FOREIGN SHOCKS IN AN ESTIMATED MULTI-SECTOR MODEL*

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Abstract

How are macroeconomic fluctuations in open economies affected by international business cycles? To shed some light on this question, I develop and estimate a medium scale DSGE model for a small open economy. The model incorporates i) international markets for firm-to-firm trade in production inputs, and ii) producer heterogeneity where technology and price setting constraints vary across industries. Using Bayesian techniques on Canadian and US data, I document several macroeconomic regularities in the small open economy, all attributed to international disturbances. First, foreign shocks are crucial for domestic fluctuations at all forecasting horizons. Second, productivity is the most important driver of business cycles. Investment efficiency shocks on the other hand have counterfactual implications for international spillover. Third, the relevance of foreign shocks accumulates over time. Fourth, business cycles display strong co-movement across countries, even though shocks are uncorrelated and the trade balance is countercyclical. Fifth, exchange rate pass-through to aggregate CPI inflation is moderate, while pass-through at the sector level is positively linked to the frequency of price changes. Few of these features have been accounted for in existing open economy DSGE literature, but all are consistent with reduced form evidence. The model presented here offers a structural interpretation of the results.

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1 Introduction

How and to what extent do international business cycle shocks propagate across countries? These questions are fundamental in open economy macroeconomics, and of first order importance for welfare evaluation and policy making. Yet, our understanding is limited regarding the main disturbances and transmission channels at play. On the one side, a vast number of empirical studies suggest substantial propagation of international shocks to open economies.[1] However, due to it's reduced form nature, the VAR approach is largely silent when it comes to exact identification of structural innovations. Estimated DSGE models, in contrast, facilitate formal identification of a rich set of business cycle shocks. But once confronted with data, these models typically have a hard time accounting for even moderate amounts of international spillover. Perhaps the most striking example is offered by Justiniano and Preston (2010), who document how an estimated New Keynesian model attributes virtually all business cycle fluctuations to domestic shocks.[2]

In this paper I revisit the role of international business cycle disturbances within a multi-sector open economy framework. To this end I develop and estimate a two-country New Keynesian model, and shed light on how macroeconomic fluctuations are determined in small open economies (SOEs). Key features of the model are i) international markets for firm-to-firm trade in production inputs, and ii) producer heterogeneity where firms operate in segmented markets and face different technological constraints. These modeling choices are guided by data: International input-output matrices reveal substantial intermediate goods trade, both across diversified industries within countries, and across country borders. Table 1 reports the intermediate goods share in gross output in all OECD countries where data were available, as well as in the BRICS economies. About 50% of gross output in most countries is sold as input to other firms. The intermediate goods shares are even higher in exports and imports data – about 60% of all trade between Canada and US is between firms. Thus, open economy models with only final products (consumption and investment) miss out on more than half of the cross-country trade in physical goods that actually takes place. Clearly, this might give rise to a mismatch between theory and reality when it comes to international spillover and synchronization.

The way I model firm-to-firm trade and producer heterogeneity builds on Bouakez, Cardia, and Ruge-Murcia (2009) and Bergholt and Sveen (2014). Crucially, these features create sectoral trade interdependence both within and across economies: First, imported intermediates represent a new cost-channel for spillover of foreign shocks. In contrast to existing models, where exchange rates only affect domestic firms indirectly via changes in demand, they also shift supply schedules in the current framework. This direct exchange rate effect on the domestic production frontier is particularly relevant for firms who compete in international markets, even more so if these markets are characterized by frequent and large price changes. Second, intersectoral firm-to-firm linkages induce substantial spillover to relatively non-traded industries. For example, when the price of manufactured goods deflate, the supply of domestic service firms shifts out. This

[1] See e.g. Kose, Otrok, and Whiteman (2003, 2008), Aastveit, Bjornland, and Thorsrud (2011), Crucini, Kose, and Otrok (2011), Mumtaz, Simonelli, and Surico (2011), and Kose, Otrok, and Prasad (2012).

[2] This puzzling result is not an exception. Other examples (although they do not necessarily discuss it explicitly) include Adolfson, Laséen, Lindé, and Villani (2007, 2008), de Resende, Dib, and Kichian (2010), Rabanal and Tuesta (2010), Dib (2011), and Christiano, Trabandt, and Walentin (2011). Schmitt-Grohé (1998) demonstrate that also the real business cycle literature fail to account for international spillover.

Table 1: Intermediate trade in OECD and BRICS countries

Country	*Share*	*Country*	*Share*	*Country*	*Share*	*Country*	*Share*
OECD							
Australia	0.51	Finland	0.55	Korea	0.59	Slovenia	0.58
Austria	0.49	France	0.51	Luxembourg	0.63	Spain	0.52
Belgium	0.59	Germany	0.50	Netherlands	0.53	Sweden	0.53
Bulgaria	0.57	Greece	0.44	New Zealand	0.55	Switzerland	0.50
Canada	0.50	Hungary	0.62	Norway	0.47	Turkey	0.43
Czech Republic	0.63	Ireland	0.56	Poland	0.55	UK	0.53
Denmark	0.49	Italy	0.54	Portugal	0.54	US	0.46
Estonia	0.60	Japan	0.49	Slovakia	0.63	OECD	0.54
BRICS							
Brazil	0.51	China	0.64	India	0.48	Russia	0.49
South Africa	0.50	BRICS	0.52				

Note: Intermediate goods share of gross output (OECD data).

is because manufactured goods are important inputs in service production. It follows that even the supply of completely non-traded firms in general will react to international shocks. These intersectoral firm-to-firm linkages are crucial as most of aggregate GDP is produced by domestic service firms. Third, feedback loops in the domestic production network accelerate initial impulses, resulting in higher order propagation effects.

While Bergholt and Sveen (2014) explain basic mechanisms in a stylized environment, I extend the setup along several dimensions to facilitate a quantitative assessment, as in e.g. Adolfson et al. (2007). I estimate structural parameters using Bayesian techniques on 9 Canadian and 8 US time series, but restrict them to fit I-O data in both countries. I then conduct a broad evaluation of the open economy dimension of macroeconomic fluctuations in Canada (the SOE). Several important results emerge: First, as in wide empirical literature, foreign shocks account for substantial variation in macroeconomic variables at all forecasting horizons (20-70%). Second, in a forecasting perspective the role of foreign shocks tends to build up over time, in line with VAR evidence (see e.g. Cushman and Zha (1997) and Justiniano and Preston (2010)). Third, while a cocktail of disturbances is responsible for macroeconomic fluctuations in the very short run, total factor productivity stands out as the most prominent type of shock over the business cycle. This contrasts the major role of investment efficiency shocks found in recently estimated DSGE models, see Justiniano, Primiceri, and Tambalotti (2010, 2011) and Jacob and Peersman (2013). I argue that these shocks have counterfactual implications for international synchronization patterns. Fourth, consistent with the empirical pass-through literature (e.g. Gopinath, Itskhoki, and Rigobon (2010) and Gopinath and Itskhoki (2010)) I find higher exchange rate pass-through in sectors with frequent price changes. This feature facilitates international spillover of shocks. Finally, when firm-to-firm trade and sectoral heterogeneity are shut down, the model assigns almost all business cycle fluctuations to domestic events.

The rest of the paper is organized as follows. A multi-sector DGSE model is described in section 2. Section 3 presents data, calibration and Bayesian estimates. Main empirical results are reported in section 4. In section 5 I discuss how these results are facilitated by important transmission channels in the model. Section 6 presents results from a counterfactual model without intermediate trade and sector heterogeneity. Section 7 concludes.

2 The model

I derive a general equilibrium system consisting of two blocks – “home” and “foreign”. Home is referred to as the domestic economy, while the rest of the world is captured by the foreign block. My focus is on the limiting case where home is small and has negligible influence on the world economy. A log-linear approximation around the non-stochastic steady state is presented below.[3] To save space, I restrict attention to the domestic block.

2.1 Households

Consider a small open economy (the home economy) with a measure one of symmetric households. The representative household consists of a continuum of members, with a fixed share μ_j working in each production sector $j \in [1, \ldots, \mathcal{J}]$ in the domestic economy $\left(\sum_{j=1}^{\mathcal{J}} \mu_j = 1\right)$. Household members consume, work and invest in order to maximize expected lifetime utility. The maximization problem is subject to a sequence of budget constraints, with revenues coming from returns on capital, labor income, dividends from ownership of firms, returns on domestic and foreign bonds, and government transfers. Optimality conditions for the representative household with respect to consumption, domestic and foreign bond holdings, capital and investment follow below, with prices being quoted in terms of consumption units:

$$\lambda_t = z_{U,t} - \frac{\sigma}{1-\chi_C}\left(c_t - \chi_C c_{t-1}\right) \tag{1}$$

$$\lambda_t = \mathbb{E}_t\left(\lambda_{t+1}\right) + r_t - \mathbb{E}_t\left(\pi_{t+1}\right) \tag{2}$$

$$\lambda_t = \mathbb{E}_t\left(\lambda_{t+1}\right) + r_t^* - \mathbb{E}_t\left(\pi_{t+1} - \Delta e_{t+1}\right) - \epsilon_B nfa_t + z_{B,t} \tag{3}$$

$$q_t = -\left(r_t - \mathbb{E}_t\left(\pi_{t+1}\right)\right) + \mathbb{E}_t\left(\left[1-\beta\left(1-\delta\right)\right] r_{t+1}^k + \beta\left(1-\delta\right) q_{t+1}\right) \tag{4}$$

$$p_{r,t}^i = q_t + z_{I,t} - \epsilon_I\left[\left(i_t - i_{t-1}\right) - \beta \mathbb{E}_t\left(i_{t+1} - i_t\right)\right] \tag{5}$$

The first equation aligns the shadow value of the budget constraint in period t, λ_t, with the marginal utility of aggregate consumption c_t. $\sigma > 0$ and $\chi_C \in [0,1]$ govern the intertemporal elasticity of substitution and habit persistence in consumption, respectively. $z_{U,t}$ is a stationary shock to intertemporal preferences. Optimality conditions (2) and (3) equate the marginal utility of more consumption today with the expected present value of more future consumption, obtained by investing in domestic and foreign bonds. π_t and Δe_t are the CPI inflation rate and the nominal depreciation rate, respectively. Nominal interest rates on domestic and foreign bonds are denoted r_t and r_t^*, while nfa_t is the ratio of net foreign assets to GDP (measured in absolute deviations from steady state. $\epsilon_B > 0$ introduces a risk premium on foreign asset returns, as in Adolfson et al. (2007, 2008) and Christiano et al. (2011). If domestic households are net borrowers, they are charged a premium. If they are net lenders, they receive a lower return than foreign households. The risk premium also ensures that steady state is well-defined, see e.g. Schmitt-Grohé and Uribe (2003). $z_{B,t}$ denotes temporary deviations from interest rate parity, so-called risk premium shocks. The present value of one more unit of new capital, q_t, is characterized by equation (4). $r_t - \mathbb{E}_t\left(\pi_{t+1}\right)$ is the expected real return (real interest rate) foregone

[3] A detailed description of the full non-linear model is provided in the appendix.

by not investing in bonds, while r_t^k is the rental rate on capital in place. The parameters $\beta \in (0,1)$ and $\delta \in [0,1]$ denote the time discount factor and the capital depreciation rate, respectively. Finally, equation (5) determines optimal demand for aggregate investment goods. It effectively equates the relative investment price $p_{r,t}^i$ with the marginal gain of investment – the present value of capital net of investment adjustment costs. The latter is governed by $\epsilon_I \geq 0$, as in Christiano, Eichenbaum, and Evans (2005). $z_{I,t}$ is a stationary shock to the marginal efficiency of investment, a so-called MEI shock. The optimality conditions (1)-(5) summarize intertemporal household decisions in goods and asset markets. They are augmented with a capital accumulation equation of the form

$$k_{t+1} = (1-\delta) k_t + \delta (z_{I,t} + i_t), \tag{6}$$

where k_t is capital operational in period t.

