatrix} 1+...+0.08\chi_o \\ 1+...+0.70\chi_o \\ 1+...+2.83\chi_o \end{bmatrix}, \quad \text{for } \rho_o = 0$$
$$\text{and} \tag{22}$$
$$\begin{bmatrix} c_{m,t}/\widehat{c}_m \\ y_{m,t}/\widehat{y}_m \\ i_{m,t}/\widehat{i}_m \end{bmatrix} = \begin{bmatrix} 1+...+0.14\chi_o \\ 1+...+0.48\chi_o \\ 1+...+1.67\chi_o \end{bmatrix}, \quad \text{for } \rho_o = 0.95.$$

As can be seen, the response to oil shocks almost doubles for consumption when the autocorrelation goes from 0 to 0.95. In contrast, the responses of output and investment are then both reduced.

5 Sensitivity analysis

This section now evaluates how robust the results are to some of the other assumptions in the benchmark calibration.

5.1 Varying the elasticity of substitution for intermediate goods

Figure 3 shows that varying σ does not affect the findings from the previous section. In fact, over the relatively wide interval for σ, output and inputs are positively correlated across countries, and consumption is not substantially more correlated than output in the model with oil. In contrast, without oil the two famous puzzles reappear: output and inputs are negatively (or marginally positively) correlated across countries and consumption is substantially more correlated than output.

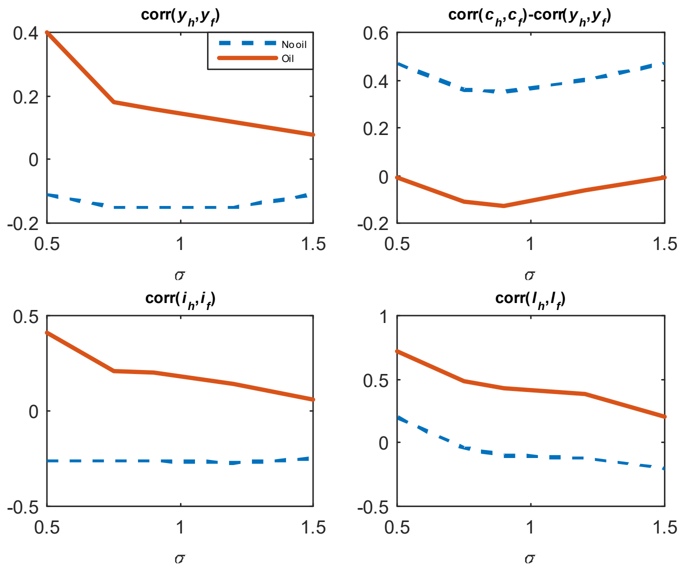

Figure 3: Varying σ, the elasticity of substitution for intermediate goods in the annual model, and with shocks to the innovations of A and B that are uncorrelated between the two regions. The results are similar in the quarterly model.

Hence, the results in the paper are robust to varying the elasticity of substitution for intermediate goods, at least over the range of values for which this elasticity has empirical support.

5.2 Productivity shocks and relative country size

Table 5 presents results for the specification where productivity shocks only are realized in country h. This allows us to evaluate to what extent shocks in the relatively smaller country can spill over to the larger country/region.

Table 5: International correlations in the model

Productivity shocks only in country h					
	y_h, y_f	c_h, c_f	l_h, l_f	o_h, o_f	i_h, i_f
Model with oil	0.54	0.16	0.73	0.37	0.65
Model without oil	0.02	0.99	-0.98	-	-0.92

All variables are in logarithms and have been detrended with the HP filter. The time frequency is quarterly. y is output, c is consumption, l is hours worked, o is energy, and, i is investments.

As in the previous sections, the model with oil resolves both the quantity anomaly and the international comovement puzzle, whereas these puzzles, again, rematerialize in the model without oil.

We have also verified that the results do not depend critically on the values for population size ($\bar{L}_f$). Also, with symmetrical countries, the model without oil produces the two puzzles whereas the model with oil resolves them.

