Financial spillovers and global risk in an estimated structural three-region model

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Abstract

Recent empirical studies show that unprecedented upsurge in synchronization of financial cycles across countries is primarily driven by fluctuations in the global attitude towards risk. This paper estimates a three-region dynamic stochastic general equilibrium (DSGE) model of the Euro Area (EA), the United States (US) and the rest of the world (RoW) to analyze financial spillovers and the impact of a global financial (risk) shock. We introduce financial linkages via internationally traded firms' shares and estimate a region-specific effect of a global financial shock. The global shock identified by the model is consistent with observed common factor of the traded market indexes. The posterior estimates of financial spillovers from global risk shock are well identified and high for EA and RoW, while close to zero for US, suggesting that the US market can play a significant role in affecting the global sentiments. Our results suggest that financial linkages via cross-country equity holdings increase substantially the financial spillovers and produce model-implied co-movements of real variables closer to the one observed in the data. The 2008-09 crisis has been mostly driven by the global financial shock, while the double dip recession in EA has been associated with domestic factors. Finally, accounting for Zero Lower Bound (ZLB) environment in EA, we find that financial spillovers on real GDP and employment almost double and global financial shocks behave like uncertainty shocks dampening consumption and investment simultaneously.

Keywords: Financial spillover, global shocks, risk appetite, DSGE, Bayesian estimation, ZLB
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1. Introduction

It is quite apparent that the level of interconnectedness across economies has been growing over time, suggesting that economic developments can have important cross-country spillovers. Examples include the global repercussions of commodity price developments, contagion of financial crises, and the impact of trade policy on trading partners and along integrated value chains. Spillovers can be rather continuous ('smooth'), e.g. in the case of the trade multiplier of monetary and fiscal policy. At instances, however, they can also be discontinuous ('disruptive'), adding to economic uncertainty (e.g., in the case of banking crisis and financial panics).

The importance of foreign factors for the business cycle in open economies contrasts with the difficulty that macroeconomic models and, notably, dynamic stochastic general equilibrium (DSGE) models have to generate and reproduce sizable spillover effects. In recent years, several studies have emphasized the fact that DSGE models are not able to replicate sufficient global spillovers (e.g. Alpanda and Aysun, 2014; Aysun, 2016; Bayoumi, 2016; Georgiadis and Jančoková, 2017; Justiniano and Preston, 2010). On the one hand, most of the spillovers in DSGE models come primarily from trade relationships, but bilateral trade is a quite limited percentage of GDP. On the other hand, financial globalization and high cross-border financial linkages seem to play a key role in international business cycles, but have not become a standard element of structural DSGE models yet.

In order to amplify international spillovers, the literature has discussed and developed two strands of model extensions: (i) correlation of shocks and (ii) endogenous transmissions triggered by various financial frictions (e.g. via domestic or global banks, investors, etc), which has become particularly prominent in the aftermath of the global financial crisis. Within the first strand of literature, the prominent paper by Justiniano and Preston (2010) allows for the existence of cross-country spillovers between shocks (global commodity prices, financial panics, or technological innovations), which lift significantly the co-movement in output and inflation volatility between Canada and the US. Alpanda and Aysun (2014) show in an estimated two-country model with the Euro Area (EA) and the US that cross-border correlation in financial shocks considerably improves the ability to replicate international co-movement in macroeconomic time series. Similarly, Aysun (2016) uses an estimated EA-US two-country model and shows that correlated demand and financial shocks can replicate the EA-US co-movement in economic activity, demand and inflation found in the data. Within the second strand of literature, Alpanda and Aysun (2014) introduce cross-border bank lending in an EA-US model and show that the channel strengthens spillovers in economic activity. However, spillovers from this endogenous propagation are more moderate than the co-movement achieved by allowing for internationally correlated shocks. In a similar spirit, Kollmann et al. (2011) introduce a global bank with cross-border deposits and loans and a capital requirement in a two-country model to generate endogenous transmission of loan losses that lead to simultaneous declines in economic activity. The estimated EA-US model version by Kollmann (2013) equally concludes that financial shocks generate positive co-movement in economic activity in the presence of internationally operating financial intermediaries with credit frictions.

Recent empirical studies show that the unprecedented upsurge in synchronization of financial cycles across countries is primarily driven by fluctuations in risk appetite and that a large part of cross country variations in return of risky assets is explained by one global factor (e.g. Miranda-Agrippino and Rey, 2015; Jordà et al., 2019).

We take these findings into account and contribute to the literature in several dimensions: (i) We introduce financial spillovers through cross-country equity holdings, i.e. we allow households to trade internationally firms' assets, which are subject to heterogeneous households' preference shocks and a common global risk shock ('global risk appetite') that both affect investment in the domestic and foreign countries simultaneously; (ii) we analyze the financial spillovers in a fully estimated three-region dynamic stochastic general equilibrium (DSGE) model of the Euro Area (EA), the United States (US) and the rest of the world (RoW); (iii) we provide results on the impact of financial spillovers when the zero bound on monetary policy is occasionally binding.

Our estimation results suggest that financial spillovers stemming from idiosyncratic shocks to investment risk premia increase by incorporating financial linkages via international equity holdings. Our model replicates the co-movement of investment growth across the three regions in the data. We find that the 2008-09 crisis has been mostly driven by the global financial shock (risk appetite), while the double-dip recession in EA has been associated in prevalence with domestic factors. The estimated global risk shock tracks very closely the common factor extracted from three stock market indexes: S&P 500, STOXX 600 and MSCI global, validating the modeling approach. Accounting for the ZLB environment, our results show that (i) financial spillovers amplify without accommodating monetary policy, and (ii) global financial shocks (risk appetite) behave like uncertainty shocks that dampen consumption and investment simultaneously.

Our results are in line with empirical studies showing that major waves of capital flows are primarily associated with global factors (e.g. Forbes and Warnock, 2012). This paper also relates to Perri and Quadrini (2018) who explain the high degree of international synchronization in real and financial variables by changes in market expectations. They show that the credit booms and cycles can be driven by self-fulfilling expectations about the liquidity of financial markets, but which however can not explain the sluggish recovery. Our model, also, relates to Devereux and Yetman (2010) in that they analyze the international transmission of shocks through cross country asset holdings. They focus, though, on various transmission channels of real domestic shocks, where spillovers arise due to leverage constrained investors.

The remainder of the paper proceeds as follows. Section 2 outlines the structure of our model. Section 3 describes the model solution and estimation methodology. Section 4 discusses posterior estimates and model fit. Section 5 assesses the impact of financial spillovers (dynamic responses, cross-correlations, historical decompositions, smoothed estimates of the financial shocks). Section 6 presents results from the model with occasionally binding constraint (zero lower bound) in EA. Section 7 summarizes the paper and concludes.

2. The model

The model set-up builds upon Giovannini et al. (2018) and features three regions: Euro Area (EA), the United States (US) and the rest of the world (RoW). Given our focus on international spillovers, we extend the latter by adding capital in RoW. The economies are composed of households, non-financial firms operating either in the domestic market or in the import-export sector and a central bank. EA and the US also feature a government sector.

We distinguish between two types of households: Ricardian households are infinitely-lived and have access to financial markets, can smooth their consumption and own the firms; liquidity-constrained households consume their disposable wage and do not own any financial wealth. Both types of households provide labour services to domestic firms, at the wage set by a labour union with monopoly power.

In the domestic production sector, monopolistically competitive firms produce a variety of differentiated intermediate goods, which are assembled by perfectly competitive firms into a domestic final output good (value added). In a final step, perfectly competitive firms produce total output by combining value added with industrial supplies.

In the import sector, perfectly competitive firms (import retailers) buy economy-specific goods from the foreign country and assemble them into a final imported good. Final good packagers combine the final imported good with domestic output into final aggregate demand components goods.

The fiscal authority purchases domestic final goods and makes lump-sum transfers to households that is financed by issuing debt and levying distortionary taxes on labour, capital, and consumption, as well as non-distortionary lump-sum taxes. The monetary authority sets the nominal interest rate following a Taylor rule defined on country aggregate inflation and the output gap.

The RoW economy is similar to EA and US, except a couple of features. Precisely, RoW economy is the only producer of industrial supplies (IS), that consists of energy (oil) and other commodities. It does not have a government sector and is inhabited only by Ricardian households, which supply labour inellasticatlly.

2.1. Households

There is a continuum of households, indexed by $j \in [0,1]$, living in each k region. A share ω_k^s of Ricardian households - savers (s) - owns firms and trades assets in the financial market. The remaining share is liquidity-constrained (c) and consumes its entire disposable wage and transfer income each period. Households preferences are defined over consumption and leisure. Additionally, Ricardian's utility depends on the beginning-of-period financial asset holdings.

2.1.1. Ricardian households

Ricardian preferences are given by the infinite horizon expected life-time utility:

$$U_{j,k}^s = E_0 \sum_{t=0}^{\infty} (\tilde{\beta}_{k,t})^t u_{j,k,t}^s(.),$$

where $\tilde{\beta}_{k,t}$ is the stochastic discount factor. [1] They have full access to financial markets, allowing them to accumulate wealth, $A_{j,k,t}$, which consists of domestic private risk-free bonds, $B_{j,k,t}^{rf}$, domestic government bonds, $B_{j,k,t}^{G}$, internationally traded shares, $P_{l,k,t}^{S} S_{j,l,k,t}$, $\forall\ l \in \{EA, US, RoW\}$ and one internationally traded bond, $B_{j,RoW,k,t}$:

$$A_{j,k,t} = B_{j,k,t}^{rf} + B_{j,k,t}^{G} + e_{RoW,k,t} B_{j,RoW,k,t} + \sum_{l} s_{l,k}^{S} P_{l,k,t}^{S} S_{j,l,k,t} e_{l,k,t},$$

where $P_{l,k,t}^{S}$ is the nominal price of shares of country l held by country k at time t. The international bond and shares are issued in foreign currency, hence financial wealth depends on the nominal exchange rate $e_{l,k,t}$. We abstract from optimal portfolio problem, and calibrate the portfolio weights $(s_{l,t}^{S})$ to observed sample means.

[1] $\tilde{\beta}_{k,t} = \beta_k \exp(\varepsilon_{k,t-1}^{c})$, features a shock to the subjective rate of time preference (saving shock)$\varepsilon_{k,t}^{c}$.

The instantaneous utility function of savers, $u^s(.)$, is defined as:

$$u^s_{j,k,t}(C^s_{j,k,t}, N^s_{j,k,t}, \frac{U^A_{j,k,t-1}}{P^{C,vat}_{k,t}}) = \frac{1}{1-\theta_k}(C^s_{j,k,t} - h_k C^s_{k,t-1})^{1-\theta_k} - \frac{\omega^N_k \varepsilon^U_{k,t}}{1+\theta^N_k}(C_{k,t})^{1-\theta_k}(N^s_{j,k,t})^{(1+\theta^N_k)}$$
$$- (C^s_{j,k,t} - h_k C^s_{k,t-1})^{-\theta_k}\frac{U^A_{j,k,t-1}}{P^{C,vat}_{k,t}},$$

where $C^s_{k,t} = \int_0^1 C^s_{j,k,t} dj$, h_k measures the strength of external habits in consumption and $\omega^N_{k,t}$ the stochastic weight of the disutility of labour that captures variation in labour supply shock. The disutility of holding risky financial assets, $U^A_{j,k,t-1}$, takes the following form:

$$U^A_{j,k,t-1} = \left(\alpha^{b_0}_k + \varepsilon^B_{k,t-1}\right)B^G_{j,k,t-1} + \left(\alpha^{bw_0}_k + \varepsilon^{bw}_{k,t-1}\right)e_{RoW,k,t}B_{j,RoW,k,t-1} + \frac{\alpha^{bw_1}_k}{2}\frac{(e_{RoW\,kt-1}B_{RoW,k,t-1})^2}{P^Y_{k,t-1}Y_{k,t-1}}$$
$$+ \sum_l s^S_{l,k}\left(\alpha^{S_0}_k + \varepsilon^S_{l,t-1}\right)e_{l,k,t}P^S_{l,k,t-1}S_{j,l,k,t-1}.$$

Internationally traded bonds are subject to transaction costs which are a function of the average net foreign asset position relative to GDP. The asset specific risk premium depends on an asset specific exogenous shock ε^x, $x \in \{B, S, bw\}$, and an asset specific intercept α^x, $x \in \{b_0, S_0, bw_0\}$. Similar to Krishnamurthy and Vissing-Jorgensen (2012) and Fisher (2015), the approach of modelling the disutility of holding risky assets captures the households preferences for safe assets, i.e. the risk-free short term bonds, which generates endogenously a wedge between the return on risky assets and safe bonds.[2] This allows capturing both the international spillovers that occur via the financial market channel, and the financial frictions that have contributed to the financial crisis[3].

The j^{th} Ricardian household faces the following budget constraint:

$$\begin{aligned} P^{C,vat}_{k,t}C^s_{j,k,t} + A_{j,k,t} &= (1-\tau^N_k)W_{k,t}N^s_{j,k,t} + (1+i^{rf}_{k,t-1})B^{rf}_{j,k,t-1} + (1+i^G_{k,t-1})B^G_{j,k,t-1} \\ &+ \sum_l s^S_{l,k}e_{l,k,t}(P^S_{l,k,t} + P^Y_{l,t}\Pi^f_{l,t})S_{j,l,k,t-1} + (1+i^W_{t-1})e_{RoW,k,t}B_{j,RoW,k,t-1} \\ &+ T^s_{j,k,t} - tax^s_{j,k,t}, \end{aligned} \quad (1)$$

[2]This modification is along the lines of the money-in-utility approach by Sidrauski (1967), in which model agents derive utility from their holdings of money. In our model, it reflects the costs of holding risky assets relative to risk-free assets. A similar framework is used by Vitek (2014, 2017).