Next I turn to sectoral allocations. c_t and i_t are composite functions of sectoral consumption and investment goods, $c_{j,t}$ and $i_{j,t}$. In turn, these quantities are combinations of domestically produced $(c_{Hj,t}, i_{Hj,t})$ and imported $(c_{Fj,t}, i_{Fj,t})$ goods, respectively. At least some international trade takes place in all sectors. However, the trade intensity is sector specific, implying that import shares in c_t and i_t depend both on the import shares in each sector, and on the sector weights in aggregate demand baskets. Cost minimization gives rise to a set of optimality conditions involving associated (real) price indexes, $p_{rj,t}$, $p_{rHj,t}$ and $p_{rFj,t}$:

$$\begin{aligned} c_{j,t} &= -\nu p_{rj,t} + c_t & i_{j,t} &= -\nu \left(p_{rj,t} - p_{r,t}^i\right) + i_t \\ c_{Hj,t} &= -\eta (p_{rHj,t} - p_{rj,t}) + c_{j,t} & i_{Hj,t} &= -\eta (p_{rHj,t} - p_{rj,t}) + i_{j,t} \\ c_{Fj,t} &= -\eta (p_{rFj,t} - p_{rj,t}) + c_{j,t} & i_{Fj,t} &= -\eta (p_{rFj,t} - p_{rj,t}) + i_{j,t} \end{aligned} \tag{7}$$

The elasticity of substitution between goods from different sectors is $\nu > 0$, while $\eta > 0$ denotes the elasticity of substitution between countries. Thus, households substitute their demand towards sectors and countries with relatively low prices. Up to first order, one can express aggregate CPI inflation π_t and investment goods inflation π_t^i as linear combinations of domestic sector prices:[4]

$$\pi_t = \sum_{j=1}^{\mathcal{J}} \xi_j \pi_{j,t} \qquad \pi_t^i = \sum_{j=1}^{\mathcal{J}} \varpi_j \pi_{j,t} \qquad p_{rj,t} = \alpha_j p_{rHj,t} + (1-\alpha_j) p_{rFj,t}$$

The weights ξ_j, ϖ_j and α_j represent cost shares in steady state.

Sectoral labor markets are constructed similar to that in Erceg, Henderson, and Levin (2000), but I add a friction in the sense that labor cannot move freely between sectors or countries within the business cycle horizon.[5] To fix ideas, consider the labor market in sector j. Firms buy labor services from a sector specific labor union. In turn, the union provides these services by combining working hours from the μ_j household members employed in the sector. Among individual workers, only a randomly drawn fraction $1 - \theta_{wj}$ can adjust nominal wages optimally each period. Remaining workers index their wages partially to lagged CPI inflation. Nominal wage dynamics follow.

$$\pi_{wj,t} = \beta \mathbb{E}_t (\pi_{wj,t+1}) + \iota_w (\pi_{t-1} - \beta \pi_t) + \kappa_{wj} (mrs_{j,t} - \omega_{j,t}) \tag{8}$$

[4]Note that sectoral prices are linked to aggregate CPI inflation by the identity $\pi_{j,t} = p_{rj,t} - p_{rj,t-1} + \pi_t$.

[5]Still, workers within each country do not have incentives to change sector occupation over time, as real wages are equal across sectors in steady state.

$\kappa_{wj} = \frac{(1-\theta_{wj})(1-\beta\theta_{wj})}{\theta_{wj}\left(1+\frac{1+\epsilon_w}{\epsilon_w}\varphi\right)}$ governs the responsiveness of $\pi_{wj,t}$ to time varying markups in the real wage $\omega_{j,t}$ over $mrs_{j,t}$, the marginal rate of substitution between hours worked and consumption. φ is the inverse Frisch elasticity of labor supply, while ϵ_w represents the steady state markup over competitive wages. $\iota_w \in [0,1]$ is the degree of indexation among non-optimizing workers. The marginal rate of substitution is

$$mrs_{j,t} = z_{U,t} + z_{N,t} + \varphi n_{j,t} - \lambda_t, \tag{9}$$

where $z_{N,t}$ is referred to as a labor supply shock.

2.2 Firms

Domestic sector j is populated by a continuum of profit maximizing firms. Firms cannot change sectoral occupation over time, in analogy with labor.[6] Each firm produces differentiated consumption, investment and intermediate goods, which are sold in domestic and foreign markets. Production technology is Cobb-Douglas in materials, labor and capital, augmented with fixed costs. Aggregate output in sector j becomes

$$y_{j,t} = (1+\epsilon_p)\left[z_{Aj,t} + \phi_j m_{j,t} + \psi_j n_{j,t} + (1-\phi_j-\psi_j)\, k_{j,t}\right], \tag{10}$$

where $z_{Aj,t}$ is a sector specific productivity shock, ϵ_p is the steady state price markup on differentiated goods, and $\phi_j, \psi_j, (\phi_j + \psi_j) \in (0,1)$.

A defining feature of the model is the presence of segmented markets for firm-to-firm trade. I follow Bouakez et al. (2009) and Bergholt and Sveen (2014), and let $m_{j,t}$ be a composite of different materials produced in the different sectors. In principle, domestic production requires intermediate inputs from *all* firms in *all* industries in *all* countries. Bergholt and Sveen (2014) show how this setup amplifies the interdependencies between sectors, and therefore increases the potential role for international shocks in otherwise closed sectors such as the service industry. Cost minimization implies a set of optimality conditions for the use of intermediate inputs:

$$\begin{aligned} m_{lj,t} &= -\nu\left(p_{rl,t} - p^m_{rj,t}\right) + m_{j,t} \\ m_{Hlj,t} &= -\eta\left(p_{rHl,t} - p_{rl,t}\right) + m_{lj,t} \\ m_{Flj,t} &= -\eta\left(p_{rFl,t} - p_{rl,t}\right) + m_{lj,t} \end{aligned} \tag{11}$$

In analogy with consumption and investment bundles, $m_{lj,t}$ denotes sector j's demand for materials from sector l, while $m_{Hlj,t}$ and $m_{Flj,t}$ represent the domestic and imported components, respectively. $p^m_{rj,t} = \sum_{l=1}^{\mathcal{J}} \zeta_{lj} p_{rl,t}$ is the composite price index associated with $m_{j,t}$. Importantly, the weights ζ_{lj} can be found from I-O matrices in each country. The system in (11) shows that optimal factor demand is directed towards those industries and countries with relatively low factor prices. Finally, material demand is high when other factors of production are relatively costly, as seen below:

$$m_{j,t} - n_{j,t} = \omega_{j,t} - p^m_{rj,t} \tag{12}$$

$$k_{j,t} - m_{j,t} = p^m_{rj,t} - r^k_t \tag{13}$$

[6] A free entry condition prevents arbitrage opportunities of changing sectoral occupation in steady state.

Producer prices are sticky á la Calvo (1983). Every period, each individual firm can set it's price optimally with probability $1-\theta_{pj}$. Remaining firms resort to a partial indexation rule. Nominal inflation dynamics for goods sold domestically and abroad follow:

$$\pi_{Hj,t} = \kappa_1 \mathbb{E}_t\left(\pi_{Hj,t+1}\right) + \kappa_2 \pi_{Hj,t-1} + \kappa_{j3}\left(rmc_{j,t} - p_{rHj,t} + z_{M,t}\right) \tag{14}$$

$$\pi^*_{Hj,t} = \kappa_1 \mathbb{E}_t\left(\pi^*_{Hj,t+1}\right) + \kappa_2 \pi^*_{Hj,t-1} + \kappa_{j3}\left(rmc_{j,t} - p^*_{rHj,t} + z_{M,t}\right) \tag{15}$$

The slope coefficients are defined as $\kappa_1 = \frac{\beta}{1+\beta\iota_p}$, $\kappa_2 = \frac{\iota_p}{1+\beta\iota_p}$, and $\kappa_{j3} = \frac{(1-\theta_{pj})(1-\beta\theta_{pj})}{\theta_{pj}(1+\beta\iota_p)}$, where $\iota_p \in [0,1]$ is the degree of indexation among non-optimizing price setters. Intuitively, inflation comes about from time varying markups in $p_{rHj,t}$ and $p^*_{rHj,t}$, the prices on domestic goods and exports, over marginal costs $rmc_{j,t}$. $z_{M,t}$ is referred to as a markup shock. Equation (15), with $\pi^*_{Hj,t}$ being expressed in international currency, follows from the assumption that export prices are set in buyer's currency – so called local currency pricing (LCP). I choose LCP rather than producer currency pricing (PCP) for two reasons. First, only 4% of Canadian exports to the US is priced in Canadian dollars. Second, PCP implies full pass-through from exchange rates into domestic inflation, at odds with the empirical pass-through literature (Gopinath et al., 2010). Marginal costs are

$$rmc_{j,t} = -z_{Aj,t} + \phi_j p^m_{rj,t} + \psi_j \omega_{j,t} + \left(1-\phi_j-\psi_j\right) r^k_t. \tag{16}$$

Note for future reference that sector level terms of trade is defined as the domestic currency export-to-import price ratio, i.e. $\tau_{j,t} = p^*_{rHj,t} - p_{rFj,t}$.

2.3 Domestic absorption and GDP

Aggregate domestic absorption of sector j-goods is defined as the sum of consumption, investment and material components:

$$x_{j,t} = \gamma^c_j c_{j,t} + \gamma^i_j i_{j,t} + \sum_{l=1}^{\mathcal{J}} \gamma^m_{jl} m_{jl,t} \tag{17}$$

The coefficients γ^c_j, γ^i_j and γ^m_{jl} depend on the steady state and are defined in the appendix. I let $x_{Hj,t}$ be domestic absorption of domestically produced j-goods, and $x_{Fj,t}$ be the imported counterpart:

$$x_{Hj,t} = -\eta\left(p_{rHj,t} - p_{rj,t}\right) + x_{j,t} \tag{18}$$

$$x_{Fj,t} = -\eta\left(p_{rFj,t} - p_{rj,t}\right) + x_{j,t} \tag{19}$$

In analogy to domestic producer prices, imported inflation can be written as

$$\pi_{Fj,t} = \kappa^*_1 \mathbb{E}_t\left(\pi_{Fj,t+1}\right) + \kappa^*_2 \pi_{Fj,t-1} + \kappa^*_{j3}\left(rmc^*_{j,t} + s_t - p_{rFj,t} + z^*_{M,t}\right), \tag{20}$$

where $\kappa^*_1 = \frac{\beta}{1+\beta\iota^*_p}$, $\kappa^*_2 = \frac{\iota^*_p}{1+\beta\iota^*_p}$, and $\kappa^*_{j3} = \frac{\left(1-\theta^*_{pj}\right)\left(1-\beta\theta^*_{pj}\right)}{\theta^*_{pj}\left(1+\beta\iota^*_p\right)}$. s_t is the real exchange rate between the two countries, $rmc^*_{j,t}$ represents marginal costs abroad, and $z^*_{M,t}$ is an international markup shock. Similarly to domestic absorption of imports, one can define $x^*_{Hj,t}$ as global absorption of domestically produced j-goods:

$$x^*_{Hj,t} = -\eta\left(p^*_{rHj,t} - s_t - p^*_{rj,t}\right) + x^*_{j,t} \tag{21}$$

$p^*_{rj,t}$ and $x^*_{j,t}$ represent sector specific prices and quantities in global markets. Market clearing implies that $y_{j,t} = \alpha_{xj} x_{Hj,t} + (1 - \alpha_{xj}) x^*_{Hj,t}$, where α_{xj} is the steady state share of domestic output that is supplied at home. GDP and the trade balance at sector level are derived according to the expenditure approach:

$$gdp_{j,t} = \gamma_j^1 (p_{rj,t} + x_{j,t}) + tb_{j,t} - \gamma_j^2 (p^m_{rj,t} + m_{j,t}) \tag{22}$$

$$tb_{j,t} = \gamma_j^{ex} (p^*_{rHj,t} + x^*_{Hj,t}) - \gamma_j^{im} (p_{rFj,t} + x_{Fj,t}) \tag{23}$$

The trade balance is expressed relative to sector GDP and in absolute deviation from steady state. γ_j^{ex} and γ_j^{im} represent sector specific export/import-to-GDP ratios respectively, while γ_j^1 and γ_j^2 are found as solutions to the steady state of the model. Finally, by aggregating across sectors we get economy wide GDP and trade balance:

$$gdp_t = \sum_{j=1}^{\mathcal{J}} \gamma_j gdp_{j,t} \qquad \text{and} \qquad tb_t = \sum_{j=1}^{\mathcal{J}} \gamma_j tb_{j,t} \tag{24}$$

The parameter γ_j is the steady state share of sector j in aggregate GDP. From the global economy's point of view, their debt is in zero net supply because the home economy engages in only a negligible part of the financial assets trade. Furthermore, I assume that foreign investors do not hold financial assets in the home economy.