5.3 The elasticity of substitution between capital/labor and oil and the autocorrelation coefficient for oil shocks

Table 6 reveals how the results depend on the elasticity of substitution between capital/labor and oil (ε). This exercise shows that the success of the model to solve the consumption-comovement puzzle relies on a relatively low value for ε. For values larger than or equal to 0.15, the consumption correlation puzzle re-emerges in the model. Output, investments and both inputs, however, all display positive cross-country correlations for larger values of ε as well. The ability to solve the international comovement puzzle is thus less sensitive to this parameter.

6 Discussion about the assumptions

As with all economic models, the model here is a stylized version of the real world, and it incorporates several simplifying assumptions. This discussion focuses on some of these assumptions and the potential implications of relaxing them.

Table 6: International correlations in the model

	y_h, y_f	c_h, c_f	l_h, l_f	o_h, o_f	i_h, i_f
$\varepsilon = 0.12$	0.58	0.52	0.68	0.21	0.61
$\varepsilon = 0.15$	0.50	0.56	0.59	0.24	0.51
$\varepsilon = 0.20$	0.39	0.59	0.45	0.29	0.35
$\varepsilon = 0.30$	0.23	0.61	0.20	0.39	0.10
$\varepsilon = 0.40$	0.15	0.62	0.01	0.50	-0.06

All variables are in logarithms and have been detrended with the HP filter. The time frequency is quarterly. y is output, c is consumption, l is hours worked, o is energy, and, i is investments.

6.1 An elastic oil supply

With an elastic oil supply and the realistic assumption that it is costly to increase the oil supply, some of the effects found above could potentially be mitigated. The negative effect of a positive productivity shock in h on the capital/labor productivity in country f, however, would still be present. The reason is that these shocks would still lead to an increase in the oil price and a reduction of oil use in country f. Similarly, unless it is costless to increase the oil supply, a negative shock to O would still lead to a lower supplied quantity and a higher oil price. The identified mechanisms would thus still hold, but some of the cross-country correlations in Tables 3 and 4 would potentially be reduced. Whether this would move the model results closer or further away from the data is an open question (given that the cross-country correlations are too high in the model).

6.2 Oil and other energy inputs

As stated in Section 3, oil is the only energy input in the model. This is a standard assumption in many macroeconomic models with energy as an input into production.[41] The assumption would be potentially restrictive, however, if substantial substitution between oil and other energy sources takes place immediately after any shock. Olovsson (2016) shows that this is not the case for the United States. Specifically, the non-fossil energy sources have only been of minor importance in the U.S. over the period 1949-2014, and there is basically no short-run substitution between these energy inputs and oil use during this period.[42] In addition, the fossil fuels are highly positively correlated; the correlation between oil use and total fossil-fuel use is about 0.9 in the United States. Changes in oil use, thus, correspond to changes in total fossil-fuel use on an almost one-to-one basis,

[41] See, for example, Kim and Loungani (1992), Rotemberg and Woodford (1996), Backus and Crucini (2000), and Bodenstein, Erceg and Guerrieri (2011).

[42] The correlation between changes in these inputs is -0.14.

implying that there is limited substitution between the different fossil fuels.

Even though there is some heterogeneity, the same seems to be true for the countries considered in Section 2. We looked at a subset of the countries in the ROW and found that the non-fossil energy sources have yet only been of minor importance, and the mean (median) correlation between changes in non-fossil fuel and fossil-fuel use is -0.09 (-0.12).[43] Moreover, oil use is generally highly positively correlated with the usage of the other fossil fuels.[44] This is shown in Appendix A.8, that plots oil use alongside total fossil-fuel use for the considered countries and verifies that these energy-use series are strongly correlated (the mean correlation is about 0.85). The figures also show that, for these countries, changes in oil use closely correspond with changes in total fossil-fuel use and there is limited substitution between fossil and non-fossil fuels. We therefore conclude that it is not restrictive to focus on oil as the only energy input.

7 Conclusions

To what extent is the international business cycle affected by the fact that an essential input, i.e., oil is traded on a world market? We answer that question by setting up a model with two countries that use capital, labor and oil as inputs to produce tradable intermediate goods needed to produce a final good and one country that sells oil. The model features factor-specific technology shocks as well as exogenous shocks to the oil supply. The inclusion of oil-supply shocks allows us to identify a specific source for a global contribution to the international business cycle and quantify its importance. We make use of Kilian's measure of exogenous variations of the oil supply.