[3]Observationally, this approach is equivalent to assuming exogenous risk premia as well as endogenous risk premia derived, e.g., in the spirit of Bernanke et al. (1996).

where $P^{C,vat}_{k,t}$ is the private consumption deflator[4], $W_{k,t}$ denotes the nominal wage rate, $N^s_{j,k,t}$ is the employment in hours, $T^s_{j,k,t}$ are government transfers and $tax^s_{j,k,t}$ lump-sum taxes paid by savers. $i^{rf}_{k,t}$, $i^G_{k,t}$, and i^W_t are returns on domestic private risk-free bonds, domestic government bonds, and internationally traded bonds, respectively. As Ricardian households own the firms, they receive nominal profits in form of dividends, $\Pi^f_{k,t}$, that are distributed by differentiated goods producers according to the number of shares held by the households. We define the gross nominal return on shares S_t as:

$$1 + i^S_{k,t} = \frac{P^S_{k,t} + P^Y_{k,t}\Pi^f_{k,t}}{P^S_{k,t-1}}.$$

The Ricardian households maximise the present value of the expected stream of future utility subject to equation (1), by choosing the amount of consumption, $C^s_{j,k,t}$, and next period asset holdings, $B^{rf}_{j,k,t}$, $B^G_{j,k,t}$, $S_{j,k,t}$, $B^W_{j,k,t}$. The optimality conditions are similar to standard Euler equations, which can be found in Appendix A.1

2.1.2. Financial linkages

Following multiple evidence of increased global financial integration (see Jordà et al., 2019) and failure of not taking into account powerful financial channels in DSGE models (e.g. Georgiadis and Jančoková, 2017; Alpanda and Aysun, 2014), we introduce financial linkages by allowing households to trade internationally domestic firms' shares (asset in continuation). Optimal asset choice determines the interest rate as in eq. 2, which depends on implied riskiness of each region's households. Hence, if EA households' preferences of holding free assets increase (i.e. upsurge in asset's riskiness), this would affect the assets' interest rates in other regions proportionally to its weight in EA portfolio. Assets' interest is given by:

$$1 = \tilde{\beta}_t E_t \sum_l s^S_{l,k} \left[\frac{\lambda^s_{j,l,t+1}}{\lambda^s_{j,l,t}} \frac{e_{l,k,t+1}}{e_{l,k,t}} \frac{(1 + i^S_{k,t+1}) - \left(\alpha^{S_0}_k + \varepsilon^S_{l,t}\right)}{1 + \pi^{C,vat}_{l,t+1}} \right], \tag{2}$$

where $\alpha^{S_0}_k$ captures the constant spread between domestic risk free asset and shares, while $\varepsilon^S_{l,t}$ captures the time varying "risk appetite" of assets' holders. Additionally, in line with empirical evidence (Jordà et al., 2019), we introduce a global shock that affects all regions

[4] $P^{C,vat}_{k,t}$ is the VAT adjusted private consumption deflator, $P^{C,vat}_{k,t} = (1 + \tau^C_k)P^C_{k,t}$, where τ^C is the tax rate on consumption (VAT).

proportionally to its estimated coefficient, that we call 'global risk appetite'. It is defined as:

$$\varepsilon_{k,t}^{S} = \rho_k^S \varepsilon_{k,t-1}^{S} + \epsilon_{k,t}^{S} + \tau_k^{ra}(\varepsilon_t^{ra} - \rho_k^S \varepsilon_{t-1}^{ra}), \qquad \forall k \in \{EA, US, RoW\},$$

where $\lambda_{l,k,t}^{s}$ is the Lagrange multiplier, $\varepsilon_{k,t}^{S}$ and $\epsilon_{k,t}^{S}$ are domestic investment risk premium shocks and its innovation, respectively, ε_t^{ra} is the global risk appetite and τ_k^{ra} is the estimated impact of the latter.

2.1.3. Liquidity-constrained households

Liquidity-constrained households have no access to financial markets and, in each period, they consume their disposable net income, which consists of labour income and net lump-sum transfers from the government.

2.1.4. Wage setting

Households are providing differentiated labour services, $N_{j,k,t}^{r}$, in a monopolistically competitive market. We assume that there is a labour union that bundles proportionally labour hours provided by both types of domestic households into a homogeneous labour service and resells it to intermediate goods producing firms. Since both households face the same labour demand schedule, each household works the same number of hours as the average of the economy. Additionally, we allow for real wage rigidity as in Blanchard and Galí (2007) and Coenen and Straub (2005), where the slow adjustment of real wages occurs through distortions rather than workers' preferences. The wage rule is determined by equating the marginal utility of leisure, $U_{k,t}^{N}$, to the weighted average of the marginal utility of consumption, $\lambda_{k,t}$, times the real wage adjusted for a wage mark-up factor μ_{kt}^{w} :

$$\left[\mu_{kt}^{w} \frac{U_{k,t}^{N}}{\lambda_{k,t}} \frac{P_{k,t}^{C,vat}}{P_{k,t}^{Y}}\right]^{1-\gamma_k^{wr}} \left[(1-\tau_k^N)\frac{W_{k,t-1}}{P_{k,t-1}^{Y}}\right]^{\gamma_k^{wr}} = (1-\tau_k^N)\frac{W_{k,t}}{P_{k,t}^{Y}}.$$

2.2. Production sector

2.2.1. Total output demand

Total output $O_{k,t}$ is produced by perfectly competitive firms by combining the value added, $Y_{k,t}$, with industrial supplies, $IS_{k,t}$, using the following CES production function:

$$O_{k,t} = \left[\left(1 - s_k^{IS}\exp(\varepsilon_{k,t}^{IS})\right)^{\frac{1}{\sigma_k^O}} (Y_{k,t})^{\frac{\sigma_k^O - 1}{\sigma_k^O}} + \left(s_k^{IS}\exp(\varepsilon_{k,t}^{IS}\right)^{\frac{1}{\sigma_k^O}} (IS_{k,t})^{\frac{\sigma_k^O - 1}{\sigma_k^O}}\right]^{\frac{\sigma_k^O}{\sigma_k^O - 1}} \tag{3}$$

where s_k^{IS} is the industrial supplies input share which is affected by the exogenous process $\varepsilon_{k,t}^{IS}$[5] and σ_k^o is the elasticity of substitution between factors. Each firm maximizes its expected profits:

$$\max_{Y_{k,t}, IS_{k,t}} P_{k,t}^O O_{k,t} - P_{k,t}^Y Y_{k,t} - P_{k,t}^{IS} IS_{k,t}$$

subject to the production function (3). The respective first order conditions for the intermediate domestic output and industrial supplies are given by:

$$Y_{k,t} = \left(1 - s_k^{IS} u_{k,t}^{IS}\right) \left(\frac{P_{k,t}^Y}{P_{k,t}^O}\right)^{-\sigma_k^o} O_{k,t}, \tag{4}$$

$$IS_{k,t} = s_k^{IS} u_{k,t}^{IS} \left(\frac{P_{k,t}^{IS}}{P_{k,t}^O}\right)^{-\sigma_k^o} O_{k,t}. \tag{5}$$

Industrial supplies are assumed to be imported exclusively from the RoW. Hence, their price is taken as given:

$$P_{k,t}^{IS} = e_{Row,k,t} P_{Row,k,t}^{IS} + \tau^{IS} P_t^{Y0},$$

where $e_{Row,k,t}$ is the exchange rate, measured as price of foreign currency in terms of domestic currency, τ^{IS} and P^{Y0} are the excise duty and (global) GDP deflator, respectively. The price index of the composite total output is:

$$P_{k,t}^O = \left[(1 - s_k^{IS} u_{k,t}^{IS})(P_{k,t}^Y)^{\sigma_k^o - 1} + s_k^{IS} u_{k,t}^{IS} (P_{k,t}^{IS})^{\sigma_k^o - 1} \right]^{\frac{1}{1-\sigma_k^o}}.$$

2.2.2. Value added and intermediate goods producers

Value added, $Y_{k,t}$, is produced by perfectly competitive firms by combining a large number of differentiated goods, $Y_{i,k,t}$, produced by monopolistically competitive firms. Differentiated goods are produced using total capital, $K_{i,k,t-1}^{tot}$, and labour, $N_{i,k,t}$, which are combined in a Cobb-Douglas production function:

$$Y_{i,k,t} = \left[A_{k,t}^Y (N_{i,k,t} - FN_{i,k,t})\right]^{\alpha_k} (CU_{i,k,t} K_{i,k,t-1}^{tot})^{1-\alpha_k} - A_{k,t}^Y FC_{i,k}, \tag{6}$$

where α_k is the steady-state labour share, $A_{k,t}^Y$ is an exogenous common labour-augmenting stochastic productivity subject to trend and level shocks, $CU_{i,k,t}$ and $FN_{i,k,t}$ are firm-specific levels of capacity utilisation and labour hoarding, respectively.[6] $FC_{i,k}$ captures fixed costs

[5] Note that s_k^{IS} is perturbed by a trend shock to the degree of country openness.

[6] According to Burnside and Eichenbaum (1996), firms prefer not to layoff workers when the demand is temporarily low, because firing workers may be more costly than hoarding them. Additionally, the inclusion

in production. Total capital is the sum of private ($K_{i,k,t}$) and public ($K^G_{i,k,t}$) installed capital.

Monopolistically competitive firms maximise the real value of the firm, $\frac{P^S_{k,t}}{P^Y_{k,t}} S_{k,t}$, which is the discounted stream of expected future profits, subject to the output demand determined by the value added sector, the technology constraint (6), and the law of motion of capital, $K_{i,k,t} = I_{i,k,t} + (1 - \delta_k) K_{i,k,t-1}$.[7] The period t profit of an intermediate goods firm i is given by:

$$\Pi^f_{i,k,t} = (1 - \tau^K_k)\Big(\frac{P^Y_{i,k,t}}{P^Y_{k,t}} Y_{i,k,t} - \frac{W_{k,t}}{P^Y_{k,t}} N_{i,k,t}\Big) + \tau^K_k \delta_k \frac{P^I_{k,t}}{P^Y_{k,t}} K_{i,k,t-1} - \frac{P^I_{k,t}}{P^Y_{k,t}} I_{i,k,t} - adj_{i,k,t},$$

where $I_{i,k,t}$ is the physical investment at price $P^I_{i,k,t}$, τ^K_k is the corporate tax, δ_k the capital depreciation rate and $adj_{i,k,t}$ is the quadratic adjustment costs á la Rotemberg (1982), measured in terms of production input factors. Adjustment costs are associated with the output price, $P^Y_{i,k,t}$, labour input, $N_{i,k,t}$, investment, $I_{i,k,t}$, as well as capacity utilisation variation, $CU_{i,k,t}$, and labour hoarding, $FN_{i,k,t}$. The associated FOCs of the inputs can be found in the appendix Appendix A.2.

2.3. Trade

Final good packagers

The final aggregate demand component goods are produced by perfectly competitive firms by combining domestic output, $O^{\mathcal{D}}_{k,t}$, with imported goods, $M^{\mathcal{D}}_{k,t}$, where $\mathcal{D} = \{C, I, G, I^G, X\}$, using the following CES production function:

$$\mathcal{D}_{k,t} = A^{p^{\mathcal{D}}}_{k,t} \Big[(1 - u^M_{k,t} s^{M,\mathcal{D}}_k)^{\frac{1}{\sigma^z_k}} (O^{\mathcal{D}}_{k,t})^{\frac{\sigma^z_k - 1}{\sigma^z_k}} + (s^{M,\mathcal{D}}_{k,t})^{\frac{1}{\sigma^z_k}} (M^{\mathcal{D}}_{k,t})^{\frac{\sigma^z_k - 1}{\sigma^z_k}} \Big]^{\frac{\sigma^z_k}{\sigma^z_k - 1}},$$

where σ^z_k is the elasticity of substitution of imports, $A^{p^{\mathcal{D}}}_{k,t}$ is a shock to productivity in the sector producing goods, $\mathcal{D}$, and $s^{M,\mathcal{D}}_{k,t}$ is a stochastic share of good-specific import demand components.

$$O^{\mathcal{D}}_{k,t} = (A^{p^{\mathcal{D}}}_{k,t})^{\sigma^z_k - 1} \Big(1 - s^{M,\mathcal{D}}_{kt}\Big) \Big(\frac{P^O_{k,t}}{P^{\mathcal{D}}_{k,t}}\Big)^{-\sigma^z_k} \mathcal{D}_{k,t},$$

$$M^{\mathcal{D}}_{k,t} = (A^{p^{\mathcal{D}}}_{k,t})^{\sigma^z_k - 1} s^{M,\mathcal{D}}_{k,t} \Big(\frac{P^M_{k,t}}{P^{\mathcal{D}}_{k,t}}\Big)^{-\sigma^z_k} \mathcal{D}_{k,t},$$

of labor hoarding, $FN_{i,k,t}$, allows to match the observed co-movement between output and working hours.

[7] We assume that the total number of shares $S^{tot}_{k,t} = 1$.