2.4 Monetary and fiscal policy

The model is closed with a specification of monetary and fiscal policy. I follow previous work in the DSGE literature (see e.g. Justiniano and Preston (2010); Smets and Wouters (2007); Lubik and Schorfheide (2007)) and assume that monetary policy can be approximated by a Taylor-type rule of the form

$$r_t = \rho_r r_{t-1} + (1 - \rho_r) (\rho_\pi \pi_t + \rho_y gdp_t + \rho_{dy} \Delta gdp_t + \rho_{de} \Delta e_t) + z_{R,t}. \tag{25}$$

ρ_r, ρ_π, ρ_y, ρ_{dy} and ρ_{de} are policy coefficients, and $z_{R,t}$ is a monetary policy shock. Regarding fiscal policy, the government faces a period-by-period budget constraint with Ricardian taxes and newly issued government bonds on the income side, and public spending and maturing bonds on the expenditure side. Under the assumption that public debt is zero in steady state, one can write, up to a first order approximation, public spending as fully financed by (possibly time varying) lump-sum taxes.

2.5 Exogenous disturbances

I assume that all exogenous disturbances in the model follow a univariate AR(1) representation in log-linear form:

$$\mathbf{z}_t = \rho_z \mathbf{z}_{t-1} + \sigma_z \varepsilon_{z,t}, \qquad \varepsilon_{z,t} \overset{i.i.d.}{\sim} N(0,1) \tag{26}$$

$\mathbf{z}_t = [z_{U,t}, z_{N,t}, z_{B,t}, z_{I,t}, z_{M,t}, z_{R,t}, z_{A1,t}, \ldots, z_{A\mathcal{J},t}]'$ is the vector of exogenous disturbances. ρ_z and σ_z are diagonal, and all non-zero elements in ρ_z are bounded between zero and one. Fluctuations in the foreign economy are subject to a similar set of disturbances, except that foreign risk premium shocks are negligible due to the small economy assumption.

3 Estimation

Sector heterogeneity induces a non-symmetric equilibrium across different industries. I solve for the steady state analytically and use the solution to parameterize a log-linear approximation of the model. The steady state solution is provided in the appendix. Several model parameters are estimated using Bayesian techniques. This approach has been popularized by e.g. Geweke (1999), Smets and Wouters (2003, 2007), and An and Schorfheide (2007). Before discussing the results I describe data, the calibration, and priors.

3.1 Data

To estimate the model I use HP filtered quarterly data from Canada and US (1982Q4-2007Q4).[7] Canada is treated as the SOE, while US proxies the world economy. This country-pair has been analyzed in a number of two-country SOE-studies, see e.g. Schmitt-Grohé (1998) and Justiniano and Preston (2010). I divide each economy into three sectors – the raw material sector, the manufacturing sector, and the service sector. These are classified according to the North American Industry Classification System (NAICS). Raw materials constitute NAICS industries 11-21, manufacturing 22-33, and services 41-56 and 71-72 respectively. The industries are exhaustive in the sense that they aggregate to privately produced GDP. Sector level GDP series are interpolated as the raw data are available only at annual frequency. In addition, I use as observables quarterly consumption, investment, hours, CPI inflation, and policy rates from both countries, as well as the bilateral real exchange. This leaves me with a total of 17 time series used for estimation.[8] Details about the data set are relegated to the appendix.

3.2 Calibration and priors

A subset of the parameters is calibrated according to data and previous studies. Their values are reported in Table 2. Parameters not related to the multi-sector setup are set to common values in the literature (see e.g. Smets and Wouters (2007), Adolfson et al. (2007, 2008), Justiniano and Preston (2010), and Christiano et al. (2011)). Regarding ν, I choose a value of 0.5 based on Atalay (2013), who estimate sectoral substitution elasticities between 0.85 and essentially zero. $\nu = 1.5$ gives similar results. The remaining parameters are sector specific, and these deserve further attention. To parameterize sector specific steady state ratios I rely on the Canadian and US I-O matrices, obtained from the Structural Analysis Input Output (Total) Database constructed by OECD. The data reveal large differences across industries. For instance, while almost 70% of consumption goods is services, manufacturing firms produce the vast majority of investment goods. Raw materials, while only accounting for about 2% of aggregate consumption and investment in Canada, constitutes 16% of GDP because of its exports and large supply of intermediates. Regarding trade, Canadian export-to-GDP ratio varies from 7% in the service sector to about 102% in the manufacturing sector. These sector differences represent

[7] Results are similar if data are linearly detrended.

[8] Raw data are collected from Federal Reserve Economic Database (FRED), Statistics Canada, and Bureau of Economic Analysis. They are available to the public and can be downloaded from http://research.stlouisfed.org/fred2/, http://www.statcan.gc.ca/, and http://www.bea.gov/.

Table 2: Calibration

β	Time discount factor	0.99	ν	Sectoral elasticity	0.5
σ	Inverse intertemporal elasticity	1	δ	Capital depreciation	0.025
φ	Inverse labor supply elasticity	2	ϵ_B	Risk premium elasticity	0.01
ϵ_w, ϵ_p	Mark-up, labor and goods markets	1/7			

		SOE			*ROW*		
		(1)	(2)	(3)	(1)	(2)	(3)
ϕ_j	Materials share, gross output	0.37	0.66	0.34	0.35	0.54	0.33
ψ_j	Labor share, gross output	0.12	0.21	0.32	0.10	0.22	0.29
γ_j^{ex}, γ_j^{im}	Trade share, sector GDP	0.67	1.02	0.07	–	–	–
ξ_j	Sector share, consumption	0.02	0.31	0.67	0.01	0.29	0.70
ϖ_j	Sector share, investment	0.02	0.85	0.13	0.03	0.77	0.20
		0.32	0.21	0.03	0.40	0.18	0.01
ζ_{lj}	Input-output matrix	0.38	0.61	0.32	0.33	0.58	0.28
		0.30	0.18	0.65	0.27	0.24	0.71

Note: Calibrated values in benchmark model. The sectors are (1) raw materials, (2) manufacturing, and (3) services. The two I-O matrices at the bottom display the fraction of total materials used in each sector that comes from each of the other sectors. Columns represent consumption (input), and rows production (output).

a key source of disaggregate heterogeneity in the model. Turning to data on materials, we see that substantial trade in intermediate goods takes place across sectors, as illustrated by the non-zero off-diagonal elements of the I-O matrices. For instance, the service sector in Canada buys about 32% of its materials from the manufacturing sector (which trade extensively in foreign markets). This is the sense in which trade across sectors provides indirect import in the model, and thereby serves as a potential amplification mechanism for foreign shocks.

The remaining parameters are estimated. I choose priors in the mid range of those used by Adolfson et al. (2007), Justiniano and Preston (2010), and Christiano et al. (2011), with identical distributions across countries on same parameters.[9] The substitution elasticity between domestic and foreign goods is centered around 1 – above estimates by Heathcote and Perri (2002), Corsetti, Dedola, and Leduc (2008), and Gust, Leduc, and Sheets (2009), but below estimates by Adolfson et al. (2007). Regarding Calvo parameters for wage stickiness, I am not aware of any studies pointing to substantial sectoral differences. Thus, θ_{wj} is centered around $0.75 \; \forall \; j$. Priors on sectoral price stickiness are inspired by a number of microeconomic studies, who show that raw materials and manufactured goods change prices much more frequently than service goods. For instance, looking at disaggregate US data, Bils and Klenow (2004), Nakamura and Steinsson (2008) and Bouakez et al. (2009) find virtually flexible prices in agricultural and raw materials, while estimated price durations in services range from 1.6 quarters (Bils and Klenow, 2004) to 9 quarters (Bouakez et al., 2009). I choose priors in the mid range of these estimates: Calvo parameters are set such that average price durations in raw materials, manufacturing and services are equal to 1.18, 1.25, and 5 quarters respectively. Priors for the seventeen structural shocks are comparable with e.g. Adolfson et al. (2007), although technology shocks

[9] Justiniano and Preston (2010) on the other hand scale up priors on foreign shocks to twice the size of domestic shocks. This is done in order to induce a more important role for international business cycles.

Table 3: Prior and posterior distributions

		Prior	Posterior domestic			Posterior foreign		
		Prior(P1,P2)	Mode	Mean	5%-95%	Mode	Mean	5%-95%
χ_C	Habit	B(0.50,0.10)	0.61	0.57	0.42-0.71	0.56	0.59	0.49-0.70
ϵ_I	Inv. adj. cost	N(5.00,1.00)	0.77	1.07	0.55-1.59	2.59	2.91	1.38-4.37
η	H-F elasticity	G(1.00,0.15)	0.83	0.83	0.74-0.92	–	–	–
θ_{w1}		B(0.75,0.07)	0.76	0.74	0.62-0.87	0.75	0.73	0.59-0.85
θ_{w2}	Calvo wages	B(0.75,0.07)	0.38	0.37	0.24-0.49	0.75	0.73	0.61-0.86
θ_{w3}		B(0.75,0.07)	0.71	0.69	0.55-0.85	0.72	0.71	0.60-0.83
θ_{p1}		B(0.15,0.05)	0.11	0.13	0.06-0.21	0.21	0.21	0.17-0.26
θ_{p2}	Calvo prices	B(0.20,0.05)	0.14	0.14	0.09-0.20	0.30	0.30	0.25-0.35
θ_{p3}		B(0.80,0.07)	0.66	0.64	0.57-0.71	0.80	0.81	0.76-0.85
ι_w	Indexation, π_w	B(0.50,0.15)	0.30	0.35	0.13-0.56	0.52	0.57	0.31-0.82
ι_p	Indexation, π_p	B(0.50,0.15)	0.17	0.21	0.08-0.34	0.87	0.85	0.76-0.94
ρ_r	Smoothing, r	B(0.60,0.05)	0.73	0.74	0.69-0.78	0.76	0.75	0.71-0.80
ρ_π	Taylor, π	N(1.80,0.20)	1.95	2.00	1.72-2.30	1.70	1.73	1.47-1.98
ρ_y	Taylor, gdp	N(0.13,0.05)	0.03	0.04	0.02-0.06	0.08	0.08	0.05-0.12
ρ_{dy}	Taylor, Δgdp	N(0.13,0.05)	0.12	0.12	0.05-0.18	0.15	0.15	0.09-0.20
ρ_{de}	Taylor, Δe	N(0.10,0.05)	0.10	0.11	0.05-0.16	–	–	–
ρ_A	Technology	B(0.70,0.10)	0.90	0.89	0.84-0.94	0.90	0.90	0.86-0.94
ρ_R	Mon. pol.	B(0.70,0.10)	0.29	0.29	0.20-0.38	0.31	0.33	0.23-0.42
ρ_I	Investment	B(0.70,0.10)	0.51	0.49	0.36-0.62	0.40	0.40	0.28-0.52
ρ_U	Preferences	B(0.70,0.10)	0.41	0.46	0.29-0.62	0.59	0.56	0.42-0.70
ρ_N	Labor supply	B(0.70,0.10)	0.72	0.66	0.51-0.81	0.72	0.69	0.52-0.86
ρ_M	Markup	B(0.70,0.10)	0.50	0.51	0.36-0.65	0.54	0.55	0.44-0.66
ρ_B	UIP	B(0.70,0.10)	0.85	0.84	0.76-0.92	–	–	–
σ_{A1}		IG(0.20,2.00)	0.09	0.48	0.04-1.97	5.49	5.61	4.87-6.31
σ_{A2}	Sd technology	IG(0.50,2.00)	0.71	0.65	0.28-1.01	1.16	1.16	1.00-1.32
σ_{A3}		IG(0.20,2.00)	0.90	0.90	0.73-1.08	0.61	0.61	0.50-0.72
σ_R	Sd mon. pol.	IG(0.20,2.00)	0.25	0.26	0.21-0.30	0.11	0.12	0.10-0.13
σ_I	Sd investment	IG(0.50,2.00)	2.25	3.12	1.69-4.48	5.61	6.31	3.24-9.24
σ_U	Sd preferences	IG(0.20,2.00)	1.66	1.62	1.11-2.12	1.16	1.29	0.94-1.64
σ_N	Sd labor supply	IG(0.50,2.00)	0.24	3.93	0.12-10.95	0.23	0.47	0.11-0.85
σ_M	Sd markup	IG(0.50,2.00)	0.71	0.70	0.52-0.88	1.36	1.37	1.13-1.60
σ_B	Sd UIP	IG(0.20,2.00)	0.42	0.45	0.31-0.59	–	–	–
σ_{e1}		IG(0.20,1.00)	6.48	6.56	5.73-7.40	0.09	0.14	0.05-0.24
σ_{e2}	Sd mea. err.	IG(0.20,1.00)	3.27	3.15	2.57-3.73	2.98	3.01	2.65-3.37
σ_{e3}		IG(0.20,1.00)	0.73	0.76	0.64-0.88	0.13	0.14	0.09-0.20