The two "countries" in the model are identified as the U.S. and the Rest of the World. The focus on the U.S. is obvious; it is, and has for many decades been, by far, the world's largest consumer of oil. The large influence that the U.S. economy has had on the oil price has also been empirically documented.

The analysis shows that oil is quantitatively important for the international business cycle. Specifically, the model resolves both the consumption correlation puzzle and the international comovement puzzle. It predicts a cross-country correlation of consumption that is lower than that of output, as well as strongly positive cross-country correlations of employment and investment. These cross-country correlations are, in fact, somewhat

[43] Here, we only have annual data.

[44] The non-fossil sources are generally trending upwards so there is potentially a transition to more carbon-free fuels. This trend, however, is less important for short-run dynamics.

too high relative to the data.

The results are driven by a combination of the opposing effects of the different shocks. Shocks to the capital/labor productivity have similar effects as standard total-factor-productivity shocks in models without oil, i.e., they produce negative cross-country correlations of inputs and output, and positively correlated of consumption. Shocks to the oil supply are global and have two effects: they affect the capital/labor productivity and they generate wealth effects. The productivity effect induces positive comovements of labor supply, production, and consumption. To what extent these shocks increase the correlation for output relatively more than for consumption depends crucially on to what extent the shocks are persistent. If the oil supply shocks are transitory - as they are estimated to be - then the wealth effect is small, and the response in consumption is smaller than that in output. Shocks to the energy efficiency, finally, have qualitatively similar effects as shocks to the oil supply, i.e., they are relatively transitory and they induce positive comovements of output, labor supply, investments and consumption. Introducing nominal frictions into the model seems like an interesting next step but we leave this for future research.

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A Appendix

A.1 Quarterly data

For computation of correlations, the quarterly data was taken from OECD's Quarterly National Accounts (QNA), FRED and EIA. Real GDP, investment and consumption were all taken from QNA. More precisely, the series "Gross domestic product - expenditure approach", "Private final consumption expenditure" and "Gross fixed capital formation" were used (and expressed in measure VPVOBARSA). For employment data, we used data measured in hours for as many countries as possible. For all ROW countries except Belgium and Japan, these were available from QNA (series "Employment, total" in terms of measure "HRSSA: Hours worked, seasonally adjusted"). For Belgium we used the same series but measured in terms of people. For Japan we used data on employment in terms of people from FRED (series "Employed Population: Aged 15-64: All Persons for Japan, Persons, Quarterly, Seasonally Adjusted"). For the US we used employment data in terms of hours from FRED (series "Hours of Wage and Salary Workers on Nonfarm Payrolls: Total, Billions of Hours, Quarterly, Seasonally Adjusted Annual Rate").

The data on oil use was taken from EIA, series "Consumption Refined Petroleum Products (1000 bbl/d)". The data for GDP, consumption and investment covers Q1 1980 - Q4 2016. The employment data covers Q1 1995 - Q4 2016 except for Ireland where the data starts in Q1 1998. The oil-use data covers the period Q1 1984 - Q1 2016 for all countries except Germany where the data starts in Q1 1991.

For the estimation of the productivity processes, we restricted the set of ROW countries to those that we had employment data in terms of hours for (which excluded Belgium and Japan). In addition to the data used for computing correlations, we used the following data. For all series except the income shares of labor and oil, ROW values were obtained as a sum of the values for the different ROW countries. The labor share of income for the ROW countries was obtained by combining nominal (measure "CQRSA") labor income ("Compensation of employees") and nominal GDP ("Gross domestic product - expenditure approach", same measure) to compute the labor share of income in each country. The aggregate ROW labor share was then computed as an average between the countries weighted by real GDP (same as above). The US labor share was taken from the Bureau of Labor Statistics.[45] Oil expenditure was computed using oil consumption (same as above) and the price of oil ("Global price of WTI Crude, U.S. Dollars per Barrell, Quarterly") deflated using a GDP deflator (both from FRED). These expenditures were aggregated across ROW countries to get real expenditure on oil and this expenditure was then divided by aggregated ROW real GDP. Due to a lack of data, we ignored capital in the estimation process with the motivation that the capital stock does not vary much on a quarterly basis. The same assumption is found in Cooley and Prescott (1995) and in Heathcote and Perri (2002).