The price deflator associated to the demand components is:

$$P_{k,t}^{\mathcal{D}} = (A_{k,t}^{p^{\mathcal{D}}})^{-1}\left[(1-u_{k,t}^{M}s_{k}^{M,\mathcal{D}})(P_{k,t}^{O})^{1-\sigma_k^z} + u_{k,t}^{M}s_{k}^{M,\mathcal{D}}(P_{k,t}^{M})^{1-\sigma_k^z}\right]^{\frac{1}{1-\sigma_k^z}}.$$

We define total non-IS imports as:

$$M_{k,t} = M_{k,t}^{C} + M_{k,t}^{I} + M_{k,t}^{G} + M_{k,t}^{IG} + M_{k,t}^{X}.$$

Import retailers (Economy-specific final import demand)

Final non-IS imported goods are produced by perfectly competitive firms combining economy-specific final imports. The associated demand for goods from country l is:

$$M_{l,k,t} = s_{l,k,t}^{M}\left(\frac{P_{l,k,t}^{M}}{P_{k,t}^{M}}\right)^{-\sigma_k^{FM}} M_{k,t}\frac{size_k}{size_l},$$

and import prices are:

$$P_{k,t}^{M} = \left[\sum_{l} s_{l,k,t}^{M}(P_{l,k,t}^{M})^{1-\sigma_k^{FM}}\right]^{\frac{1}{1-\sigma_k^{FM}}}$$

where σ_k^{FM} is the price elasticity of demand for country l's goods and $P_{l,k,t}^{M}$ being the economy-specific import goods prices. Since all products from country l are initially purchased at export price, $P_{l,t}^{X}$, the economy-specific import goods price can be also expressed as:

$$P_{l,k,t}^{M} = e_{l,k,t}P_{l,t}^{X}.$$

2.4. Fiscal policy

The government finances its consumption, $G_{k,t}$, investment, $I_{k,t}^{G}$, transfers, $T_{k,t}$, and the servicing of the outstanding debt by issuing one-period bonds, $B_{k,t}^{G}$, and collecting constant linear taxes on labour, τ_k^N, capital, τ^K and consumption, τ^C. It also collect lump-sum taxes, $tax_{k,t}$, that adjust residually to close the budget constraint. The expenditure factors follow a feedback rule in line with discretionary fiscal effort as defined by the European Commission (2013).

2.5. Monetary policy

Monetary policy follows a (Taylor, 1993) rule, that responds sluggishly to the annualised wide inflation gap, $\pi_{k,t}^{c,vat,QA}$, and the annualised output gap.[8]

$$i_{k,t} - \bar{i} = \rho_k^i(i_{k,t-1} - \bar{i}) + (1 - \rho_k^i)\Bigg[\eta_k^{i\pi} 0.25\Big(\pi_{k,t}^{C,vat,QA} - \bar{\pi}_k^{C,vat,QA}\Big)$$
$$+ \eta_k^{iy}\Bigg(\log\Big(0.25\sum_{r=1}^{4} Y_{k,t-r}\Big) - \log\Big(0.25\sum_{r=1}^{4} Y_{k,t-r}^{pot}\Big)\Bigg)\Bigg] + \varepsilon_{k,t}^i, \tag{7}$$

where $\bar{i} = \bar{r} + \bar{\pi}^{Yobs}$ is the steady-state nominal interest rate, equal to the sum of the steady state real interest rate and GDP inflation. The policy parameters (ρ^i, $\eta^{i\pi}$, η^{iy}) capture interest rate inertia and the response to annualised inflation and output gap, respectively.

2.6. Closing the economy

Market clearing requires that:

$$Y_{k,t}P_{k,t}^Y + \tau^{IS} IS_{k,t}P_t^{Y0} = P_{k,t}^C C_{k,t} + P_{k,t}^I I_{k,t} + P_{k,t}^{IG} IG_{k,t} + P_{k,t}^G G_{k,t} + TB_{k,t},$$

where the trade balance, $TB_{k,t}$, is defined as the difference between exports and imports:

$$TB_{k,t} = P_{k,t}^X X_{k,t} - \sum_l \frac{size_l}{size_k} P_{l,k,t}^M M_{l,k,t} - P_{RoW,k,t}^{IS} IS_{RoW,k,t} e_{RoW,k,t}.$$

Net foreign assets, $B_{k,t}^W$, evolve according to:

$$e_{RoW,k,t}B_{k,t}^W = (1 + i_{t-1}^{bw})e_{RoW,k,t}B_{k,t-1}^W + TB_{k,t} + ITR_k P_{k,t} Y_{k,t},$$

where ITR_k represents international transfers, which are calibrated to allow a non-zero steady-state of the trade balance.

Finally, net foreign assets of all countries sum to zero:

$$\sum_l NFA_{l,t} size_l = 0.$$

[8]We define potential output, $Y_{k,t}^{pot}$, as the output level that would prevail if labour input equaled steady-state per capita hours worked, capital stock is utilised at full capacity and TFP equaled its trend component.

2.7. Commodity supplier

In our model, RoW is the only supplier of industrial supplies (IS). A competitive sector supplies two distinct industrial supply goods (IS), namely oil (IS^{Oil}) and commodities (IS^{Com}), to domestic and foreign final good firms. The industrial supply goods prices are flexible. Normalized by the RoW GDP deflator, they are an increasing function of RoW IS goods production demand in the three regions:

$$\ln\Big(\frac{P^n_{RoW,t}}{P^Y_{RoW,t}}\Big) = \eta\Big(\sum_l \ln(IS^n_{l,t}) + \ln(IS^n_{RoW,t})\Big) - \varepsilon^n_t, \quad \forall n \in \{Oil, Com\},$$

where ε^n_t is a disturbance that captures exogenous IS supply shocks. The parameter η is the inverse of the price elasticity of IS goods.

EA, US and RoW demand for IS is determined by final good producers in the respective regions, and is given by eq. 5. However, we assume that the IS intensity of RoW final good production is constant, i.e. there are no stochastic RoW IS-specific demand shocks.[9]

In contrast, since we observe volumes and price data on IS imports by EA and US from RoW, we have EA and US IS-specific demand shocks. Empirically, the IS import price indexes from EA and US differ but are highly positively correlated. To account for those differences (which may reflect different industrial supplies import mixes), we assume that competitive RoW export firms bundle oil and commodities into destination-specific IS aggregates. The respective IS bundle prices are given by:

$$P^{IS}_{RoW,l,t} = \varepsilon^{P^{IS}}_{RoW,l,t}\Big[s^{Oil}_l\Big(P^{Oil}_{RoW,t}\Big)^{1-\sigma^{IS}} + (1-s^{Oil}_l)\Big(P^{Com}_{RoW,t}\Big)^{1-\sigma^{IS}}\Big]^{\frac{1}{1-\sigma^{IS}}}, \quad \forall l \in \{EA, US\}$$
$$P^{IS}_{RoW,RoW,t} = \Big[s^{Oil}_{RoW}\Big(P^{Oil}_{RoW,t}\Big)^{1-\sigma^{IS}} + (1-s^{Oil}_{RoW})\Big(P^{Com}_{RoW,t}\Big)^{1-\sigma^{IS}}\Big]^{\frac{1}{1-\sigma^{IS}}}.$$

3. Model solution and econometric approach

We compute an approximate model solution by linearizing the model around its deterministic steady-state. A subset of parameters is calibrated at quarterly frequency to match long-run properties, the remaining parameters are estimated using Bayesian methods.[10] As in Bayesian practice, the likelihood function (evaluated by implementing the Kalman Filter) and the prior distribution of the parameters are combined to calculate the posterior distribu-

[9] This assumption is due to the lack of data on RoW industrial supplies production and demand. Therefore, a RoW IS-specific demand shock is not identified in our empirical model.

[10] We use the Dynare software 4.5 to solve the linearised model and to perform the estimation (see Adjemian et al., 2011).

tion. The posterior Kernel is then simulated numerically using the slice sampler algorithm as proposed by Planas et al. (2015).[11]

The estimation uses quarterly and annual data for the period 1999q1 to 2017q4.[12] Data for the EA are taken from Eurostat. Corresponding data for the US come from the Bureau of Economic Analysis (BEA) and the Federal Reserve. RoW series are constructed on the basis of the IMF International Financial Statistics (IFS) and World Economic Outlook (WEO) databases. The estimated model uses 65 observed series and assumes 66 exogenous shocks.[13] The large number of shocks is dictated by the fact that we use a large number of observables for estimation. Furthermore, many shocks are needed to capture key dynamic properties of macroeconomic and financial data (see Kollmann et al., 2015).

We calibrate the model such that steady-state ratios of main spending aggregates to GDP match average historical ratios for the EA, US and RoW. The steady-state shares of EA, US, and RoW GDP in world GDP are set at 17%, 27% and 56%, respectively. Trade related parameters such as the degree of openness or preferences for imports are calibrated to match the average shares of import content in the demand components as computed by Bussière et al. (2013). Steady-state net foreign asset positions of the three regions are set at zero. The EA, US and RoW steady-state ratios of private consumption and investment to GDP are set to 56%, 68%, 72% and 18%, 17%, 27% respectively. The global steady-state real GDP growth rate and inflation are set at 0.35% and 0.5% per quarter, respectively. Finally, the quarterly depreciation rate of capital is 1.4% in the EA, 1.6% in the US and 1.5% in RoW. We set the effective rate of time preferences to 0.25% per quarter. The steady-state shares of Ricardian households are calibrated to 67% in the EA and 73% in the US following the survey in Dolls et al. (2012). We set the steady-state government debt/annual GDP ratio at 74% of GDP in the EA and 78% in the US.[14] Table 1 provides an overview of selected calibrated parameters.

We calibrate the countries' portfolio weights to average gross holdings of equities observed in the data.[15] The numbers are reported in Table 2, where the weights in any given row represent the shares held by region displayed in the column in total equities issued by the

[11] The slice sampler algorithm was introduced by Neal (2003). Planas et al. (2015) reconsider the slices along the major axis of the ellipse to better fit the distribution than any of Euclidean slices. The slice sampler has been shown to be more efficient and offer better mixing properties than the Metropolis-Hastings sampler (Calés et al., 2017).

[12] The model is estimated at quarterly frequency, interpolating annual data for the series that are not available at higher frequency.

[13] The list of observables can be found in Appendix B.

[14] Since the RoW model block is more simplified, we abstract, e.g., from a detailed fiscal sector and liquidity-constrained households.

[15] Data are taken from the FinFlows dataset and cover 2001-2017 (https://finflows.jrc.ec.europa.eu).

Table 1: Selected calibrated structural parameters.

		EA	US	RoW
Preferences				
Intertemporal discount factor	β	0.998	0.998	0.998
Savers share	ω^s	0.67	0.73	1.00
Import share in consumption	$s^{M,C}$	0.10	0.05	0.05
Import share in investment	$s^{M,I}$	0.15	0.12	0.15
Import share in export	$s^{M,X}$	0.13	0.06	0.19
Weight of disutility of labor	ω^N	8.09	8.25	79.61
Production				
Cobb-Douglas labor share	α	0.65	0.65	0.65
Depreciation of private capital stock	δ	0.014	0.016	0.015
Share of oil in total output	s^{Oil}	0.04	0.03	0.04
Linear capacity utilization adj. costs	$\gamma^{u,1}$	0.02	0.02	0.02
Steady-state ratios				
Private consumption share	C/Y	0.56	0.68	0.72
Private investment share	I/Y	0.18	0.17	0.27
Size of the country (% of world)	$size$	16.98	26.77	56.25

Table 2: Calibrated portfolio weights

Issuer \ Holder	EA	US	RoW
EA	0.74	0.12	0.14
US	0.09	0.73	0.18
RoW	0.06	0.13	0.81

country displayed in the row.

4. Estimation results

4.1. Posterior estimates

The posterior estimates (with 90% highest posterior density (HPD) intervals) of key model parameters for EA, US and RoW are reported in Table 3. The estimated monetary policy parameters show a higher coefficient for the response to inflation in EA (1.33) compared to US (1.20) and RoW (1.14). However, the interest rate inertia in RoW (0.93) and the response to output (0.39) are higher than in EA and US. The estimated habit persistence is high for all countries, implying a slow adjustment of consumption to changes in income. Risk aversion has been estimated slightly higher in RoW and US compared to EA. The inverse of the labour supply elasticity is fairly similar, while the import price elasticity coefficient is significantly higher in US. Oil price elasticity is low for all countries. The estimated share of forward-looking price setters is marginally higher in EA (0.44) compared to US (0.38), but significantly higher in RoW (0.72).

Due to lack of labour market data in RoW, we abstract from various related rigidities and allow households to supply labour inelastically. Further down, we will focus only on the comparison between EA and US. Price adjustment costs and nominal wage adjustment costs have been estimated slightly higher in EA compared to US. Real wage rigidity is high for both countries. The labour market rigidity is linked to the two adjustment cost parameters in labour demand and labour hoarding. The former appears to be rather similar (around 20), whereas the latter features more rigid levels in US (2.4) compared to EA (1.7). All three region face similar levels of capacity utilization adjustment costs. Investment adjustment costs have been estimated rather high, in particular for RoW. EA and US parameters are somewhat lower, with a slightly higher mode in EA (140) than in US (125).

The posterior estimates of financial spillovers ('global risk appetite') are well identified and particularly high in EA (2.80) and RoW (2.18). The coefficient for US is slightly positive (0.30) but seems to play a rather marginal role. It suggests that global financial spillovers play a significant role for EA and RoW, while US is rather unaffected. The posterior distributions of the country-specific coefficients can be found in Figure C.1.

From an empirical point of view, it is important to mention that the data density is higher in our model compared to a model without financial linkages and a global financial shock.[16]

4.2. Theoretical moments and model fit

In order to evaluate the capability of the model to fit the data, Table 4 compares sample and model-implied moments for a subset of key statistics. In particular, we focus on volatilities and persistence of real GDP, consumption, investment, employment, and the trade balance-to-GDP ratio, as well as, the cross-correlation of GDP with its main components. The estimated model tend to overestimate slightly the volatility of real variables in EA and US. However, the relative magnitudes seem to be preserved, e.g. std(GI)/std(GY). Of particular note is the high volatility of investment, which is in line with the data patterns.

First-order autocorrelations are fairly well seized in all three countries, except the low autocorrelation of GDP growth in EA. Most of the correlations between GDP growth and its components are fairly well captured, also. More precisely, all country models replicate well the correlation of consumption, investment and employment (for EA and US) with output.