Note: B denotes the beta distribution, N normal, G gamma, IG inverse gamma, P1 prior mean, P2 prior standard deviation. Posterior moments are computed from 500000 draws generated by the Random Walk Metropolis-Hastings algorithm, where the first 200000 are used as burn-in. The volatility of shocks is multiplied by 100 relative to the text.

in services are less volatile than in other sectors. This reflects estimates by Bouakez et al. (2009), who point to much less volatility in services. TFP differences used here are fairly conservative compared with their results. Finally, I include a measurement error in each of the observation equations linking observed GDP series to the model. This is motivated by the interpolation of sectoral GDP data, which might introduce certain high or low frequency properties not related to the business cycle. The measurement errors are assumed to be i.i.d. with prior standard deviations centered around 0.2. This is similar to the prior measurement errors on wages used by Justiniano, Primiceri, and Tambalotti (2013).

3.3 Posterior estimates

To build the posterior parameter distribution, I simulate two Random Walk Metropolis-Hastings chains with 500000 draws per chain, starting at the posterior mode. The first 200000 draws are used as burn-in. I tune the scale of the jumping distribution and obtain acceptance ratios equal to 0.34 and 0.33. Posterior estimates are reported in Table 3. Most parameters are found to be in line with those found in previous studies, with notable exceptions discussed below. First, the posterior mode and mean of investment adjustment costs are significantly smaller in both countries than what is typically found in the DSGE literature, but still higher than microeconomic estimates (see Groth and Khan (2010)). This might be due to internal propagation in the model, a point which I will turn back to later. Second, the estimated price rigidities display large differences across sectors in both countries, with service sector prices being more sticky than prices in other sectors. This is consistent with a number of microeconomic studies as discussed earlier (e.g. Bils and Klenow (2004)), and cannot be accounted for by one-sector models á la Smets and Wouters (2007). A low Calvo parameter in manufacturing is perhaps also related to the inclusion of construction firms in that sector, as Bouakez et al. (2009) find that US construction prices are perfectly flexible. Third, there is much less indexation to previous prices and wages in the Canada than in the US. This might have to do with the open economy dimension, as other parameters are fairly similar across countries. Also Justiniano and Preston (2010) report less indexation in Canada compared with the US. Finally, as in Lubik and Schorfheide (2007), I find some evidence of systematic response by monetary authorities to exchange rate fluctuations. Turning to the shock processes, we see that technology shocks are the most persistent, and that the most volatile disturbances in the model are productivity innovations in raw material sectors and marginal efficiency of investment shocks. Moreover, productivity is substantially less volatile in the foreign service sector, in line with results in Bouakez et al. (2009). Finally, note that data are uninformative about some parameters, in particular those associated with labor supply shocks.

4 Empirical results

So far I have presented an estimated multi-sector DSGE model for SOEs. This section documents the main empirical finding from the estimated model – the significance of foreign business cycle shocks for macroeconomic fluctuations in Canada. I restrict attention to Canadian GDP, consumption, investment, hours, CPI inflation, real wages, net exports, and the policy rate. Table 4 reports the variance decomposition of domestic forecast errors (FEVDs) at different forecasting horizons. The first column shows the importance of all foreign innovations combined. Remaining columns report contributions of individual disturbances.[10] Three results stand out. First, at all horizons a substantial fraction of the forecast error is attributed to foreign shocks. Second, their role in the variance decomposition tends to build up over time. Third, while a cocktail of disturbances is responsible for macroeconomic fluctuations in the very short run, foreign productivity shocks stand out as the prominent source of long run volatility. These findings are discussed next.

[10] Shocks to the UIP condition are likely a mix of domestic and foreign events. Christiano et al. (2011) label UIP shocks as foreign, while Justiniano and Preston (2010) include them in the domestic block. I take a conservative view, and follow the latter definition throughout the analysis.

Table 4: Forecast error variance decomposition of foreign shocks (percent)

Variable	*All foreign shocks*	*Decomposition*							
		σ^*_{A1}	σ^*_{A2}	σ^*_{A3}	σ^*_{R}	σ^*_{I}	σ^*_{U}	σ^*_{N}	σ^*_{M}
		Panel A: 1 quarter horizon							
GDP	22.01	7.17	0.83	0.00	0.01	7.11	0.08	0.00	6.81
Consumption	11.68	5.74	3.46	0.46	0.09	0.59	0.12	0.00	1.22
Investment	22.30	8.78	7.22	0.73	0.08	2.50	0.25	0.00	2.75
Hours	17.50	1.42	3.71	0.49	0.01	11.46	0.39	0.00	0.01
Interest	37.36	11.53	11.56	1.67	0.80	5.35	0.53	0.00	5.93
Inflation	41.86	15.76	12.36	1.27	0.21	4.49	0.42	0.00	7.35
Wage	45.53	20.82	13.93	1.37	0.24	0.89	0.28	0.00	7.99
Trade balance	37.55	3.01	7.11	1.45	0.22	24.35	1.03	0.00	0.38
		Panel B: 4 quarter horizon							
GDP	48.30	23.31	14.86	1.46	0.16	1.81	0.12	0.00	6.58
Consumption	20.13	11.41	5.65	0.77	0.05	0.76	0.20	0.00	1.28
Investment	34.88	16.16	12.13	1.11	0.04	2.61	0.33	0.00	2.49
Hours	22.98	6.28	5.69	0.61	0.13	7.73	0.23	0.00	2.31
Interest	38.24	13.69	10.48	1.67	0.38	7.24	0.65	0.00	4.12
Inflation	41.44	15.79	11.87	1.24	0.23	4.64	0.46	0.00	7.21
Wage	49.83	27.12	15.84	1.74	0.10	0.34	0.29	0.00	4.39
Trade balance	33.80	1.91	2.83	0.60	0.15	26.48	0.79	0.00	1.04
		Panel C: 8 quarter horizon							
GDP	53.17	26.99	18.00	1.94	0.10	1.77	0.14	0.00	4.21
Consumption	19.93	11.90	5.08	0.74	0.04	1.11	0.15	0.00	0.92
Investment	38.45	19.31	13.44	1.09	0.03	2.45	0.27	0.00	1.86
Hours	29.19	10.35	8.72	0.94	0.12	6.60	0.23	0.00	2.23
Interest	36.56	12.46	10.56	1.49	0.37	6.51	0.60	0.00	4.57
Inflation	42.29	15.74	12.15	1.22	0.23	5.03	0.49	0.00	7.43
Wage	50.89	28.53	16.30	1.92	0.06	1.19	0.20	0.00	2.68
Trade balance	31.79	1.78	3.76	0.97	0.16	23.27	0.72	0.00	1.13
		Panel D: 20 quarter horizon							
GDP	63.17	29.47	22.91	2.07	0.08	5.43	0.10	0.00	3.10
Consumption	39.72	19.43	13.10	1.27	0.05	4.20	0.10	0.00	1.57
Investment	43.56	18.17	14.05	0.98	0.04	8.52	0.23	0.00	1.59
Hours	29.91	10.35	8.91	0.92	0.11	7.22	0.22	0.00	2.17
Interest	35.15	12.08	10.23	1.44	0.35	6.13	0.57	0.00	4.35
Inflation	42.98	16.04	12.46	1.30	0.23	5.14	0.48	0.00	7.33
Wage	65.20	31.99	23.14	2.22	0.06	5.66	0.12	0.00	2.02
Trade balance	33.23	2.12	4.39	1.23	0.14	23.46	0.70	0.00	1.19
		Panel E: Long run horizon							
GDP	73.77	29.76	30.50	2.27	0.08	8.63	0.10	0.00	2.42
Consumption	75.04	26.98	32.91	2.24	0.06	11.30	0.08	0.00	1.48
Investment	44.88	17.39	15.57	1.11	0.04	9.10	0.21	0.00	1.47
Hours	33.27	11.52	10.62	1.03	0.11	7.62	0.21	0.00	2.16
Interest	43.37	14.85	14.73	1.63	0.31	7.43	0.49	0.00	3.92
Inflation	46.70	17.05	14.74	1.42	0.22	5.92	0.45	0.00	6.91
Wage	82.15	31.63	35.31	2.53	0.06	10.95	0.10	0.00	1.56
Trade balance	32.07	1.99	4.45	1.26	0.13	22.42	0.65	0.00	1.17

Note: Calculated at the posterior mean. Note that when the forecasting horizon s becomes large, the contribution of a shock to the s step ahead forecast error converges to that shock's contribution to the unconditional volatility. Thus, Panel E reports each shock's contribution to long run volatility.

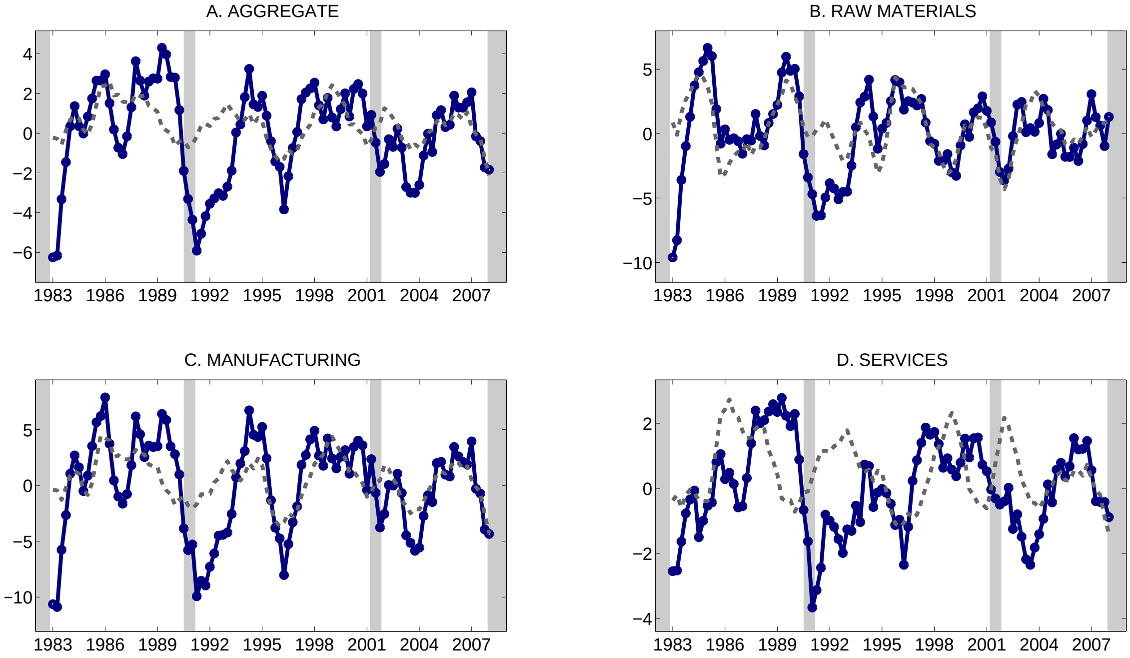
4.1 On the role of foreign shocks

Are foreign shocks important for macroeconomic volatility in small open economies? The model presented here answers "yes" when it is confronted with Canadian data. This is in line with ample empirical evidence. For instance, Kose et al. (2003) estimate a FAVAR model with separate world, region, and country specific factors. They report that the world and region factors combined explain about 45-75% of the volatility in Canadian GDP, consumption and investment. Similar results are obtained in VAR studies of different countries and sample periods, and with alternative identifying assumptions regarding shocks. Recent examples include Kose et al. (2008), Crucini et al. (2011), Mumtaz et al. (2011), and Kose et al. (2012). Estimated SOE-DSGE models, in contrast, have a hard time accounting for international business cycle transmission. Let us take GDP as an example: Justiniano and Preston (2010), using a benchmark model, find that foreign shocks explain about 1% of the fluctuations in Canadian GDP at all forecasting horizons. Adolfson et al. (2007) estimate a medium scale model on Swedish data, and report that foreign shocks explain between 9% (1 quarter) and 1% (20 quarters) of Swedish GDP.[11] Christiano et al. (2011) extend the Swedish model to include financial frictions and unemployment, and find that 8% of GDP is explained by a set of five foreign disturbances (including UIP shocks) within the 8 quarters horizon. The limited role for foreign shocks seems to hold also in DSGE models for large economies (see Jacob and Peersman (2013)).