The estimation is based on data for the years 1998-2016.

[45] https://www.bls.gov/opub/mlr/2017/article/estimating-the-us-labor-share.htm

A.2 Annual data

For all annual data series, we used data covering 1980-2014. For computing the correlations we used data from Penn World Table 9.0 (PWT), OECD's Quarterly National Accounts (QNA) and EIA. Data on GDP and consumption were taken from PWT (series "rgdpna" and "rconna"). To get employment in terms of hours, we used the product of the series "emp" and "avh" (both from PWT). Data on investment was taken from QNA (series "Gross Fixed Capital Formation"). Data on oil use was taken from EIA (series "Total Petroleum Consumption").[46]

Table 7: Cyclical properties in sixteen developed countries (based on annual data)

	Volatility					Correlation with output			
	std in %	Relative std							
	y	c	l	o	i	c	l	o	i
Austria	0.61	1.04	1.39	3.54	3.49	0.53	0.76	-0.02	0.64
Belgium	0.87	0.57	1.15	3.70	3.85	0.45	0.75	0.01	0.79
Denmark	0.95	1.39	1.65	2.34	5.55	0.81	0.86	0.17	0.89
Finland	0.68	0.68	1.19	2.10	3.53	0.62	0.66	0.26	0.93
France	0.96	0.57	0.86	2.08	2.79	0.41	0.55	0.00	0.90
Germany	1.30	1.31	1.09	1.60	4.61	0.80	0.40	0.58	0.75
Greece	1.08	1.49	1.81	4.17	5.67	0.73	0.81	0.30	0.79
Ireland	1.01	0.82	0.78	1.51	2.47	0.59	0.57	0.48	0.84
Italy	1.38	0.44	0.60	1.54	1.97	0.64	0.79	0.55	0.79
Japan	1.33	0.56	0.63	1.89	2.39	0.71	0.78	0.50	0.87
Netherlands	1.26	1.17	1.29	3.39	4.17	0.80	0.59	0.37	0.85
Portugal	0.85	0.90	1.34	3.39	5.43	0.51	0.81	0.11	0.87
Spain	0.97	0.98	1.34	2.64	3.98	0.89	0.79	0.14	0.90
Sweden	0.59	1.16	2.16	3.93	6.12	0.78	0.90	0.69	0.78
United Kingdom	0.54	1.90	2.27	5.63	7.90	0.78	0.62	0.58	0.50
United States	1.20	0.60	1.12	1.32	2.93	0.87	0.89	0.76	0.95
Average	0.97	0.97	1.29	2.80	4.18	0.68	0.72	0.34	0.82

The time frequency is annual. y is output, c is consumption, l is employment, o is oil use, and i is investment. All variables are in logarithms and have been detrended with the HP filter. Source: International Energy Agency, OECD QNA, PWT 9.0.

The results with annual data presented in Table 7-8 are similar to those with quarterly data. Output is more volatile than consumption, but less volatile than labor and fossil-energy use. Investments are about four times as volatile as output. Similarly, with a few exceptions, all cross-country correlations are positive.

[46]The EIA data is available at https://www.eia.gov/beta/international/rankings/#?prodact=5-2&cy=2015.

Table 8: International comovements (based on annual data)

	Contemporaneous cross correlations with same U.S. variable				
	y	c	l	o	i
Austria	0.32	0.00	0.43	0.15	0.47
Belgium	0.55	-0.09	0.56	0.21	0.50
Denmark	0.56	0.18	0.57	0.62	0.27
Finland	0.39	0.03	0.50	0.33	0.33
France	0.40	0.14	0.73	0.05	0.47
Germany	0.19	-0.12	0.12	0.27	-0.04
Greece	0.47	0.58	0.66	0.27	0.42
Ireland	0.56	0.19	0.12	0.37	0.20
Italy	0.40	-0.07	0.50	0.34	0.44
Japan	0.61	0.31	0.41	0.53	0.53
Netherlands	-0.03	-0.12	0.26	-0.03	-0.35
Portugal	0.67	0.23	0.61	0.48	0.50
Spain	0.62	0.65	0.78	0.42	0.58
Sweden	0.86	0.66	0.78	0.70	0.58
United Kingdom	0.62	0.38	0.51	0.42	0.47
Average	0.48	0.20	0.50	0.34	0.36

The time frequency is annual. y is output, c is consumption, l is employment, o is oil use, and i is investment. All variables are in logarithms and have been detrended with the HP filter. Source: International Energy Agency, OECD QNA and PWT 9.0.