[16]The data density is as a useful criterion for model evaluation in the Bayesian context. The data density evaluates the fit of the model giving a preference to simplicity, i.e. it penalizes models with more parameters.

Table 3: Prior and posterior distribution of key estimated model parameters.

		Prior distribution		Posterior distribution		
		Distr	Mean St.Dev	EA	US	RoW
Monetary Policy						
Interest rate persistence	ρ^i	G	0.70 0.12	0.85 (0.78, 0.89)	0.80 (0.75, 0.85)	0.93 (0.92, 0.95)
Response to inflation	$\eta^{i,\phi}$	G	2.00 0.40	1.33 (1.09, 1.76)	1.20 (1.07, 1.52)	1.14 (1.01, 1.41)
Response to GDP	$\eta^{i,y}$	G	0.20 0.08	0.08 (0.05, 0.12)	0.09 (0.07, 0.11)	0.39 (0.28, 0.45)
Preferences						
Consumption habit persistence	H	B	0.50 0.10	0.85 (0.80, 0.91)	0.83 (0.74, 0.89)	0.94 (0.93, 0.97)
Risk aversion	θ	G	1.50 0.20	1.48 (1.22, 1.81)	1.57 (1.29, 1.97)	1.63 (1.31, 2.13)
Inverse Frisch elasticity of labor supply	θ^N	G	2.50 0.50	2.12 (1.58, 2.84)	1.94 (1.55, 2.94)	2.50*
Import price elasticity	σ^z	G	2.00 0.40	1.27 (1.11, 1.42)	1.99 (1.64, 2.84)	1.21 (1.11, 1.37)
Oil price elasticity	σ^o	G	0.50 0.20	0.02 (0.00, 0.06)	0.03 (0.01, 0.07)	0.01*
Share of forward-looking price setters	sfp	B	1.00 0.50	0.44 (0.17, 0.90)	0.38 (0.14, 0.63)	0.72 (0.53, 0.89)
Nominal and real frictions						
Price adjustment cost	γ^P	G	60 40	22.31 (14.67, 35.70)	20.12 (13.42, 34.71)	95.25 (48.14, 133.20)
Nominal wage adjustment cost	γ^w	G	5.00 2.00	5.50 (2.43, 7.33)	3.19 (1.45, 4.41)	-
Real wage rigidity	γ^{wr}	B	0.50 0.20	0.98 (0.97, 0.99)	0.98 (0.96, 0.98)	-
Employment adjustment cost	γ^N	G	60 40	20.09 (13.04, 40.04)	19.48 (11.53, 32.66)	-
Labor hoarding quadratic adj cost	γ^{FN}	G	2.00 0.50	1.74 (1.33, 2.20)	2.36 (2.01, 3.00)	-
Capacity Utilization quadratic adj cost	γ^{CU}	G	0.003 0.0012	0.004 (0.002, 0.006)	0.004 (0.002, 0.006)	0.005 (0.002, 0.008)
Investment adjustment cost	γ^I	G	60 40	140.16 (92.07, 210.40)	125.09 (92.99, 176.83)	258.63 (174.07, 329.69)
Global risk appetite						
Financial spillover coefficient	τ^{ra}	B	0 2	2.80 (0.01, 4.17)	0.30 (-2.06, 2.64)	2.18 (0.58, 4.08)

Note: Cols. (1)-(2) list model parameters. Cols. (3)-(4) indicate the prior distribution function (B: Beta distribution; G: Gamma distribution). Identical priors are assumed across countries. Cols. (5)-(6) show the mode and the 90% HPD intervals of the posterior distributions of EA and US. * RoW labor market related coefficients and selected others are calibrated due to lack of data.

In our model the trade balance is positively correlated with output, which only match the data pattern in RoW, however.

The last column in Table 4 reports the r^2 of the 1-year ahead forecast.[17] The 1-year

[17] We define the r^2 as the ratio of the country-specific k-step ahead forecast error obtained from the Kalman filter recursions over the country-specific j–th time series in deviation from the model-implied steady-state. Since we subtract this ratio from 1, this definition implies that our r^2 has an upper bound located at 1 and is unbounded from below. This means that in the perfect case where the model generates no forecast error,

Table 4: Theoretical moments and model fit.

Variable	Std		AR(1)		Corr (x, GY)		r2
	Data	Model	Data	Model	Data	Model	1-y ahead
EA							
GDP growth (GY)	0.61	0.78	0.65	0.14	1.00	1.00	0.65
Consumption growth (GC)	0.37	0.72	0.50	0.58	0.69	0.20	0.28
std(GC)/std(GY)	0.62	0.92	-	-	-	-	-
Investment growth (GI)	1.64	2.34	0.50	0.59	0.86	0.47	0.68
std(GI)/std(GY)	2.69	3.00	-	-	-	-	-
Hours growth	0.43	0.43	0.60	0.40	0.81	0.79	0.73
δ **Trade balance to GDP**	0.32	0.42	0.12	0.03	-0.01	0.39	0.76
US							
GDP growth (GY)	0.61	0.74	0.39	0.22	1.00	1.00	0.51
Consumption growth (GC)	0.51	0.89	0.61	0.57	0.67	0.44	0.54
std(GC)/std(GY)	0.83	1.19	-	-	-	-	-
Investment growth (GI)	1.94	2.17	0.68	0.62	0.71	0.39	0.81
std(GI)/std(GY)	3.18	2.93	-	-	-	-	-
Hours growth	0.57	0.56	0.72	0.33	0.55	0.55	0.81
δ **Trade balance to GDP**	0.32	0.59	0.30	0.11	-0.26	0.34	0.62
RoW							
GDP growth (GY)	0.75	0.59	0.89	0.67	1.00	1.00	0.93
Consumption growth (GC)	0.63	0.68	0.82	0.87	0.84	0.65	0.87
std(GC)/std(GY)	0.84	1.13	-	-	-	-	-
Investment growth	1.56	1.26	0.82	0.73	0.93	0.48	0.73
std(GI)/std(GY)	2.08	2.13	-	-	-	-	-
δ **Trade balance to GDP**	0.20	0.41	0.23	0.13	0.17	0.03	0.63

Note: We use first differences for the trade balance-to-GDP ratio and quarter-on-quarter growth rates for all other variables. The r2 is reported for the absolute nominal trade balance.

ahead r^2 is positive for both countries, indicating that the model forecast errors are not very large. Overall, the theoretical moments give credit to the plausibility of the estimated structural model to replicate key features of EA, US and RoW business cycles.

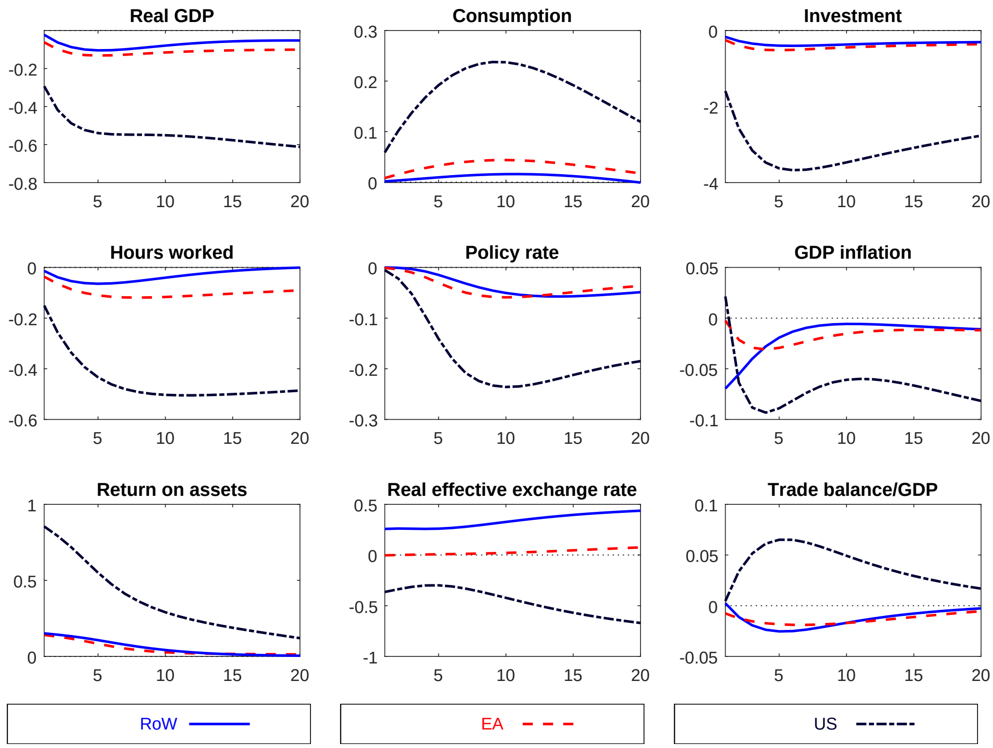
5. Assessing financial spillovers

5.1. Dynamic transmission of shocks

This section discusses estimated dynamic effects of key shocks shown in Figures 1 - 4. We concentrate on the impact of shocks to the investment risk premium originating in EA, US,

the r^2 is one and it declines monotonically as the forecast error increases. Since the volatility of the forecast error can be larger than the volatility of the observed time series, the r^2 can be negative. In that case, a constant forecast centered on the sample mean would do a better job since its r^2 coincides with zero.

Figure 1: Dynamic responses to a positive US investment risk premium shock.



Note: The trade balance (normalized by GDP), inflation (p.a.) and interest rate (p.a.) responses are expressed as percentage point deviations from steady-state. All other responses are percent deviations from steady-state. A fall in the exchange rate represents an appreciation. The responses of RoW, EA and US variables are represented by continuous, dashed and dash-dotted lines, respectively.

and RoW, as well as the global financial shock ('global risk appetite') and its international spillovers.[18] All shocks are harmonized to one standard deviation. Each panel shows the dynamic response of the following endogenous variables: real GDP, private consumption, private investment, total hours worked, policy rate, GDP inflation, return on assets, real effective exchange rate, and the trade balance-to-GDP ratio. Real variables are presented as percent deviations from their steady-state. GDP inflation, interest rate, and the trade balance-to-GDP ratio are expressed in percentage-point deviations from steady-state.

An increase in the US investment risk premium impedes investment by increasing the riskiness of domestic investments, resulting in a higher expected return on assets (Figure 1). The decrease in aggregate demand induced by the shock negatively affects labor demand, inducing a decline in employment and wages. Lower real activity and employment results

[18]The effects of standard supply (e.g. TFP, price markup) and demand shocks (e.g. saving) originating in the EA and the US on domestic GDP are qualitatively similar to those predicted by standard DSGE models (e.g. Kollmann et al., 2016).

in lower inflation. However, consumption is crowded in due to lower interest rates. The nominal and real exchange rate appreciates in US and increase the trade balances due to lower import demand. The domestic transmission mechanism is similar for EA and RoW (see Figures 2 and 3, respectively).

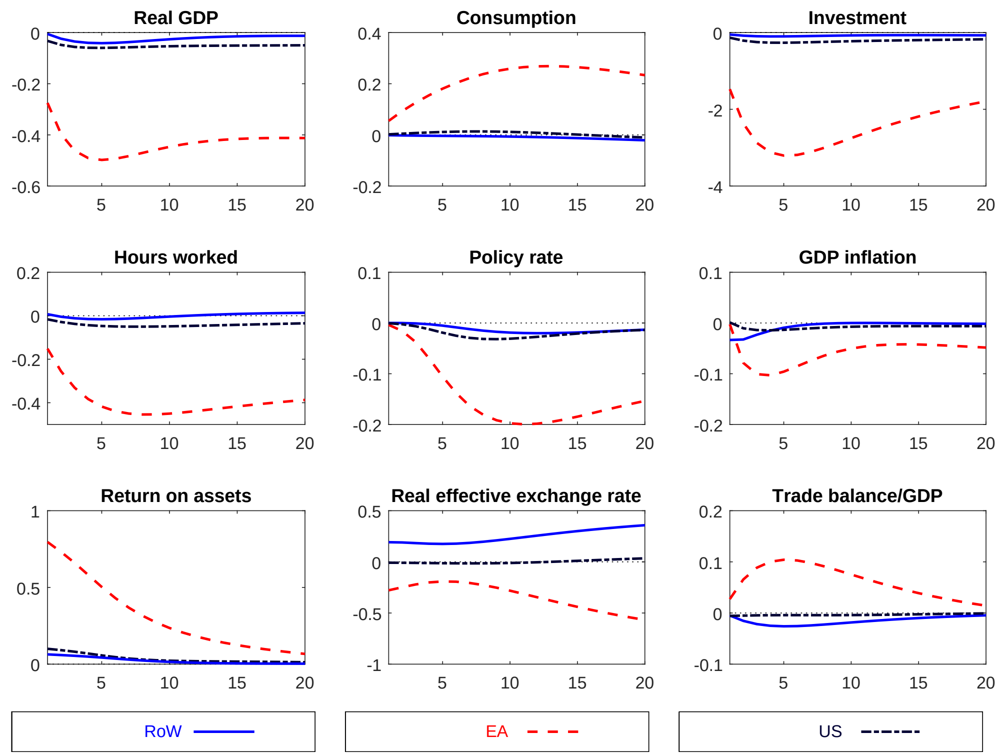
Concerning financial spillover effects across countries, our estimation results suggest a non-negligible co-movement between US and EA for GDP, investment and employment growth (Figures 1 and 2). The spillover from US to EA is slightly more pronounced than from EA to US, but in both cases, the spillover is marginally higher compared to the one towards RoW. The spillover effect from an increase in the investment risk premium in RoW to US and EA is particularly strong for real GDP growth and employment (Figure 3).