The second result, that foreign variance shares are increasing in the forecasting horizon, is consistent with a number of empirical studies as well. Justiniano and Preston (2010) estimate a SUR model and report that foreign shocks explain 22% of Canadian GDP at the 1 quarter horizon, 44% at the 4 quarter horizon, and 76% in the long run. The numbers in Table 4 closely resemble those findings. Also Cushman and Zha (1997) and Aastveit et al. (2011) document higher foreign variance shares at longer horizons. However, the DSGE model allows us to take one step further and ask, within a structural framework, why foreign variance shares rise over time. The clue lies in estimated properties of TFP. **??** in the appendix reports the FEVD of domestic shocks. In the very short run (1 quarter), no single shock is the major driver of the selected set of macroeconomic variables. Rather, innovations to different variables are caused by different disturbances. For example, GDP is driven both by shocks to service productivity, the interest rate, and the marginal efficiency of investment (MEI). Consumption and investments are explained well by preference and MEI shocks respectively, while the trade balance is captured by risk premium and MEI shocks, as in Jacob and Peersman (2013). For the unconditional volatility of macroeconomic variables (the stationary forecast error), it is clear that productivity plays a major role. All foreign and domestic TFP shocks combined are responsible for about 70-80% of aggregate volatility in GDP, consumption and wages, and about half of the movements in inflation and interest rates.[12] Arguably, the increasing importance of foreign productivity over time can be traced to the estimated AR(1) process for TFP. Productivity innovations are relatively long lasting events, explaining why they account for substantial shares of the forecasting errors at longer horizons. The fundamental question is why data prefer productivity driven business cycles. Section 5 sheds light on the issue by inspecting transmission channels and propagation mechanisms at play.

[11] These numbers are found in a working paper version, see Adolfson, Laséen, Lindé, and Villani (2005).
[12] Similar results are found for the US variables (not shown).

Figure 1: GDP in data and in the model with only foreign shocks



Note: GDP in data (blue) and in smoothed counterfactual series excluding domestic shocks (gray). Counterfactuals are calculated based on the posterior mean. Shaded bars denote NBER defined US recessions.

As an illustration of the importance of international business cycle spillover, Figure 1 plots quarterly Canadian GDP in data and in the model when only foreign shocks are included. Consider first aggregate GDP. A significant share of the movements is explained by foreign shocks, and their importance rise over the sample as the initial discrepancy caused by pre-sample conditions dies out. Further decomposition into sectoral variables suggests a tendency of more variation being explained by foreign disturbances in the raw material sector than in manufacturing, while manufacturing seems more prone to foreign shocks than services.[13]

4.2 A note on exchange rate pass-through

Exchange rate pass-through is defined as the response of prices to a change in the nominal exchange rate. High pass-through implies transmission of international business cycle shocks via the exchange rate channel. However, empirical studies suggest only a weak link between domestic prices and exchange rate fluctuations – a partial exchange rate disconnect. This is also true in the model presented here. Yet, I will argue that *sectoral differences* in exchange rate pass-through, coupled with the use of intermediate goods in production, greatly facilitates international spillover.

This section documents the degree of pass-through implied by the estimated model. To this end I calculate price responses to a UIP shock. Arguably this shock is exogenous

[13] The figure indicates that the two largest recessions in the sample, those in 81-82 and 90-92, had little to do with international events. Foreign shocks in the first case are probably hidden in pre-sample conditions. In the latter case the recession was indeed far more severe in Canada, see Voss (2009) and Cross (2011).

Table 5: Short run pass-through rates (scaled by 100)

Price measure	π_t	π_t^i	$\pi_{j,t}$	$\pi_{Fj,t}$	$\pi_{Hj,t}$	$\pi^*_{Hj,t}$	$\pi^m_{j,t}$	$\tau_{j,t}$
Aggregate	12.70	26.48	–	–	–	–	–	–
Raw materials	–	–	35.64	65.15	14.08	31.99	23.96	-33.17
Manufacturing	–	–	29.79	53.91	16.99	36.12	26.40	-17.79
Services	–	–	4.10	7.85	3.92	78.41	13.27	70.56

Note: Pass-through rates scaled by 100, calculated based on the posterior mean. $\pi^*_{Hj,t}$ in the table is expressed in terms of domestic currency, in contrast to the text.

to model fundamentals, making it comparable with exchange rate fluctuations analyzed in reduced form studies. Results are shown in Table 5, where price responses are expressed relative to the exchange rate innovation (i.e. $\Delta price_t/\Delta e_t$). On impact, a one percent shock to the risk premium causes the nominal exchange rate to depreciate by about 3.41%, while inflation rises by 0.43%. Short run pass-through to CPI inflation follows as $\frac{\Delta \pi_t}{\Delta e_t} = 12.7\%$. The corresponding pass-through to aggregate investment prices is 26.5%. Aggregate results mask significant sector heterogeneity: Pass-through to sectoral market prices (third column) is 35.6% in raw materials and 29.8% in manufacturing, compared with only 4.1% in services. In turn, these numbers are weighted averages of inflation in imported and domestically produced goods' prices. The exchange rate depreciation reduces the mark-up of importing firms. Their desire to stabilize the mark-up causes higher imported inflation (fourth column). This is standard. What is less standard, is the significant pass-through to prices on domestically produced goods (fifth column). This comes about from trade in materials, as some of the exchange rate depreciation passes through to material prices (seventh column). The resulting drop in domestic firms' mark-up and leads to higher domestic inflation. The exchange rate effect on $\pi_{Hj,t}$ adds to overall pass-through and can be high if domestic prices are changed frequently. More generally, the model predicts an inverse relationship between price stickiness and pass-through because firms with frequent price changes are more likely to respond to the exchange rate. This explains the bulk of pass-through variation across sectors. High pass-through to flexible prices is also a robust feature in data, as shown by Gopinath and Itskhoki (2010).

Without stretching the results too far, a brief comparison with empirical pass-through regressions is warranted. Campa and Goldberg (2005) estimate the short run (quarterly) exchange rate pass-through to aggregate import prices in Canada, and find an elasticity of 75%. Gopinath et al. (2010) report a lower number, about 35%. Table 5 provides results somewhere in between, about 54-65% in the trade intensive sectors manufacturing and raw materials. Finally, Goldberg and Campa (2010) estimate pass-through elasticities of the CPI in 21 developed economies (Canada is not included) and find an average elasticity of about 15%. The way in which sectoral differences facilitates international transmission of shocks is analyzed next.

5 Transmission Channels

In this section I describe the mechanisms leading to transmission of business cycle fluctuations across countries, and analyze the role of different shocks. First I point out an important feedback loop that comes about from the intersectoral linkages. It's main implication is synchronization of firms' mark-up across sectors and countries. In turn, mark-up synchronization leads to co-movement of domestic and foreign prices and quantities, a key feature of data. Shocks that generate mark-up synchronization are good candidates for international business cycle co-movement, and favored by the likelihood based estimation procedure. First, I describe these mechanisms in more detail. Second, I study impulse responses to shed light on the dynamic effects of different shocks.

5.1 THE ROLE OF INTERMEDIATE TRADE AND SECTOR HETEROGENEITY

To better understand how intermediate trade and sector heterogeneity change spillover from international business cycles to the SOE, I proceed in three steps. First, note that laws of motion for domestic producer prices ($p_{rHj,t}$ and $p^*_{rHj,t}$) in sector j can be written as below (prices on goods sold domestically and exported, respectively):

$$\begin{aligned} p_{rHj,t} &= \theta_{pj}\left(p_{rHj,t-1} - \pi_t + \iota_p \pi_{Hj,t-1}\right) + \left(1-\theta_{pj}\right)\bar{p}_{rHj,t} \\ p^*_{rHj,t} &= \theta_{pj}\left(p^*_{rHj,t-1} + \Delta e_t - \pi_t + \iota_p \pi^*_{Hj,t-1}\right) + \left(1-\theta_{pj}\right)\bar{p}^*_{rHj,t} \end{aligned} \tag{27}$$

Both prices above are quoted in domestic currency and in terms of consumption goods. The two equations state that prices on domestically produced goods are linear combinations of the lagged price level (and some terms associated with indexation and exchange rate changes) and the new prices set by firms who re-optimize in the current period, $\bar{p}_{rHj,t}$ and $\bar{p}^*_{rHj,t}$. If optimal new prices rise, we get inflationary pressure on the sector averages $p_{rHj,t}$ and $p^*_{rHj,t}$ as well. The second step is to note that the forward-looking nature of the dynamics described above is captured by two optimality conditions for newly set prices (mark-up shocks are abstracted from):

$$\begin{aligned} \bar{p}_{rHj,t} &= p_{rHj,t} + \left(1-\beta\theta_{pj}\right)\mathbb{E}_t \sum_{s=t}^{\infty} \left(\beta\theta_{pj}\right)^s \left(rmc_{j,s} - p_{rHj,s}\right) \\ \bar{p}^*_{rHj,t} &= p^*_{rHj,t} + \left(1-\beta\theta_{pj}\right)\mathbb{E}_t \sum_{s=t}^{\infty} \left(\beta\theta_{pj}\right)^s \left(rmc_{j,s} - p^*_{rHj,s}\right) \end{aligned} \tag{28}$$

These two equations show that the profit maximizing price, from the individual firm's point of view, is a linear combination of i) the sector specific average and ii) current and expected future deviations in the price mark-up over marginal costs. In the limit as θ_{pj} goes to zero, the expectation sums disappear.[14] However, when $\theta_{pj} > 0$, then all innovations that increase (decrease) real marginal costs relative to producer prices cause temporary upward (downward) pressure on $\bar{p}_{rHj,t}$ and $\bar{p}^*_{rHj,t}$. This takes us to the third step, the introduction of intermediate trade and sector heterogeneity. The linearized real marginal cost in sector j can be written as follows:

$$rmc_{j,t} = -z_{Aj,t} + \phi_j \sum_{l=1}^{\mathcal{J}} \zeta_{lj} p_{rl,t} + \psi_j \omega_{j,t} + \left(1-\phi_j-\psi_j\right) r^k_t$$

[14] Optimal prices without price setting rigidities and mark-up shocks are $p_{rHj,t} = p^*_{rHj,t} = rmc_{j,t}\ \forall\, t$.

$$= -z_{Aj,t} + \phi_j \sum_{l=1}^{\mathcal{J}} \zeta_{lj} \left[\alpha_l p_{rHl,t} + (1-\alpha_l) p_{rFl,t}\right] + \psi_j \omega_{j,t} + (1-\phi_j-\psi_j) r_t^k \tag{29}$$