For the estimation of the technology series, we complemented the data described above as follows. Data on oil prices were taken from the FRED database. We then constructed the series for the ROW and US oil shares by computing total expenditures and dividing it by total GDP. As for the quarterly data, all ROW series except labor and oil shares of income were constructed by adding across the ROW countries. We used data on real capital stocks and the labor share of income from the Penn World Table 9.0 (series "rkna" and "labsh"). The ROW income share of labor was computed as a real-GDP-weighted sum of the labor shares in the different countries. The annual oil price was taken from BP. The income share of oil was then constructed by computing aggregate real expenditures on oil (computed as the product of the real price of oil and oil consumption) and dividing it by aggregate real GDP.

A.3 First order conditions

The first-order conditions to (7) and (8) are respectively given by

$$\begin{aligned} K_i &: r_i = F_K\left(A_i, B_i, K_i, L_i, O_i\right); && (23)\\ L_i &: w_i = F_L\left(A_i, B_i, K_i, L_i, O_i\right); && (24)\\ O_i &: p_O = \frac{p_{i,i}}{p_{h,i}} F_O\left(A_i, B_i, K_i, L_i, O_i\right); && (25) \end{aligned}$$

and

$$G_{j,X_{i,j}}\left(X_{h,j}, X_{f,j}\right) = \frac{\partial Y_j}{\partial X_{i,j}} = p_{i,j}. \tag{26}$$

The first-order conditions to (9) can be written as

$$\begin{aligned} -u_l(c_i, l_i) &= p_{i,i}(\Phi) w_i(\Phi) u_c(c_i, l_i) && (27)\\ u_c(c_i, l_i) &= \beta \mathbb{E}\left[u_c(c_i', l_i')\left(p_{i,i}(\Phi') r_i(\Phi') + 1 - \delta\right)|\Phi\right] && (28)\\ u_c(c_i, l_i) &= \beta \frac{\mathbb{E}\left[p_{h,i}(\Phi') u_c(c_i', l_i')|\Phi\right]}{p_{h,i}(\Phi) q(\Phi)}. && (29) \end{aligned}$$

A.4 Estimation results

For the quarterly model, the estimated asymmetric matrices are given by

$$\tilde{\Xi}_A = \begin{bmatrix} 0.9321 & -0.0201 \\ 0.0207 & 1.0031 \end{bmatrix}, \tilde{\Xi}_B = \begin{bmatrix} 0.8462 & 0.3206 \\ 0.0120 & 0.6001 \end{bmatrix}, \text{ and } \tilde{\Xi}_Z = \begin{bmatrix} 0.9293 & -0.0255 \\ 0.0256 & 1.0057 \end{bmatrix},$$

with

$$\begin{aligned} \sigma_{\chi'_{A,h}} = 0.0054,\ \sigma_{\chi'_{A,f}} = 0.0044,\\ \sigma_{\chi'_{B,h}} = 0.0196,\ \sigma_{\chi'_{B,f}} = 0.0298,\\ \sigma_{\chi'_{Z,h}} = 0.0047,\ \sigma_{\chi'_{Z,f}} = 0.0041. \end{aligned}$$

The correlations between the shocks are respectively given by

$$corr\left(\chi'_{A,h}, \chi'_{A,f}\right) = 0.23,\ corr\left(\chi'_{B,h}, \chi'_{B,f}\right) = 0.41, \text{ and } corr\left(\chi'_{Z,h}, \chi'_{Z,f}\right) = 0.31.$$