It is important to stress that financial spillovers across countries are dampened by accommodating monetary policy responses. Given the co-movements of GDP and inflation, domestic monetary policy reduces interest rates to mitigate the decline in domestic activity. In times of occasionally binding constraints, however, when monetary policy is constrained at the zero lower bound (ZLB), the spillover from foreign investment risk premium shocks to the domestic economy would be amplified. We will discuss this scenario in section 6.

Figure 4 shows the dynamic responses to an increase in global investment risk. This global financial shock shows similar transmission mechanisms as the shocks to the domestic investment risk premium discussed above. However, it affects all countries simultaneously and to a much stronger extent. The differences across countries stem from the country-specific weights that have been estimated in our model (see Table 3). Given the estimated coefficients for EA (2.8), US (0.3), and RoW (2.2), Figure 4 depicts the degree of the transmission mechanism of the global financial shock. Since this shock enters all domestic investment risk premium equations simultaneously with an estimated country-specific coefficient, it provides an alternative interpretation of the estimated contribution of investment risk shocks to historical time series, e.g. GDP growth, as it helps to disentangle the impact of investment risk shocks originating domestically and the impact of investment risk or investment uncertainty coming from a global financial shock (see section 5.3). Due to the global scale, we interpret this shock as 'global risk appetite'.

Overall, the impulse response functions (IRFs) suggest that incorporating financial linkages by allowing households to hold foreign firms' assets increases the degree of financial spillover and, therefore, the co-movement of main variables (e.g. GDP, investment, employment) stemming from asymmetric shocks to the investment risk premium. The introduction of a global financial shock that affects all countries simultaneously given their estimated country-specific weights increases the effect of global financial spillovers, supports the synchronization of financial cycles.

Figure 2: Dynamic responses to a positive EA investment risk premium shock.



Note: The trade balance (normalized by GDP), inflation (p.a.) and interest rate (p.a.) responses are expressed as percentage point deviations from steady-state. All other responses are percent deviations from steady-state. A fall in the exchange rate represents an appreciation. The responses of RoW, EA and US variables are represented by continuous, dashed and dash-dotted lines, respectively.

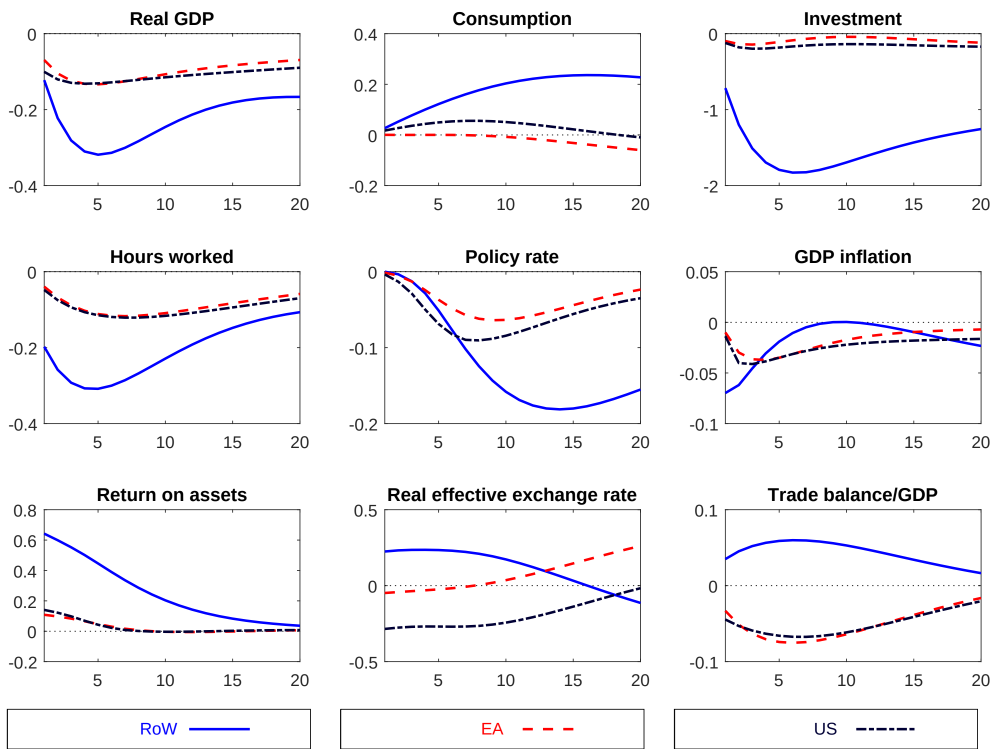
5.2. Cross-correlation

Comparing the model-implied cross-correlation of quarterly GDP growth rates and investment growth rates across the three regions, our model with financial linkages and global financial shocks is able to capture co-movements of both GDP growth and investment growth across countries (Table 5) compared to a model version without these financial linkages. Particularly the cross-correlation of investment improves substantially and fairly matches the data. Although the model-implied co-movements improved also for GDP growth, the gains are less significant. The rather poor performance with respect to RoW may be driven partly due to the interpolation of RoW annual data, which becomes rather smooth compared to the quarterly data of EA and US GDP growth.

5.3. Historical shock decomposition of real GDP growth

This subsection highlights the estimated contribution of different shocks (or shock groups) to historical time series in the period 2000q1-2017q4. Figures 5-7 plot the historical decomposition of the three regions for the annual-on-annual growth rate of real GDP. In each

Figure 3: Dynamic responses to a positive RoW investment risk premium shock.



Note: The trade balance (normalized by GDP), inflation (p.a.) and interest rate (p.a.) responses are expressed as percentage point deviations from steady-state. All other responses are percent deviations from steady-state. A fall in the exchange rate represents an appreciation. The responses of RoW, EA and US variables are represented by continuous, dashed and dash-dotted lines, respectively.

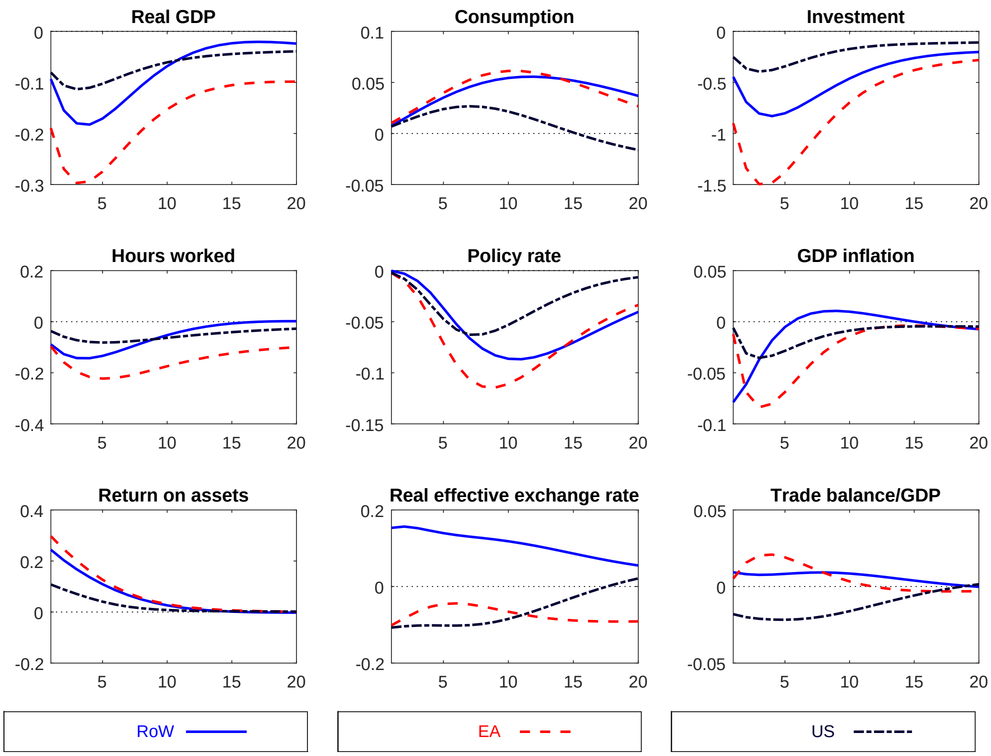
Table 5: Model-implied cross-correlations of real GDP and investment growth

	Data	Model	
		Baseline	Financial linkages
GDP cross-correlation			
EA-US	0.51	0.23	0.27
EA-RoW	0.39	-0.10	-0.08
US-RoW	0.49	-0.04	-0.01
Investment cross-correlation			
EA-US	0.50	0.12	0.36
EA-RoW	0.42	0.03	0.33
US-RoW	0.36	0.03	0.32

Note: Baseline refers to a model version without both financial linkages in terms of foreign asset holdings and global financial shock.

subplot, the continuous black line shows the historical time series, from which sample averages have been subtracted. The vertical black bars show the contribution of different (groups of) exogenous shocks to the historical data, while stacked light bars show the contribution of

Figure 4: Dynamic responses to a positive shock to global investment risk ('global risk appetite').



Note: The trade balance (normalized by GDP), inflation (p.a.) and interest rate (p.a.) responses are expressed as percentage point deviations from steady-state. All other responses are percent deviations from steady-state. A fall in the exchange rate represents an appreciation. The responses of RoW, EA and US variables are represented by continuous, dashed and dash-dotted lines, respectively.

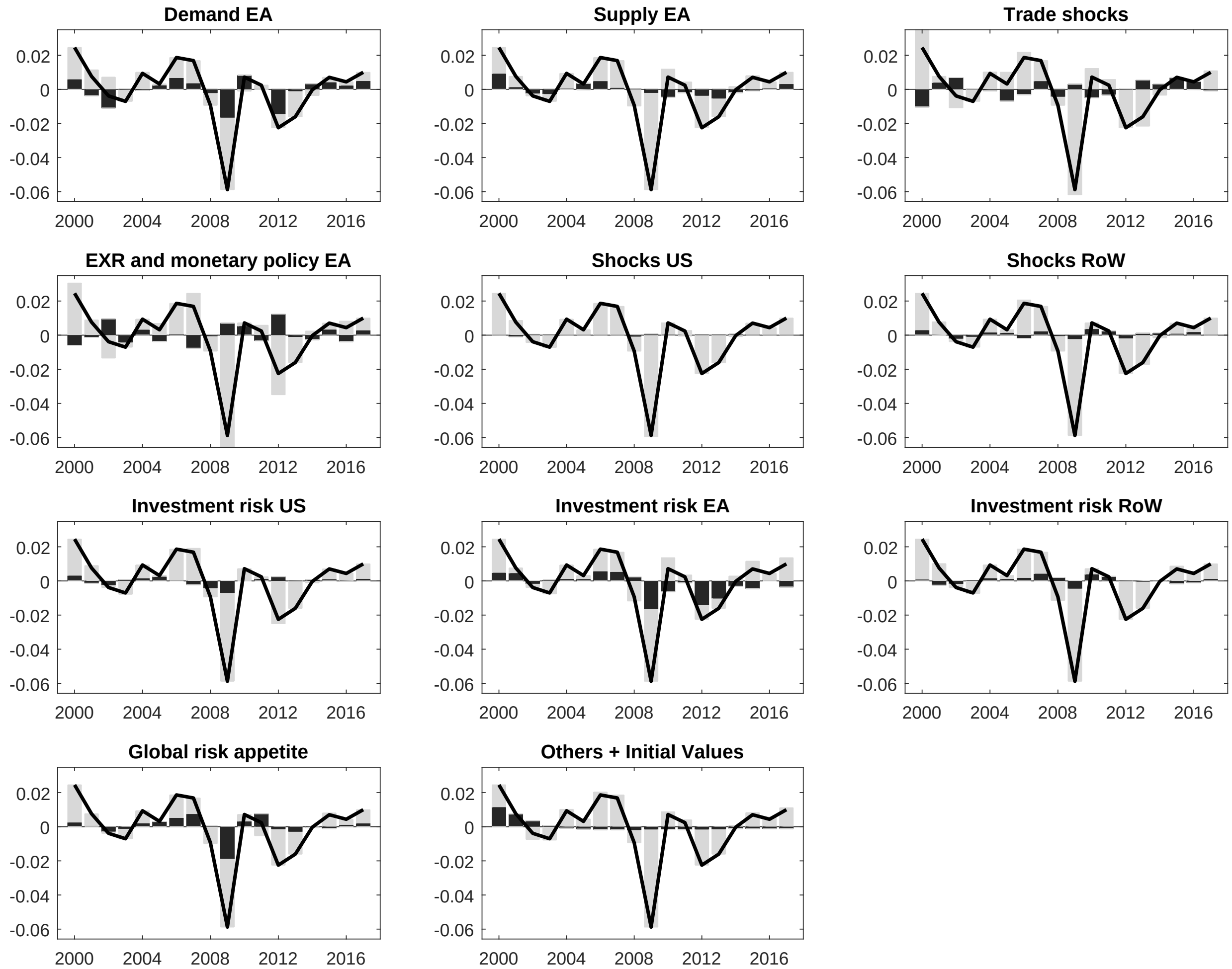
the remaining shocks. Bars above the horizontal axis (steady-state) represent positive shock contributions, while bars below the horizontal axis show negative shock contributions. The sum of all shock contributions equals the historical data.

We plot the contributions of the following (groups of) exogenous variables: (1) Domestic demand shocks ('Demand');[19] (2) domestic supply shocks and permanent shocks to TFP ('Supply'); (3) shocks to the worldwide relative preference for domestically produced goods and foreign goods, price mark-up shocks for exports and imports, and commodities demand and supply shocks ('Trade shocks'); (4) interest parity shocks (exchange rate shocks) and domestic monetary policy shocks ('EXR and monetary policy'); (5) and (6) shocks originating in the foreign economies; (7), (8) and (9) shocks to the investment risk premium in US, EA, and RoW, respectively; (10) other shocks and initial conditions.

Fluctuations in EA and US real GDP growth were largely driven by domestic demand

[19]The domestic demand shock group as well as the shock groups of the foreign countries exclude the shocks to the investment risk premia, which are plotted separately to highlight the cross-country spillovers.