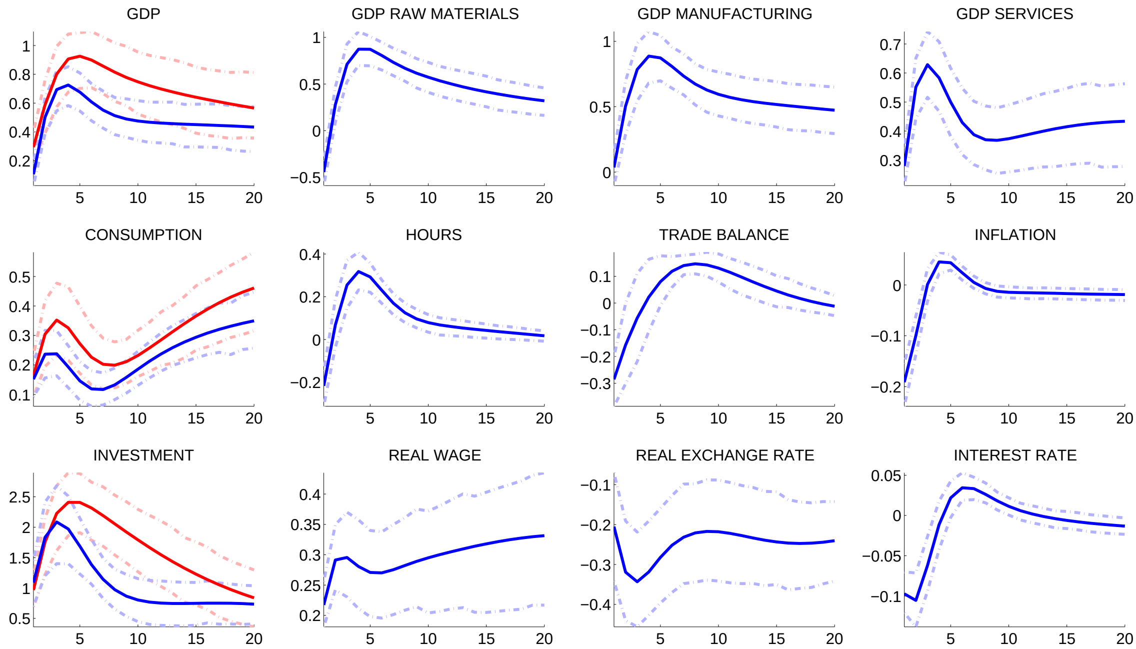
The first line shows that costs are directly affected by market prices $p_{rl,t}$ in all domestic industries $l \in \mathcal{J}$, because intermediate trade takes place across sectors. The second line demonstrates that costs depend on import prices $p_{rFl,t}$, set by firms in foreign sectors. This is true as long as the domestic absorption parameters α_j are less than one. Importantly, $p_{rFl,t}$ can be represented by a system similar to (27)-(29). Thus, shocks that affect sectoral marginal costs in the foreign economy will in principle show up in equation (29). Three important observations immediately follow from the system (27)-(29). First, intermediate trade introduces co-movement between domestic and foreign producer prices. That is, a rise (fall) in any import price $p_{rFl,t}$ directly reduces (increases) the mark-up of domestic firms (equation (29)), resulting in rising (declining) domestic producer prices $p_{rHj,t}$ and $p^*_{rHj,t}$. Second, the model features an important feedback loop. That is, the first round rise (fall) in $p_{rHj,t}$ further increases (reduces) domestic sector j's costs, because $p_{rHj,t}$ shows up in (29). There is a similar feedback loop involving foreign producer prices and foreign marginal costs. Third, the initial impulse propagates across sectors as long as $\zeta_{lj} > 0$ for some $l \neq j$. Thus, foreign shocks can hit some industries in the SOE, notably those with high trade intensity, and then propagate to others via intermediate trade. The latter kind of spillover is governed by the off-diagonals of the I-O matrix, and allows even relatively non-traded sectors to be affected by international disturbances. The setup presented here nests as special cases some common approaches in the literature, including models with i) one sector ($\mathcal{J} = 1$),[15] ii) no intermediate trade ($\phi_j = 0$), and iii) no foreign trade ($\alpha_j = 1$). However, all these dimensions matter for the transmission of foreign shocks. Obviously, if $\alpha_j = 1 \; \forall \; l \in \mathcal{J}$, then economic activity in the SOE is completely unrelated to the rest of the world. If $\phi_j = 0$, then there is one less source of co-movement in producer prices (the one described above), and hence one less mechanism that induces business cycle spillover. If $\mathcal{J} = 1$, then the entire transmission has to take place at the aggregate level without sectoral reallocations. In contrast, the multi-sector model presented here allows industries with limited trade to be affected via cross-sectoral intermediate market linkages. Thus, even fluctuations in completely non-traded industries can in principle be driven by business cycle shocks abroad.

5.2 The scope for international synchronization

To better understand the role of foreign disturbances for domestic business cycles, I analyze the impulse responses of domestic variables to selected international shocks. I explain why foreign productivity shocks generate business cycle co-movement, how foreign investment shocks create a wedge between domestic and foreign investment, and argue that the multi-sector setup facilitates higher pass-through than what is typically found in models with LCP.

[15] Or alternatively, no (ex ante) sector heterogeneity ($\phi_j = \phi$, $\gamma_{lj} = \gamma$, $\alpha_j = \alpha$).

Figure 2: A productivity shock in foreign manufacturing



Note: Foreign (red) and domestic (blue) Bayesian impulse responses to a productivity shock in foreign manufacturing (one standard deviation). Posterior mean (solid) and 90% highest posterior probability intervals (dotted). The trade balance is in absolute deviations from steady state relative to GDP.

5.2.1 Dynamic effects of productivity shocks

A productivity shock in the foreign manufacturing sector is plotted in Figure 2. Productivity innovations in the US manufacturing sector are essential for understanding macroeconomic fluctuations in the SOE, according to Table 4. One thing to note from Figure 2 and figures in the appendix is the striking co-movement in aggregate responses across countries in both GDP, consumption and investment. What is going on here? Consider first the foreign IRFs. As expected, higher foreign productivity raises foreign GDP, consumption, and investment. The set of frictions in the model, in particular sticky prices and monopolistic competition, also implies less working hours and a lower foreign interest rate (see **??**). All these effects are well known from the textbook one-sector, closed economy model. However, cheaper manufactured goods in the foreign economy not only lead to expenditure switching towards that sector, but also to cheaper manufactured intermediates. This latter effect reduces costs and prices in the other foreign industries as well, and therefore creates the feedback loop emphasized by e.g. Acemoglu, Carvalho, Ozdaglar, and Tahbaz-Salehi (2012). Regarding spillover to the SOE, note first that lower prices on manufacturing imports induce expenditure switching in that sector towards imports. While this kind of expenditure switching helps in generating co-movement between domestic and foreign absorption of manufactured (sector j) goods, it is contractionary from the point of view of domestic sector j firms. In a one-sector world, the substitution towards imports is basically be the main spillover effect. This is why previous models find little co-movement in GDP, hours, and other supply side variables across countries.

In contrast, the multi-sector structure presented here provides us with a rich story about additional mechanisms at work. First, lower imported inflation in the domestic manufacturing sector implies lower overall inflation in manufactured prices, relative to prices from other industries. This creates domestic substitution towards all manufactured goods, including those that are produced domestically. The sectoral substitution effect is expansionary from the point of view of domestic manufacturing firms. Second, the cheaper manufactured goods also reduce domestic firms' expenditures on intermediate goods. This is seen from equation (29). In fact, producer costs decline in all domestic industries because also non-manufacturing producers use manufactured goods extensively as input. Profit maximizing behavior then induces domestic firms across the economy to reduce their prices, and overall domestic inflation declines even further. That triggers another round of cheaper intermediate goods, and another round of price reductions, and so on. The interest rate naturally declines as well. Domestic prices are not perfectly adjusted, so some of the increased productivity is materialized as lower demand for labor – a well known outcome in New Keynesian models. Thus, total hours decline in the domestic economy the first periods. Cheaper domestic goods also limit the initial expenditure switching towards imports, implying further domestic expansion in demand for consumption and investment goods. For domestic producers, substitution towards imports and cost reduction are two forces that push in opposite directions. Their relative importance in each sector depends on the sectoral trade intensity, the degree of price stickiness, and the share of intermediate inputs in production. In total, the increase in foreign manufacturing productivity generates relatively large dynamics in the SOE. Part of the reason is the high trade intensity in the manufacturing sector. Another point is that manufactured goods prices are much less sticky than service prices, implying that they react more following the shock. Also, manufactured goods are important inputs in services, the largest sector in the economy.

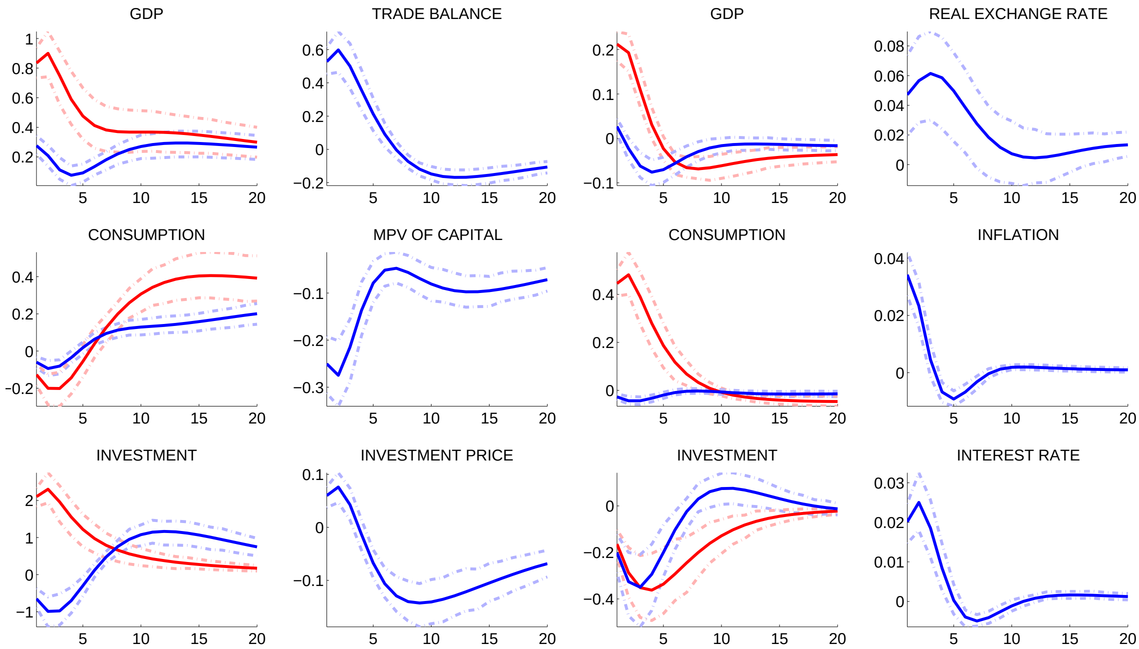
5.2.2 Dynamic effects of investment shocks

Next I describe effects of a shock to the marginal efficiency of investment (MEI) in the foreign economy. The goal is to understand why estimated DSGE models for closed economies have attributed larger macroeconomic fluctuations to this shock than what I find here. Figure 3 plots the IRFs. The MEI shock temporarily increases the amount of capital transformed from each investment unit, and thereby raises the relative return to capital investments. This induces foreign households to invest more, and cut back on consumption the first periods due to resource constraints (see Furlanetto, Natvik, and Seneca (2013) for an analysis of this issue). The net effect is still a positive shift in aggregate demand, leading to upward inflation pressure. After some periods the investments start to pay off in form of capital abundance in the foreign economy, leading to a prolonged period with higher consumption demand as well.

In the SOE, the foreign MEI shock generates responses in GDP, consumption, hours, interest rate and inflation that are qualitatively similar to those in the foreign economy. That is, due to higher imported inflation, overall price level and the interest rate in the SOE increase. This reduces domestic consumption demand and makes production more expensive. Yet, high foreign investment demand is expansionary for domestic raw material and manufactured goods producers, who export investment goods intensively.