For the annual model, the estimated asymmetric matrices are given by

$$\tilde{\Xi}_A = \begin{bmatrix} 0.8668 & 0.0673 \\ 0.0721 & 0.8685 \end{bmatrix}, \tilde{\Xi}_B = \begin{bmatrix} 0.7386 & -0.1630 \\ -0.1877 & 0.5698 \end{bmatrix}, \text{ and } \tilde{\Xi}_Z = \begin{bmatrix} 0.8772 & 0.0555 \\ 0.0749 & 0.8719 \end{bmatrix},$$

with

$$\sigma_{\chi'_{A,h}} = 0.00749,\ \sigma_{\chi'_{A,f}} = 0.0105,$$
$$\sigma_{\chi'_{B,h}} = 0.0218,\ \sigma_{\chi'_{B,f}} = 0.0184,$$
$$\sigma_{\chi'_{Z,h}} = 0.00742, \text{ and } \sigma_{\chi'_{Z,f}} = 0.0101.$$

The correlations between the shocks are respectively given by

$$corr\left(\chi'_{A,h}, \chi'_{A,f}\right) = 0.32,\ corr\left(\chi'_{B,h}, \chi'_{B,f}\right) = 0.56, \text{ and } corr\left(\chi'_{Z,h}, \chi'_{Z,f}\right) = 0.34.$$

A.5 Decomposing the effects of the different shocks

To evaluate the potential importance of the factor-specific shocks, results are also presented here for Hicks-neutral technology shocks, i.e., shocks that affect all inputs in the same way. For this specification, the production function is given by

$$X_i = F\left(\widehat{A}_i, K_i, L_i, O_i\right) = \widehat{A}_i \left[(1-\gamma)\left(K_i^{\alpha} L_i^{1-\alpha}\right)^{\frac{\varepsilon-1}{\varepsilon}} + \gamma\left(O_i\right)^{\frac{\varepsilon-1}{\varepsilon}}\right]^{\frac{\varepsilon}{\varepsilon-1}}, \tag{30}$$

where $\widehat{A}_i \equiv \exp\left(\widehat{Z}_i\right)$ is the Hicks-neutral technology shock. The processes for $\widehat{Z}_h$ and $\widehat{Z}_f$ obey the following laws of motion:

$$\begin{bmatrix} \widehat{Z}'_h \\ \widehat{Z}'_f \end{bmatrix} = \Xi \begin{bmatrix} \widehat{Z}_h \\ \widehat{Z}_f \end{bmatrix} + \begin{bmatrix} \chi'_{\widehat{Z}_h} \\ \chi'_{\widehat{Z}_f} \end{bmatrix},$$

where Ξ is a matrix of constant coefficients, and where $\chi'_{\widehat{z}_h}$ and $\chi'_{\widehat{z}_f}$ are independent and normally distributed with mean zero.

Note that the consumption correlation puzzle reappears in the model with Hicks-neutral shocks. Hence, factor-specific shocks are important in accounting for the international business cycle. The model with Hicks-neutral shocks also produces a cross-country correlation of oil use close to one, which is strongly at odds with the data.

A.6 Direct partial-equilibrium effects of changes in A and B

We show here the direct partial-equilibrium effects of changes in A and B on the productivity of labor and oil, respectively. In particular, we show that while, in general, the signs of the effects are ambiguous, an increase in A increases the marginal product of labor and an increase in B decreases the marginal product of oil.

Table 9: Model results for different combinations of shocks

	std. dev in %	std.dev/std. dev of y in %			
(A) Volatilities					
	y	c	l	o	i
Only shocks to A and B	1.44	0.37	0.33	0.98	3.56
Only shocks to A and O	1.23	0.39	0.36	1.09	3.59
Only shocks to $\widehat{A}$ and O	1.16	0.38	0.37	0.97	3.62
(B) Correlation with output					
		c	l	o	i
Only shocks to A and B		0.85	0.98	0.33	0.98
Only shocks to A and O		0.80	0.98	0.90	0.97
Only shocks to $\widehat{A}$ and O		0.80	0.97	0.78	0.97
(C) International correlations	y_h, y_f	c_h, c_f	l_h, l_f	o_h, o_f	i_h, i_f
Only shocks to A and B	0.56	0.42	0.66	-1.00	0.60
Only shocks to A and O	0.30	0.17	0.55	0.66	0.38
Only shocks to $\widehat{A}$ and O	0.45	0.65	0.53	0.97	0.44

All variables are in logarithms and have been detrended with the HP filter. The time frequency is quarterly. y is output, c is consumption, l is hours worked, o is oil, and, i is investments.