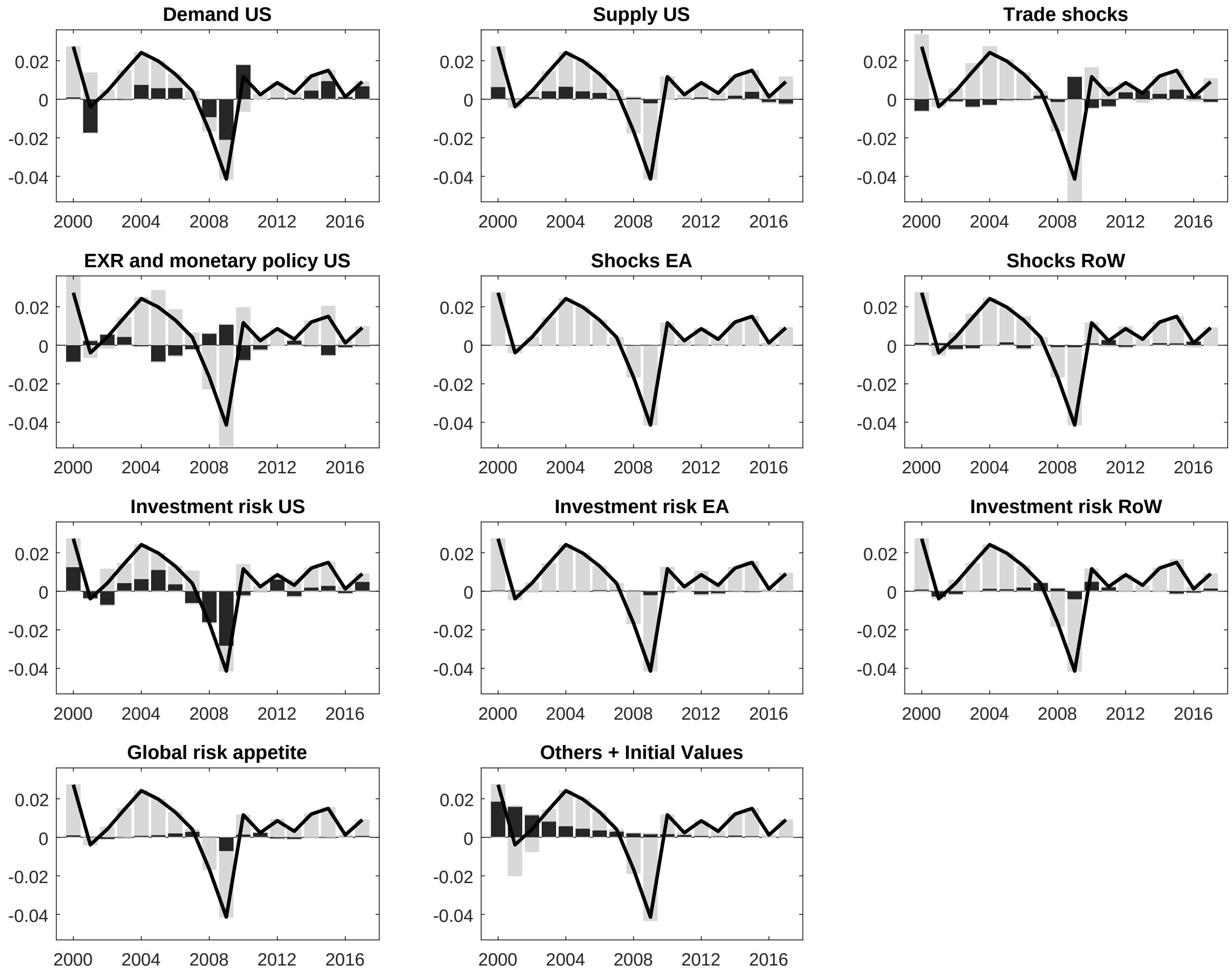
Figure 5: Historical decomposition of real GDP growth in EA



Note: Real GDP growth is shown in annual-on-annual percentage-point deviations from steady-state, which is calibrated globally to 1.35% per year. 0.01 on the y-axis corresponds to 1 pp.

shocks (in particular by household saving shocks) and by shocks to the investment risk premium (see Figures 5 and 6). After the Global Financial Crisis, domestic demand and GDP rebounded more quickly in the US than in the EA, which experienced a second recession in 2012–13 during the European debt and banking crisis. The contribution of domestic supply and TFP shocks to historical GDP fluctuations has been much smaller in the EA and US. Negative trade shocks have been more dominant in EA than US and contributed mainly to the below-trend GDP growth during the crisis years. The main drivers of the positive 'trade'-contributions have been mainly the fall in oil and commodity prices (see Giovannini et al., 2018). In both economies, monetary policy provided some GDP stabilization particularly during the financial cisis, while the euro exchange rate depreciation (explained in the model by an increase in the risk premium on euro-denominated bonds) contributed positively to

Figure 6: Historical decomposition of real GDP growth in US



Note: Real GDP growth is shown in annual-on-annual percentage-point deviations from steady-state, which is calibrated globally to 1.35% per year. 0.01 on the y-axis corresponds to 1 pp.

EA GDP growth during the double-dip recession.[20]

According to our estimated model, strong RoW GDP growth was mainly driven by persistent positive domestic TFP shocks (Figure 7). The growth of RoW TFP and GDP was, however, interrupted in 2008–09, but continued after 2010 to a somewhat lesser extent. Domestic demand and investment shocks, too, were influential drivers of RoW GDP fluctuations.

[20]Since we do not impose a zero lower bound on the nominal interest rate as a constraint on monetary policy in the estimation, the small negative contributions to GDP growth during 2013 and 2015 originate from a lower model-implied policy rate compared to the observed policy rate which is at the zero bound. Hence, the gap is closed by positive (tightening) monetary policy shocks. In our shock group, however, this effect is partly offset by the euro exchange rate depreciation.

We find in all three countries little evidence for significant aggregate demand and supply-side spillovers. Solely shocks originating in RoW contributed positively to EA GDP growth during the recovery period after the financial crisis. However, our estimation results suggest that negative shocks to the investment demand in US and RoW (an increase in investment risk premia) had noticeable spillover effects on EA GDP growth, particularly during the financial crisis (Figure 5). While positive shocks to investment risk in US were contributing negatively to EA GDP growth prior to the Global Financial Crisis in 2007-08 (-0.2 pp and -0.4pp), investment demand in EA and RoW was contributing positively to EA GDP growth during 2007-08 (0.5pp and 0.2pp for EA and 0.4pp and 0.2pp for RoW). The double-dip recession in EA during 2012-13 was, however, driven solely by an increase in domestic investment risk premia without financial spillovers from investment shocks originating in US and RoW.

Figure 6 depicts the dominant role of investment risk premium shocks in explaining US GDP growth. Those shocks account almost fully for the 2008–09 output contraction. Financial spillovers from EA contributed negatively also in the second recession during 2012-13 (up to 0.2pp), while negative shocks to investment risk in RoW contributed positively to US GDP growth (0.5pp in 2010) and supported the rapid recovery after the Global Financial Crisis.

Of particular interest is the contribution of the global financial shock ('global risk appetite') to the three region's GDP growth. Our estimates suggest that global risk appetite had the least prominent role as GDP driver in the US. Figure 6 supports the fact that the Global Financial Crisis originated in US, which is captured by positive domestic risk premium shocks in our model. Moreover, the global risk appetite was still contributing positively in 2007 (0.3pp), whereas positive shocks to the US investment risk premium contributed already negatively in 2007 (-0.6pp).

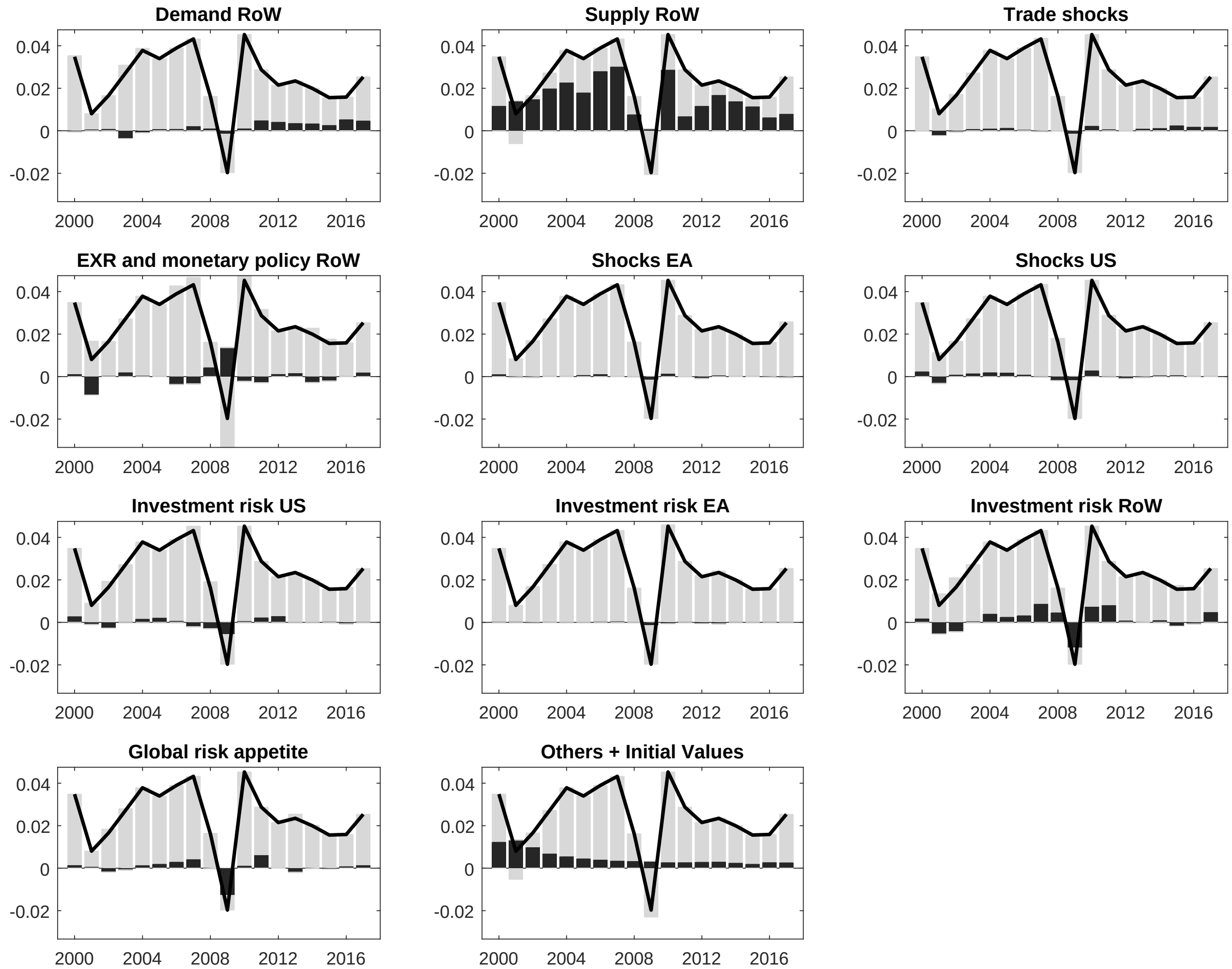
Positive global risk appetite contributed to the pre-crisis boom in EA (up to 0.7pp in 2007) until important adverse shocks occurred (Figure 5). The persistent positive shocks to the domestic investment risk premium contributed negatively (-1.4pp in 2012) to EA GDP growth during the European debt and banking crisis, whereas risk appetite did not play a significant role.

5.4. Smoothed estimates of financial shocks

This subsection provides empirical validation of the estimated global financial shock (risk appetite) and its interaction with the country-specific investment risk premium shocks.

In Figure 8 we compare the global risk shock (dashed line) identified by the model with the estimated common factor of three stock indexes (solid line): S&P 500, STOXX 600 and

Figure 7: Historical decomposition of real GDP growth in RoW

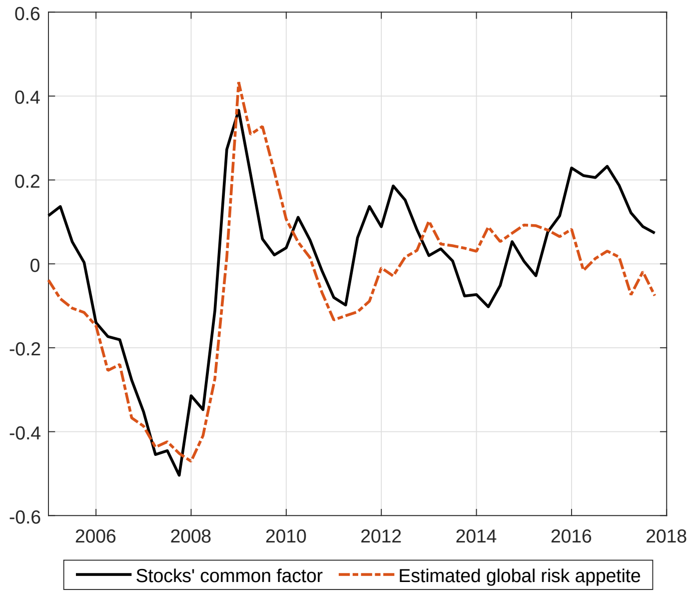


Note: Real GDP growth is shown in annual-on-annual percentage-point deviations from steady-state, which is calibrated globally to 1.35% per year. 0.01 on the y-axis corresponds to 1 pp.

MSCI global. We use the principal component analysis (PCA) to extract the common factors and plot the second ranked principal component (the first is the trend). Figure 8 shows that it follows closely the model's estimated global risk appetite shock. The correlation between the two is 0.8. The global shock matches well the trough-peak-trough movement of the common factor around the financial crisis period, and follows relatively well the subsequent dynamics.