Still, the MEI shock cannot explain all international synchronization patterns – it

Figure 3: Foreign demand shocks



Note: Foreign (red) and domestic (blue) Bayesian impulse responses to i) a foreign MEI shock (columns 1-2) and ii) a foreign preference shock (columns 3-4). Posterior mean (solid) and 90% highest posterior probability intervals (dotted). The trade balance is in absolute deviations from steady state relative to GDP.

causes strong divergence between investment in the two countries. To see why, note that domestic absorption of investment goods from sector j can be written as follows:

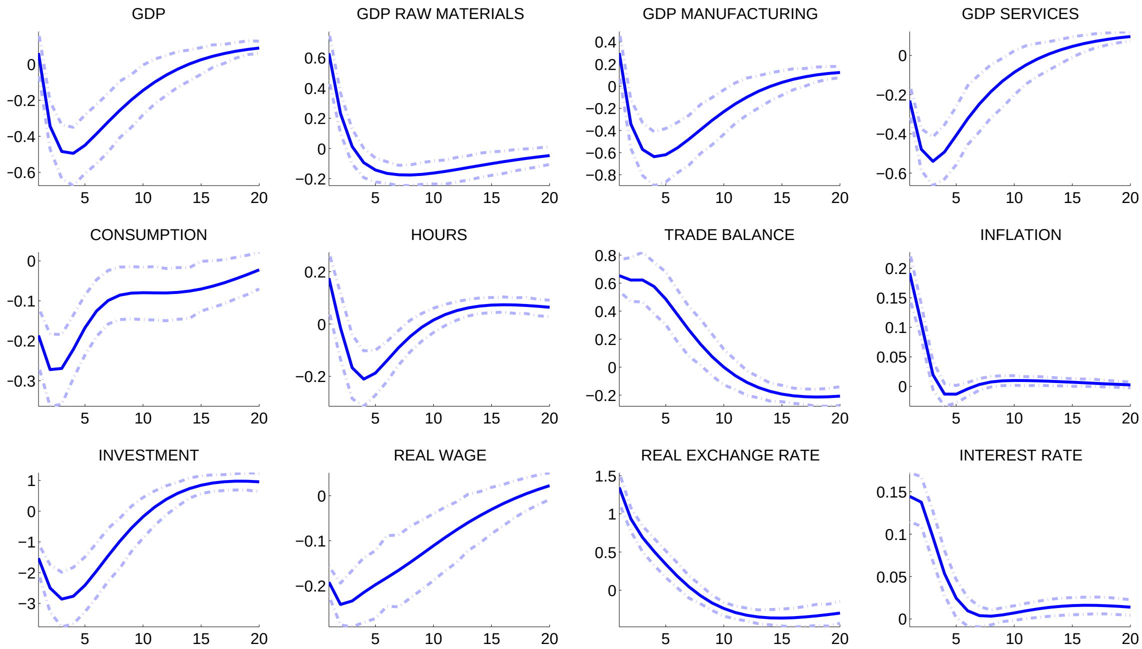
$$i_{j,t} = -\nu \left(p_{rj,t} - p^i_{r,t}\right) + i_{t-1} + \frac{1}{\epsilon_I}\mathbb{E}_t \sum_{s=t}^{\infty} \beta^{s-t} \left(q_s - p^i_{r,s}\right) \tag{30}$$

Equation (30) shows that $i_{j,t}$ is linked to the relative sector price $p_{rj,t}$, and via aggregate investment demand, to the expected path for real returns to investments, $\left\{q_s - p^i_{r,s}\right\}_{s=t}^{\infty}$.[16] Intuitively, when the value of current and future capital exceeds the cost of capital accumulation, sectoral and aggregate investment demand is high. Investment co-movement across countries is therefore stimulated by synchronization of expected capital returns. However, in the case of a foreign MEI shock, higher import prices in the SOE raises $p^i_{r,t}$, while higher real interest rates reduce the present value of installed capital.[17] This lowers domestic sectoral and aggregate investment demand, and generates a wedge between domestic and foreign investment activity that is not typically seen in the data. At the same time, some of the increase in foreign demand is targeted towards domestic goods, in particular those who can be transformed into capital abroad. The result is a large improvement in trade balances, and higher aggregate GDP. Also, domestic demand towards

[16] Investment adjustment costs are priced into $p^i_{r,t}$. Without adjustment costs, equation (30) collapses to $q_s + z_{I,s} = p^i_{r,s}\ \forall\, s$.

[17] The link between q_t and real interest rates is found by solving the linearized optimality condition for capital forward to obtain $q_t = E_t \sum_{s=t}^{\infty} \left(\beta\left(1-\delta\right)\right)^{s-t} \left[-\left(r_s - \pi_{s+1}\right) + \left(1 - \beta(1-\delta)\right) r^k_{s+1}\right]$. Thus, an increase in current or future expected real interest rates reduce the value of capital.

Figure 4: A risk premium shock



Note: Domestic Bayesian impulse responses to a UIP shock (one standard deviation). See Figure 2 for details.

domestic goods goes up, due to relatively cheaper home products. Taken together, the foreign MEI shock is able to generate co-movement between several domestic and foreign variables, but not between domestic and foreign investment. This latter point implies that the posterior weight on foreign MEI shocks is smaller, although they still explain important parts of several domestic variables.

5.2.3 Risk premium shocks and exchange rate pass-through

The empirical section established that exchange rate pass-through to import prices and the CPI is moderate, with large sectoral differences depending on the degree of price flexibility in each industry. Next I investigate these results in more detail. Insights can be found if we study the responses of a shock to the risk premium on foreign bonds. As argued earlier, this shock should be exogenous to model fundamentals, making it comparable to exchange rate shocks analyzed in empirical studies. Impulse responses to the risk premium shock are provided in Figure 4. On impact, a shock which raises the risk premium causes the nominal exchange rate to depreciate, while inflation rises moderately at the aggregate level, with sectoral price responses depending on the frequency of price adjustment.

The intuition is as follows: Higher risk premium raises demand for foreign bonds, and thereby reduces the value of domestic currency in nominal terms. This is seen from the linearized no arbitrage condition, which writes as

$$r_t = r_t^* + \mathbb{E}_t\left(\Delta e_{t+1}\right) - \epsilon_B nfa_t + z_{B,t}.$$

Clearly, following a rise in $z_{B,t}$ there must be a contemporaneous depreciation unless the monetary authority pegs the exchange rate.[18] Due to LCP, weaker currency in the SOE then directly reduces foreign firms' export income and profits. This is seen from the marginal income of foreign exporters under LCP, which is $p_{Fj,t} - e_t$ at the sector level. These firms react by raising their export prices. The result is higher imported, and thus higher overall domestic inflation. This is what we define as exchange rate pass-through.

Two forces in the model limit the pass-through to domestic prices. First, the presence of price stickiness reduces pass-through to import prices, as only a subset of the foreign exporters can adjust their prices optimally. Indeed, when $\theta^*_{pj} \rightarrow 1$ the pass-through becomes zero. In one-sector New Keynesian models with LCP, the presence of price stickiness typically leads to less pass-through than suggested by empirical literature (Gopinath et al., 2010). Second, as households now find it more profitable to save abroad, they lower consumption and investment demand to reallocate resources towards foreign bonds. The decline in domestic absorption is seen in Figure 4. Lower consumption demand is particularly relevant for service firms, who supply most domestic consumption goods. The drop in investment demand on the other hand affects GDP in the manufacturing sector, which produce most investment goods. In fact, the aggregate decline in domestic absorption is large enough to lower GDP in these two sectors.[19] Most importantly, it puts downward pressure on both domestic producer prices and import prices, and thus limits exchange rate pass-through. Taken together, the combination of LCP and contraction in domestic absorption should lead to small or even negative pass-through rates in the SOE.

Sector heterogeneity modifies the pass-through story outlined above. As seen in Table 5, we have relatively high pass-through in the sectors with frequent price changes. In the model, this relationship comes about from the simple observation that firms who re-optimize prices frequently, have higher probability of responding optimally to the exchange rate depreciation. As the optimal sector price equates $p_{Fj,t} - e_t$ with marginal costs, $p_{Fj,t}$ will rise more aggressively when price stickiness is low. Moreover, CPI measures in raw materials and manufacturing put high weights on the import price $p_{Fj,t}$, adding to the positive pass-through in these industries. The presence of intermediate trade further increases pass-through rates: Higher imported inflation drives up producer costs among those firms who import intermediate goods, and thus puts upward pressure on domestic producer prices. Again, this cost channel is particularly important for the trade intensive raw material and manufacturing firms. This explains why pass-through to both imported and domestic producer price inflation is relative high in these sectors. Moreover, cross-sectoral linkages in domestic intermediate markets allow exchange rate fluctuations to spill over to marginal costs of domestic service firms as well. Thus, both the existence of firms with relatively flexible prices, and the presence of intermediate trade channels in the model, help to increase the pass-through to domestic prices. This is consistent with the empirical work by Goldberg and Campa (2010), who find that intersectoral linkages are the most important source of exchange rate pass-through to the domestic CPI.

Table 6: Counterfactual model – Business cycle predictions

	Panel A: $100\rho_{y,y^*}$	Panel B: 1Q	4Q	8Q	20Q	LR	Panel C: $\Delta\pi/\Delta e$	
GDP	27.4	1.89	3.11	3.52	6.22	10.33	π_t	7.86
Consumption	34.8	0.94	1.22	1.93	5.47	16.43	$\pi_{F,t}$	36.77
Investment	3.2	1.37	1.37	1.28	2.69	3.42	$\pi_{H,t}$	-2.27
Hours	9.1	1.72	2.15	2.18	2.26	2.36	$\pi^*_{H,t}$	57.55
Interest	17.6	3.73	3.08	3.04	3.00	4.02	τ_t	20.78
Inflation	14.9	2.76	2.60	2.64	2.70	3.03		
Wage	39.3	4.50	4.30	5.31	10.34	19.17		
Trade balance	–	8.14	10.03	10.17	10.21	10.16		

Note: See Table 4 and Table 5 for details.

6 THE COUNTERFACTUAL MODEL ECONOMY

This paper analyzes the role of foreign shocks in a model with intermediate trade between heterogeneous firms. In this section I ask whether the role of international business cycles survives in a context without these extensions to the conventional open economy DSGE model. To this end, I estimate the particular version of the model when $\mathcal{J} = 1$ and $\phi = 0$. The model now becomes a fairly standard DSGE model for a small open economy.[20] Calibrated values are set as follows: First, I rescale labor and capital shares in both economies to keep the constant returns to scale assumption based on the numbers in Table 2. This gives $\psi = 0.543$. Second, I calibrate trade shares in GDP by subtracting the intermediate input share of imports in each sector, and then calculating aggregate (sector GDP weighted) import share in the economy. The resulting import share in GDP is 0.26 ($\alpha = 0.7405$). The remaining calibrated values are chosen as before. Also the prior distributions are as in the baseline model, except that price and wage stickiness have prior modes equal to 0.7, while the aggregate TFP shock has a mode equal to 0.2.

Business cycle predictions from the counterfactual model (based on posterior mean estimates) are provided in Table 6. Parameter estimates are reported in the appendix. Consider first model implied cross-country correlations (Panel A). For all variables under consideration, they fall to less than half of those in the baseline model. The decline is particularly large for investment. Still, the degree of co-movement is higher than that found by Justiniano and Preston (2010), and international consumption synchronization actually comes fairly close to that in data. Part of difference from Justiniano and Preston (2010) is attributed to the inclusion of investment, which is abstracted from in their study. When higher foreign productivity takes down international prices, domestic investment (and capital) is stimulated by cheaper imports.

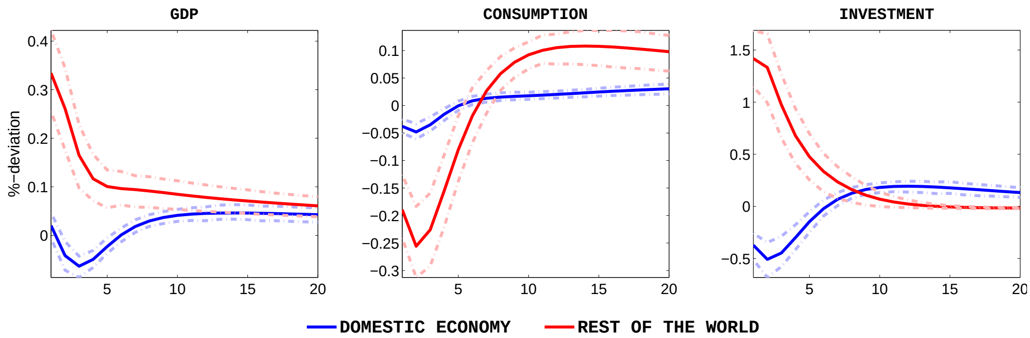
Turning to the decomposition of shocks (Panel B), we see that foreign shocks become nearly irrelevant for most domestic variables within the business cycle. They explain less than 7% of the variation in all variables except wages and the trade balance within the

[18] The SOE assumption implies that foreign variables, including r_t^*, do not change.