Removing the country index from (1), we have

$$X = \left[(1-\gamma)\left(AK^{\alpha}L^{1-\alpha}\right)^{\frac{\varepsilon-1}{\varepsilon}} + \gamma\,(BO)^{\frac{\varepsilon-1}{\varepsilon}}\right]^{\frac{\varepsilon}{\varepsilon-1}}.$$

The marginal product of labor is given by

$$\frac{\partial X}{\partial L} = (1-\gamma)(1-\alpha)X^{\frac{1}{\varepsilon}}\left(AK^{\alpha}L^{1-\alpha}\right)^{\frac{\varepsilon-1}{\varepsilon}}\frac{1}{L}.$$

The effect on this marginal product of a change in A is

$$\frac{\partial}{\partial A}\frac{\partial X}{\partial L} = \frac{\partial X}{\partial L}\left[\frac{1}{\epsilon}(1-\gamma)\frac{\left(AK^{\alpha}L^{1-\alpha}\right)^{\frac{\varepsilon-1}{\varepsilon}}}{X^{\frac{\varepsilon-1}{\varepsilon}}} + \frac{\varepsilon-1}{\varepsilon}\right]\frac{1}{A}. \tag{31}$$

With $\epsilon < 1$, the sign of this expression is ambiguous. We can identify the factor

$$(1-\gamma)\frac{\left(AK^{\alpha}L^{1-\alpha}\right)^{\frac{\varepsilon-1}{\varepsilon}}}{X^{\frac{\varepsilon-1}{\varepsilon}}} = \frac{1}{X}\left[\frac{\partial X}{\partial K}K + \frac{\partial X}{\partial L}L\right]$$

as the joint income share of K and L, which is about 0.95. Using this number along with parameter value $\varepsilon = 0.09$, we get a numerical value for the expression within the brackets in (31) of

$$\frac{1-\gamma}{\varepsilon}\frac{\left(AK^{\alpha}L^{1-\alpha}\right)^{\frac{\varepsilon-1}{\varepsilon}}}{X^{\frac{\varepsilon-1}{\varepsilon}}}+\frac{\varepsilon-1}{\varepsilon}\approx 0.44.$$

We conclude that, for relevant numerical values, an increase in A increases the marginal product of labor.

Turning, instead, to the effect of an increase in B on the marginal product of oil, we start by computing the marginal product

$$\frac{\partial X}{\partial O}=\gamma X^{\frac{1}{\varepsilon}}\left(BO\right)^{\frac{\varepsilon-1}{\varepsilon}}\frac{1}{O}.$$

The effect of a change in B is

$$\frac{\partial}{\partial B}\frac{\partial X}{\partial O}=\frac{\partial X}{\partial O}\left[\frac{1}{\varepsilon}\gamma\left(\frac{BO}{X}\right)^{\frac{\varepsilon-1}{\varepsilon}}+\frac{\varepsilon-1}{\varepsilon}\right]\frac{1}{B}. \tag{32}$$

As before, the sign of this derivative is ambiguous and we can identify the income share of oil as

$$\gamma\left(\frac{BO}{X}\right)^{\frac{\varepsilon-1}{\varepsilon}}=\frac{1}{X}\frac{\partial X}{O}O.$$

Using a numerical value of 0.05 for this share and the parameter value $\varepsilon = 0.09$, we get a numerical value of the expression in the brackets in (32) of

$$\frac{1}{\epsilon}\gamma\frac{\left(BO\right)^{\frac{\epsilon-1}{\epsilon}}}{X^{\frac{\epsilon-1}{\epsilon}}}+\frac{\epsilon-1}{\epsilon}\approx -9.6.$$

We conclude that, for relevant numerical values, an increase in B decreases the marginal product of O.

A.7 Impulse responses for the oil price

Figure 4 displays the impulse response functions for the oil price for each of the respective shocks in the model.

A shock to A generates a long-lasting increase in the oil price, whereas a shock to the supply just generates a temporary dip. A shock to energy efficiency B generates a decrease in the oil price that remains longer than the shock to the supply but shorter than the shock to A.