Given the recent studies by Miranda-Agrippino and Rey (2015) and Jordà et al. (2019), who show that the synchronization of financial cycles across countries is primarily driven by fluctuations in risk appetite and global factors, we illustrate the country-specific contribution of our estimated global financial shock (risk appetite) in Figure 9. Together with the coefficient-adjusted risk appetite shock (see dashed lines) we plot the estimated country

Figure 8: Estimated global financial shock and common factor of market indexes.



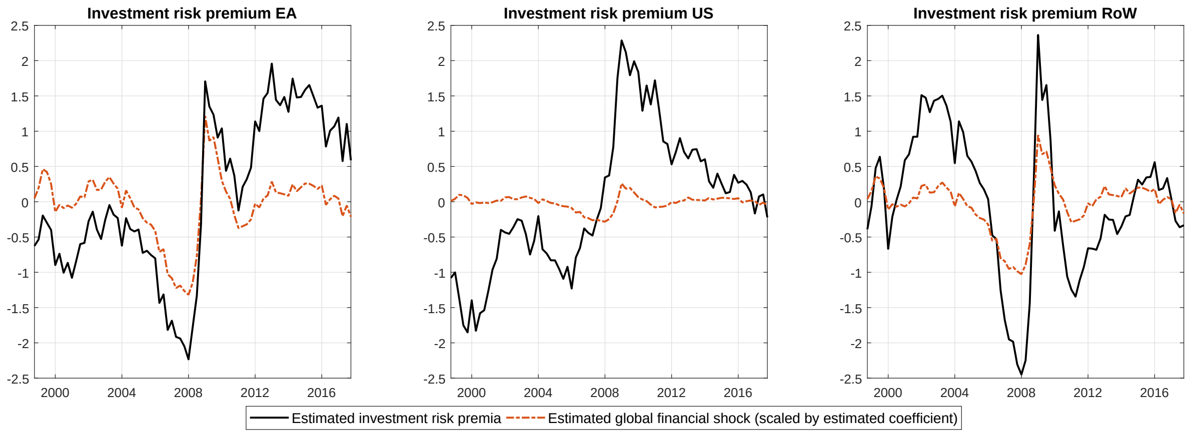
Note: The global financial shock (dashed line) is compared with the extracted common factor from S&P 500, STOXX 600 and MSCI global indexes (solid line). We linearly rescale the common factor so that the standard deviation matches the one of the estimated global shock. 1 on the y-axis corresponds to 1 percent.

specific investment risk premium shocks.

The global pattern of the shock is common to all three countries, but the impact and contribution is estimated by a country-specific coefficient as reported in Table 3. The estimated global risk appetite and the investment risk premia in EA (0.70) and RoW (0.82) are highly positively correlated, while it seems more decoupled in US (0.20). Particular striking is the timing during the financial crisis. While global risk appetite was still positive in the beginning of 2008 (a negative contribution to investment risk), positive shocks to the investment risk premium in US have been already occurring in 2006q3 (see also Figure 6).

Investment risk premia fell prior to the crisis in all three countries (in RoW from a much higher level though), and rose sharply during the financial crisis. In the aftermath of the financial crisis, the US investment risk premium fell gradually and steadily close to its pre-crisis level. The estimated EA investment risk premium initially fell more than the US premium after the financial crisis. However, the EA investment risk premium rose again sharply after the eruption of the sovereign debt crisis in 2011, fell slightly in recent years, but remained significantly above its pre-crisis level. Investment risk premia in RoW dropped sharply after the crisis, almost to its pre-crisis level, but increased steadily in the last years to its early 2000s level.

Figure 9: Estimated investment risk premia and global financial shock.



Note: The global financial shock (dashed line) is adjusted by the estimated country-specific coefficient (τ_k^{ra}). 1 on the y-axis corresponds to 1 percent.

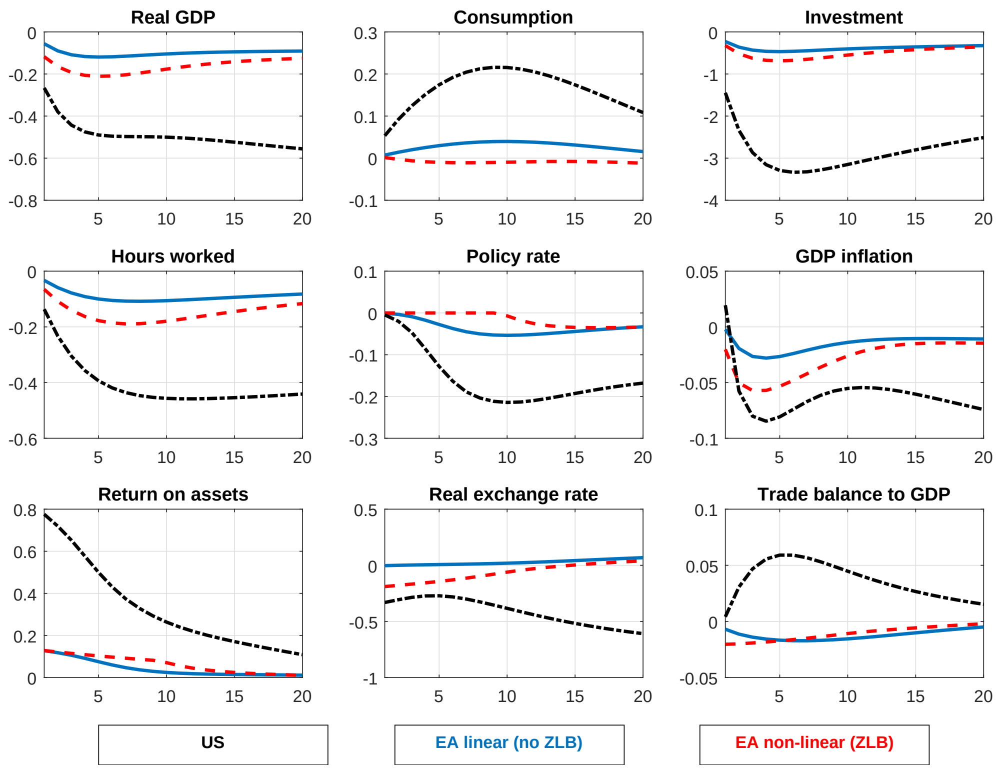
Overall, the investment risk premia seem to be positively correlated. However, the correlations of the estimated investment risk premium shocks are 0.54 for EA-US, 0.31 for EA-RoW, and -0.11 for US-RoW. It becomes evident from Figure 9 that high cross-border correlations of financial shocks arise primarily in periods of huge economic disturbances, e.g. the financial crisis in 2008-09. The correlations of the estimated investment risk premium shocks drop, for instance, significantly to -0.48 for EA-US, and to -0.65 for US-RoW in the post-crisis sample (2010-17). Comparing the correlation of the investment risk premium shock between EA and RoW for the period 2012-17, it drops to -0.28. This suggests that cross-border correlations in financial shocks as in Alpanda and Aysun (2014) or Aysun (2016) can work well for extreme economic disturbances, but can lead to misspecification in case of asymmetric shocks.

6. Assessing financial spillovers in a ZLB environment

This section provides results on the impact of financial spillovers when we allow the zero bound on monetary policy to be occasionally binding. A binding ZLB implies that a decrease in output and inflation through, e.g., negative financial spillovers of foreign shocks to the investment risk, does not lead to a loosening of nominal interest rates while the constraint is binding. Given the actual ZLB environment in EA, we concentrate our analysis on the impact of negative financial spillovers on EA GDP growth.

We implement the ZLB as in Hohberger et al. (2019), following the algorithm by **?**, where the unconstrained nominal interest rate follows the Taylor-type rule as in equation 7. As soon as the actual policy rate is below the lower bound, the nominal interest rate is constrained at $i_{EA}^{LB} = 0$. We make then use of the piecewise linear solution approach (OccBin) by Guerrieri

Figure 10: Dynamic responses to an US investment risk premium shock under ZLB in EA.



Note: The trade balance (normalized by GDP), inflation (p.a.) and interest rate (p.a.) responses are expressed as percentage point deviations from steady-state. All other responses are percent deviations from steady-state. A fall in the exchange rate represents an appreciation. The responses of US, EA linear (no ZLB) and EA non-linear (ZLB) are represented by dash-dotted, continuous and dashed lines, respectively.

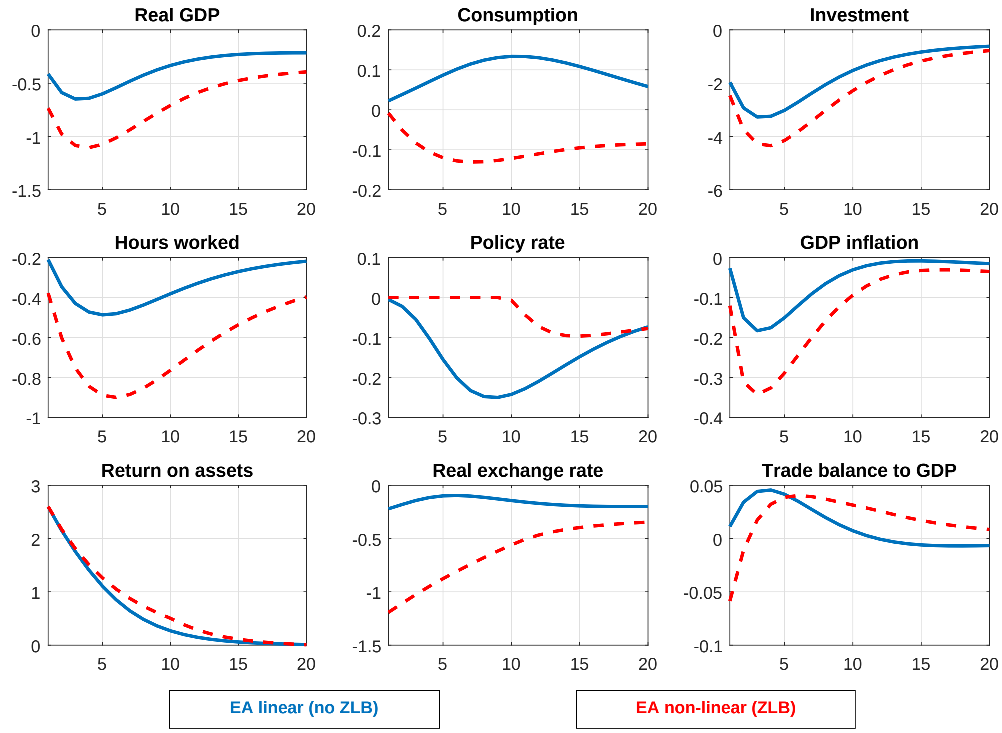
and Iacoviello (2015), which provides a sequence of smoothed variables and shocks consistent with the occasionally binding constraint, i.e. the ZLB being binding or non-binding.[21] This sequence of regimes is reported in Table C.6 in the Appendix.

6.1. Dynamic responses under ZLB

Based on the sequence of regimes in Table C.6, we perform generalized impulse response functions (GIRFs) with a ZLB that is consistent with the estimated timing and duration of the ZLB regime. More precisely, we perform the following exercise: We use as a starting point 2015q1, a period of constrained monetary policy for additional nine quarters (see Table C.6). We shut off the positive shock to the investment risk premium in US and simulate the model with all other shocks. Then we perform another simulation adding the estimated US investment risk premium shock. The difference between the two simulations provides the

[21]For a detailed description of the algorithm see, e.g., Hohberger et al. (2019).

Figure 11: Dynamic responses to a global risk appetite shock in EA under ZLB.



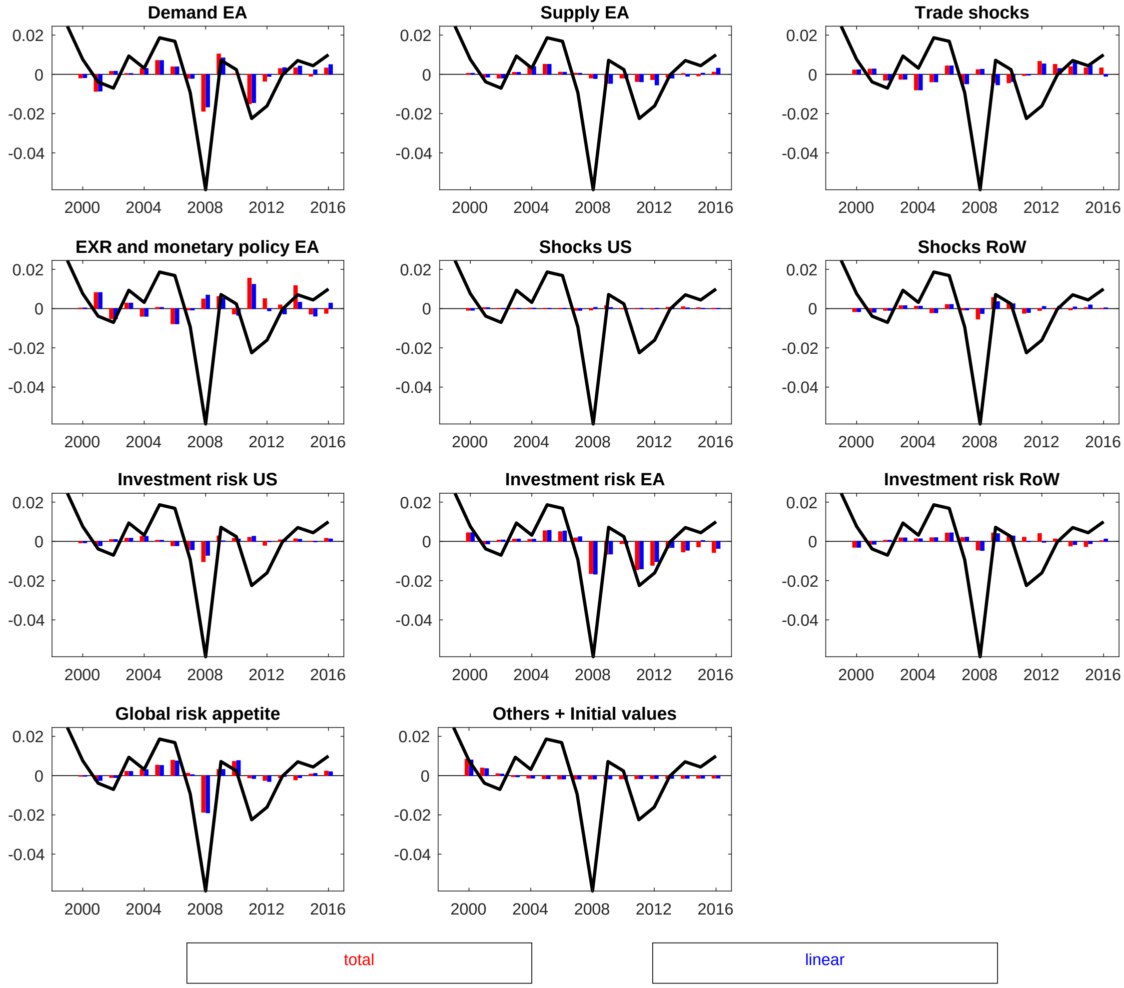
Note: The trade balance (normalized by GDP), inflation (p.a.) and interest rate (p.a.) responses are expressed as percentage point deviations from steady-state. All other responses are percent deviations from steady-state. A fall in the exchange rate represents an appreciation. The responses of EA linear (no ZLB) and EA non-linear (ZLB) are represented by continuous and dashed lines, respectively.