[19] Yet, the drop in total GDP is muted, because the accumulation of foreign assets is financed by a trade surplus driven by exports of raw materials and manufactured goods.

[20] Obviously, one counterfactual implication of this model version is the symmetric response of all firms within countries to all kinds of business cycle shocks. Bouakez et al. (2009) analyze implications of imposing such symmetry in a closed economy setting.

Figure 5: Impulse responses to a foreign MEI shock in the counterfactual model



Note: See Figure 2 for details.

5-year horizon. This is bout one tenth of the shares attributed to foreign shocks in the baseline model (Table 4). In the long run, foreign shocks account for about 2-20% of the macroeconomic volatility in the SOE, far below typical estimates in the VAR literature. Implied pass-through rates are provided in Panel C. The short run pass-through to CPI drops from 12.4% to 7.9% – still a fairly high number given that exporters in the model price their goods in local currency. The main reason is the estimated low degree of price stickiness, with a posterior centered around 0.5. In order to illustrate the limited role of foreign shocks in the counterfactual model, Figure 5 plots the impulse responses to a foreign MEI shock. As before we get a drop in domestic consumption and investment. However, unlike before we also get a drop in domestic GDP. The intuition is straight forward: Without intermediate trade, the increase in foreign investment demand does not call for more exports of materials. Instead, the main transmission channel to domestic GDP is via a higher domestic real interest rate, which lowers domestic consumption and investment demand. Thus, without intermediate trade, the foreign MEI shock cannot even explain international co-movement in GDP. Finally, note that the negative effect on foreign consumption is amplified in the one-sector model, a reasonable result given that consumption and investment now are close substitutes.

7 Conclusions

I ask how and to what extent international business cycle disturbances cause macroeconomic fluctuations in small open economies. To shed some light on these questions, I construct and estimate a medium scale small open economy model with several shocks and frictions typically used in the DSGE literature. The model is embedded with i) trade in intermediate goods between firms, and ii) sectoral producer heterogeneity. These extensions to the workhorse one-sector open economy model are sufficient to reconcile DSGE theory with data along international dimensions. When the model is fitted to Canadian and US data, a set of important empirical results emerge: First foreign shocks explain a major share of macroeconomic fluctuations in the SOE. Second, posterior estimates emphasize the role of productivity, in the sense that technology shocks, not investment efficiency fluctuations, are the major drivers of business cycles. Third, foreign shocks become increasingly important over longer forecasting horizons. Fourth, the model generates substantial business cycle synchronization, even though trade balances are countercyclical and shocks are uncorrelated. Fifth, exchange rate pass-through is moderate, with sectoral pass-through depending on the frequency of price changes. While these results are consistent with reduced form literature such as VAR and FAVAR studies, they are typically not found in the literature using open economy DSGE models.

The model presented here allows us to gain insight about the mechanisms that cause these results. An important implication of intermediate trade is that it synchronizes producer prices and costs in the cross-section of firms, both within and across borders. This helps in generating co-movement in an environment with producer heterogeneity and otherwise segmented markets. Foreign shocks in particular can enter the SOE through some industries exposed to international trade, and then propagate to others via domestic factor markets. Synchronized producer prices across sectors and countries generate substantial international co-movement in i) current and future real interest rates, which determines consumption, and ii) the expected path of capital returns, a key statistic for investment decisions. However, synchronization of real interest rates comes at the cost of too high consumption co-movement across countries. I find that foreign technology shocks are particularly well suited for international business cycle synchronization. These are also relatively persistent, an important reason why foreign shocks become essential at longer forecasting horizons. Foreign investment efficiency shocks on the other hand cause international divergence in the present value of capital and investment. Investment is positively correlated across countries, implying that the likelihood based estimation procedure attributes a smaller role to investment efficiency shocks.

One obvious limitation with the present model is the lack of meaningful interactions between financial markets and the macroeconomy. Indeed, the recent financial crisis has demonstrated the potential importance of financial frictions for international business cycles. By now, there is a large (an growing) literature on financial frictions in closed economies. Yet, for many, if not most small open economies, the recent financial crisis was associated with foreign events. Therefore, a topic for future research is the propagation of financial distress across countries, e.g. an open economy extension of the market frictions studied by Christiano, Motto, and Rostagno (2014). However, for such an analysis to make sense, one should be equipped with a model that can account for macroeconomic spillover as well. This paper offers a preliminary, but instructive step towards that end.

REFERENCES

Aastveit, K. A., H. C. Bjornland, and L. A. Thorsrud (2011). The world is not enough! Small open economies and regional dependence. Working Paper 2011/16, Norges Bank.

Acemoglu, D., V. M. Carvalho, A. Ozdaglar, and A. Tahbaz-Salehi (2012). The network origins of aggregate fluctuations. *Econometrica 80*(5), 1977–2016.

Adolfson, M., S. Laséen, J. Lindé, and M. Villani (2005). Bayesian estimation of an open economy DSGE model with incomplete pass-through. Working Paper Series 179, Sveriges Riksbank (Central Bank of Sweden).

Adolfson, M., S. Laséen, J. Lindé, and M. Villani (2007). Bayesian estimation of an open economy DSGE model with incomplete pass-through. *Journal of International Economics 72*(2), 481–511.

Adolfson, M., S. Laséen, J. Lindé, and M. Villani (2008). Evaluating an estimated New Keynesian small open economy model. *Journal of Economic Dynamics and Control 32*(8), 2690–2721.

An, S. and F. Schorfheide (2007). Bayesian analysis of DSGE models. *Econometric reviews 26*(2-4), 113–172.

Atalay, E. (2013). How important are sectoral shocks? Manuscript.

Bergholt, D. and T. Sveen (2014). Sectoral Interdependence and Business Cycle Synchronization in Small Open Economies. *Norges Bank Working Paper Series 2014*(04).

Bils, M. and P. J. Klenow (2004). Some evidence on the importance of sticky prices. *Journal of Political Economy 112*(5), 947–985.

Bouakez, H., E. Cardia, and F. J. Ruge-Murcia (2009). The transmission of monetary policy in a multisector economy. *International Economic Review 50*(4), 1243–1266.

Calvo, G. A. (1983). Staggered prices in a utility-maximizing framework. *Journal of Monetary Economics 12*(3), 383–398.

Campa, J. M. and L. S. Goldberg (2005). Exchange rate pass-through into import prices. *The Review of Economics and Statistics 87*(4), 679–690.

Christiano, L. J., M. Eichenbaum, and C. L. Evans (2005). Nominal rigidities and the dynamic effects of a shock to monetary policy. *Journal of political Economy 113*(1), 1–45.

Christiano, L. J., R. Motto, and M. Rostagno (2014). Risk shocks. *American Economic Review 104*(1), 27–65.

Christiano, L. J., M. Trabandt, and K. Walentin (2011). Introducing financial frictions and unemployment into a small open economy model. *Journal of Economic Dynamics and Control 35*(12), 1999–2041.

Corsetti, G., L. Dedola, and S. Leduc (2008). International risk sharing and the transmission of productivity shocks. *The Review of Economic Studies 75*(2), 443–473.

Cross, P. (2011). How did the 2008-2010 recession and recovery compare with previous cycles? Technical Report 1.

Crucini, M., A. Kose, and C. Otrok (2011). What are the driving forces of international business cycles? *Review of Economic Dynamics 14*(1), 156–175.

Cushman, D. O. and T. Zha (1997). Identifying monetary policy in a small open economy under flexible exchange rates. *Journal of Monetary Economics 39*(3), 433–448.

de Resende, C., A. Dib, and M. Kichian (2010). Alternative optimized monetary policy rules in multi-sector small open economies: The role of real rigidities. Working Papers 10-9, Bank of Canada.

Dib, A. (2011). Monetary policy in estimated models of small open and closed economies. *Open Economies Review 22*(5), 769–796.

Erceg, C. J., D. W. Henderson, and A. T. Levin (2000). Optimal monetary policy with staggered wage and price contracts. *Journal of Monetary Economics 46*(2), 281–313.

Furlanetto, F., G. J. Natvik, and M. Seneca (2013). Investment shocks and macroeconomic co-movement. *Journal of Macroeconomics, Elsevier 37*(C), 208–216.

Geweke, J. (1999). Using simulation methods for Bayesian econometric models: inference, development,and communication. *Econometric Reviews 18*(1), 1–73.

Goldberg, L. S. and J. M. Campa (2010). The sensitivity of the CPI to exchange rates: Distribution margins, imported inputs, and trade exposure. *The Review of Economics and Statistics 92*(2), 392–407.

Gopinath, G. and O. Itskhoki (2010). Frequency of price adjustment and pass-through. *The Quarterly Journal of Economics 125*(2), 675–727.

Gopinath, G., O. Itskhoki, and R. Rigobon (2010). Currency choice and exchange rate pass-through. *American Economic Review 100*(1), 304–36.

Groth, C. and H. Khan (2010). Investment adjustment costs: An empirical assessment. *Journal of Money, Credit and Banking 42*(8), 1469–1494.

Gust, C., S. Leduc, and N. Sheets (2009). The adjustment of global external balances: Does partial exchange-rate pass-through to trade prices matter? *Journal of International Economics 79*(2), 173–185.

Heathcote, J. and F. Perri (2002). Financial autarky and international business cycles. *Journal of Monetary Economics 49*(3), 601–627.

Jacob, P. and G. Peersman (2013). Dissecting the dynamics of the US trade balance in an estimated equilibrium model. *Journal of International Economics 90*(2), 302–315.

Justiniano, A. and B. Preston (2010). Can structural small open-economy models account for the influence of foreign disturbances? *Journal of International Economics 81*(1), 61 – 74.

Justiniano, A., G. Primiceri, and A. Tambalotti (2011). Investment shocks and the relative price of investment. *Review of Economic Dynamics 14*(1), 101–121.

Justiniano, A., G. E. Primiceri, and A. Tambalotti (2010, March). Investment shocks and business cycles. *Journal of Monetary Economics 57*(2), 132–145.

Justiniano, A., G. E. Primiceri, and A. Tambalotti (2013, April). Is there a trade-off between inflation and output stabilization? *American Economic Journal: Macroeconomics 5*(2), 1–31.

Kose, M. A., C. Otrok, and E. Prasad (2012). Global business cycles: Convergence or decoupling? *International Economic Review 53*(2), 511–538.

Kose, M. A., C. Otrok, and C. H. Whiteman (2003). International business cycles: World, region, and country-specific factors. *American Economic Review 93*(4), 1216–1239.

Kose, M. A., C. Otrok, and C. H. Whiteman (2008). Understanding the evolution of world business cycles. *Journal of International Economics 75*(1), 110–130.

Lubik, T. A. and F. Schorfheide (2007). Do central banks respond to exchange rate movements? A structural investigation. *Journal of Monetary Economics 54*(4), 1069–1087.

Mumtaz, H., S. Simonelli, and P. Surico (2011). International comovements, business cycle and inflation: a historical perspective. *Review of Economic Dynamics 14*(1), 176–198.

Nakamura, E. and J. Steinsson (2008). Five facts about prices: A re-evaluation of menu cost models. *The Quarterly Journal of Economics 123*(4), 1415–1464.

Rabanal, P. and V. Tuesta (2010). Euro-dollar real exchange rate dynamics in an estimated two-country model: An assessment. *Journal of Economic Dynamics and Control 34*(4), 780–797.

Schmitt-Grohé, S. (1998). The international transmission of economic fluctuations:: Effects of U.S. business cycles on the Canadian economy. *Journal of International Economics 44*(2), 257–287.

Schmitt-Grohé, S. and M. Uribe (2003). Closing small open economy models. *Journal of International Economics 61*(1), 163 – 185.

Smets, F. and R. Wouters (2003). An estimated dynamic stochastic general equilibrium model of the Euro area. *Journal of the European Economic Association 1*(5), 1123–1175.

Smets, F. and R. Wouters (2007). Shocks and frictions in US business cycles: A Bayesian DSGE approach. *American Economic Review 97*(3), 586–606.

Voss, G. (2009). Aspects of Canadian and US business cycles. *Bank of Canada Working Paper Series*.