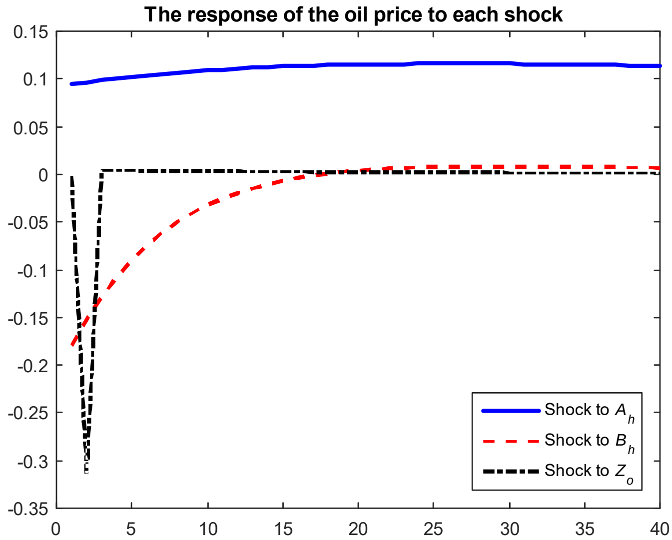

Figure 4: Impulse responses for the oil price.

A.8 Oil and fossil-fuel use

Figures 5-7 illustrate the high correlations between oil use and total fossil-fuel use for a number of countries.

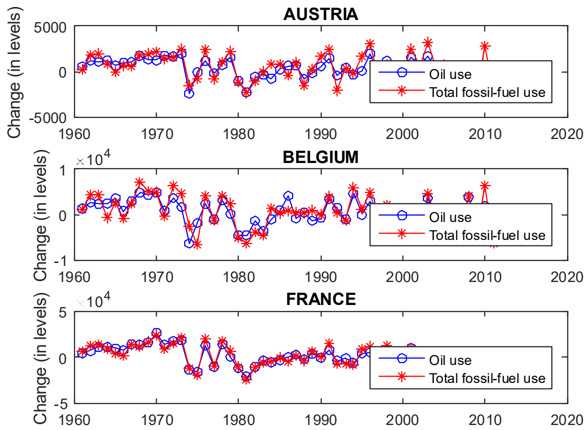

Figure 5: Annual changes in oil and total fossil-energy use. Source: the U.S. Energy Information Administration.

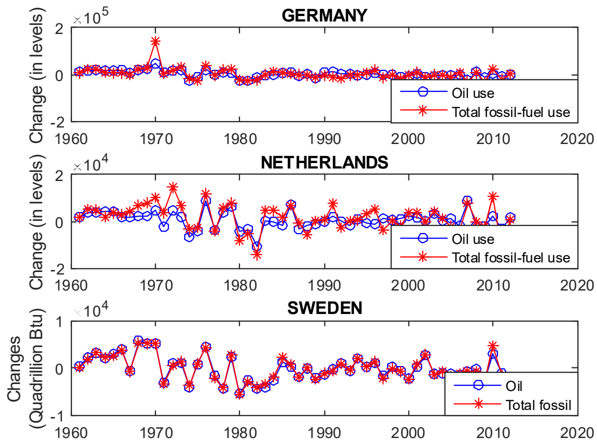

Figure 6: Annual changes in oil and total fossil-energy use. Source: the U.S. Energy Information Administration.

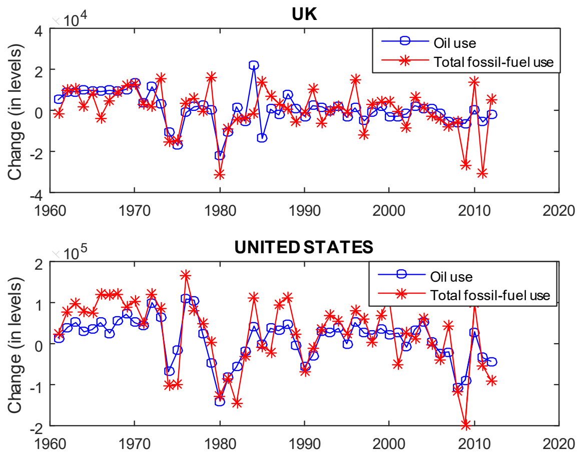

Figure 7: Annual changes in oil and total fossil-energy use. Source: the U.S. Energy Information Administration.

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