GIRF under ZLB (see Figure 10).

Figure 10 presents the impulse responses of US and EA endogenous variables for a positive shock to the US investment risk premium, in which the ZLB is binding in the EA for nine quarters. The initial shock is an increase (1 standard deviation) in the US investment risk premium of similar magnitude as in the linear case (see Figure 1). Figure 10 shows that financial spillover effects from US to EA amplify when EA monetary policy is constrained at the ZLB. More precisely, the co-movement between US and EA real GDP and employment doubles, and EA consumption remains fairly unaffected without accommodating monetary policy responses.

Figure 11 depicts the dynamic responses of a global financial shock, i.e. a fall in global risk appetite, for EA in a ZLB environment. It provides two valuable insights: First, the negative effects of such global shock on EA endogenous variables are much more pronounced, and second, the crowding in of consumption becomes a crowding out under ZLB. Hence, the shock to the global risk appetite under ZLB mimics an uncertainty shock that dampens aggregate real activity, i.e. consumption and investment simultaneously.

Figure 12: Historical decomposition of real GDP growth in EA under ZLB.



Note: Real GDP growth is shown in annual-on-annual percentage-point deviations from steady-state, which is calibrated as the mean over the sample period. 0.01 on the y-axis corresponds to 1 pp. Black solid lines are data.

6.2. Shock decomposition of real EA GDP growth

This subsection provides an extension of the standard historical shock decompositions to the case of occasionally-binding regimes. The non-linearities stemming from the piecewise linear solution of a model with occasionally binding constraints violate the additive property of shock contributions that pertain to linearized models, i.e. in the non-linear context, the contribution of individual smoothed shocks is not the mere additive superposition of each shock.

Following Hohberger et al. (2019) we apply a counterfactual-based simulation method proposed to measure the effect of given (groups of) shocks in the non-linear context. More precisely, we first compute a 'complementary counterfactual' by setting the targeted shock (or shock group) to zero and subsequently perform OccBin simulations propagating all other historical shocks. The 'complementary counterfactual' provides paths for endogenous variables (e.g., real GDP growth) in the absence of this shock (group). We then calculate the 'total contribution' as the difference between the observed variables and the complementary counterfactual (Figure 12).

Figure 12 depicts that negative contributions to EA real GDP growth during the 2008-09 global recession have been more pronounced due to the expected binding constraint, e.g. the negative spillover from US investment risk in 2009 amplifies from -0.7pp to -1.0pp. The heightened domestic investment risk in EA during the double-dip recession is only marginally amplified (ZLB expectation), while we see particularly more negative contributions in 2015-17 (-0.5pp, -0.3pp, and -0.6pp, respectively, compared to -0.4pp, 0pp, and -0.4pp in the linear case). Given the rather small negative contributions of the global financial shock during the ZLB periods (only in 2015), the differences of global risk appetite compared to the linear shock decomposition are rather marginal. The big positive contribution of EA monetary policy to GDP growth in 2015 captures the beginning of unconventional measures (quantitative easing) by the European Central Bank.

7. Conclusion

We estimate a three region DSGE model of the Euro Area (EA), United States (US) and rest of the world (RoW) to analyze financial spillovers and the impact of a global financial shock. We introduce financial linkages via internationally traded firms' shares. Following recent empirical evidence showing that the unprecedented rise in synchronization of financial cycles across countries is primarily driven by fluctuations in risk appetite, and in particular one global factor, we estimate the region-specific effect of global financial shock.

We find that financial spillovers caused by idiosyncratic shocks to investment risk premia increase by incorporating financial linkages via cross country equity holding. The global financial shock identified by the model is consistent with the observed market indexes and plays a significant role in explaining the 2008-2009 crisis. Our estimation results suggest that the US investment risk premium was already contributing negative to countries' GDP growth in 2007, while global risk appetite had still a positive effect. In the aftermath of the global financial crisis, fluctuations were largely driven by domestic demand shocks, including the 2012-13 European debt and banking crisis. Our model is also able to reproduce the high cross country correlations observed in the data.

Introducing an occasionally Zero Lower Bound in the policy rate of EA, almost doubles the response of EA real GDP to negative US, as well as, global risk premia shocks. The latter, also, changes the transmission mechanism, by mimicking an uncertainty shock, that is triggering a crowding out of consumption together with a decrease in investment.

References

References

Adjemian, S., H. Bastani, M. Juillard, F. Karamé, J. Maih, F. Mihoubi, G. Perendia, J. Pfeifer, M. Ratto, and S. Villemot (2011): "Dynare: Reference Manual Version 4," Dynare Working Papers 1, CEPREMAP.

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, 2690–2721.

Alpanda, S. and U. Aysun (2014): "International transmission of financial shocks in an estimated DSGE model," *Journal of International Money and Finance*, 47, 21–55.

Aysun, U. (2016): "Searching for the source of macroeconomic integration across advanced economies," *Oxford Economic Papers*, 68, 316–339.

Bayoumi, T. (2016): "Dynamic Stochastic General Equilibrium Models and Their Discontents," *International Journal of Central Banking*, 12, 403–411.

Bernanke, B., M. Gertler, and S. Gilchrist (1996): "The Financial Accelerator and the Flight to Quality," *The Review of Economics and Statistics*, 78, 1–15.

Blanchard, O. and J. Galí (2007): "Real Wage Rigidities and the New Keynesian Model," *Journal of Money, Credit and Banking*, 39, 35–65.

Burnside, C. and M. Eichenbaum (1996): "Factor-Hoarding and the Propagation of Business-Cycle Shocks," *American Economic Review*, 86, 1154–1174.

Bussière, M., G. Callegari, F. Ghironi, G. Sestieri, and N. Yamano (2013): "Estimating Trade Elasticities: Demand Composition and the Trade Collapse of 2008-2009," *American Economic Journal: Macroeconomics*, 5, 118–151.

Calés, L., F. Pericoli, and M. Ratto (2017): "Rotated Slice Sampling: applications for the Bayesian Estimation of DSGE models," mimeo, European Commission.

Coenen, G. and R. Straub (2005): "Does Government Spending Crowd in Private Consumption? Theory and Empirical Evidence for the Euro Area," *International Finance*, 8, 435–470.

Devereux, M. B. and J. Yetman (2010): "Leverage Constraints and the International Transmission of Shocks," *Journal of Money, Credit and Banking*, 42, 71–105.

Dolls, M., C. Fuest, and A. Peichl (2012): "Automatic stabilizers and economic crisis: US vs. Europe," *Journal of Public Economics*, 96, 279–294.

European Commission (2013): "Report on Public Finances in EMU 2013," European Economy 4/2013.

Fisher, J. D. (2015): "On the Structural Interpretation of the Smets–Wouters "Risk Premium" Shock," *Journal of Money, Credit and Banking*, 47, 511–516.

Forbes, K. J. and F. E. Warnock (2012): "Capital flow waves: Surges, stops, flight, and retrenchment," *Journal of International Economics*, 88, 235–251.

Georgiadis, G. and M. Jančoková (2017): "Financial globalisation, monetary policy spillovers and macro-modelling: tales from 1001 shocks," Working Paper Series 2082, European Central Bank.

Giovannini, M., S. Hohberger, R. Kollmann, M. Ratto, W. Roeger, and L. Vogel (2018): "Euro Area and U.S. External Adjustment: The Role of Commodity Prices and Emerging Market Shocks," *Journal of International Money and Finance, forthcoming*.

Guerrieri, L. and M. Iacoviello (2015): "OccBin: A toolkit for solving dynamic models with occasionally binding constraints easily," *Journal of Monetary Economics*, 70, 22–38.

Hohberger, S., R. Priftis, and L. Vogel (2019): "The macroeconomic effects of quantitative easing in the euro area: Evidence from an estimated DSGE model," *Journal of Economic Dynamics and Control*, 108.

Jordà, Ò., M. Schularick, A. M. Taylor, and F. Ward (2019): "Global Financial Cycles and Risk Premiums," *IMF Economic Review*, 67, 109–150.

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

Kollmann, R. (2013): "Global Banks, Financial Shocks, and International Business Cycles: Evidence from an Estimated Model," *Journal of Money, Credit and Banking*, 45, 159–195.

Kollmann, R., Z. Enders, and G. J. Müller (2011): "Global banking and international business cycles," *European Economic Review*, 55, 407–426.

Kollmann, R., B. Pataracchia, R. Raciborski, M. Ratto, W. Roeger, and L. Vogel (2016): "The post-crisis slump in the Euro Area and the US: Evidence from an estimated three-region DSGE model," *European Economic Review*, 88, 21–41.

Kollmann, R., M. Ratto, W. Roeger, J. in't Veld, and L. Vogel (2015): "What drives the German current account? And how does it affect other EU Member States?" *Economic Policy*, 30, 47–93.

Krishnamurthy, A. and A. Vissing-Jorgensen (2012): "The Aggregate Demand for Treasury Debt," *Journal of Political Economy*, 120, 233–267.

Miranda-Agrippino, S. and H. Rey (2015): "World Asset Markets and the Global Financial Cycle," CEPR Discussion Papers 10936, C.E.P.R. Discussion Papers.

Neal, R. (2003): "Slice Sampling," *The Annals of Statistics*, 31, 705–741.

Perri, F. and V. Quadrini (2018): "International Recessions," *American Economic Review*, 108, 935–984.

Planas, C., M. Ratto, and A. Rossi (2015): "Slice sampling in Bayesian estimation of DSGE models," mimeo, European Commission.

Rotemberg, J. J. (1982): "Monopolistic Price Adjustment and Aggregate Output," *Review of Economic Studies*, 49, 517–531.

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

Sidrauski, M. (1967): "Rational Choice and Patterns of Growth in a Monetary Economy," *The American Economic Review*, 57, 534–544.

Taylor, J. B. (1993): "Discretion versus policy rules in practice," *Carnegie-Rochester Conference Series on Public Policy*, 39, 195–214.

Vitek, F. (2014): "Policy and Spillover Analysis in the World Economy: A Panel Dynamic Stochastic General Equilibrium Approach," IMF Working Papers 14/200, International Monetary Fund.

——— (2017): "Policy, Risk and Spillover Analysis in the World Economy. A Panel Dynamic Stochastic General Equilibrium Approach," IMF Working Papers 17/89, International Monetary Fund.

Appendix A. Model description

Appendix A.1. Firms

The Ricardian households maximise the present value of the expected stream of future utility subject to equation (1). The resulting FOCs for

$$\lambda^s_{j,k,t} = (C^s_{k,t} - h_k C^s_{k,t-1})^{-\theta_k}, \tag{A.1}$$

$$1 = \tilde{\beta}_t E_t \left[\frac{\lambda^s_{j,k,t+1}}{\lambda^s_{j,k,t}} \frac{(1 + i^{rf}_{k,t}}{1 + \pi^{C,vat}_{k,t+1}} \right], \tag{A.2}$$

$$1 = \tilde{\beta}_t E_t \left[\frac{\lambda^s_{j,k,t+1}}{\lambda^s_{j,k,t}} \frac{(1 + i^G_{k,t}) - \left(\varepsilon^B_{k,t} + \alpha^{b_0}_k \right)}{1 + \pi^{C,vat}_{k,t+1}} \right], \tag{A.3}$$

$$1 = \tilde{\beta}_t E_t \sum_l s^S_{l,k} \left[\frac{\lambda^s_{j,l,t+1}}{\lambda^s_{j,l,t}} \frac{e_{l,k,t+1}}{e_{l,k,t}} \frac{(1 + i^S_{k,t+1}) - \left(\alpha^{S_0}_k + \varepsilon^S_{l,t} \right)}{1 + \pi^{C,vat}_{l,t+1}} \right]. \tag{A.4}$$

$$1 = \tilde{\beta}_t E_t \left[\frac{\lambda^s_{j,k,t+1}}{\lambda^s_{j,k,t}} \frac{(1 + i^W_{k,t}) \frac{e_{RoW,k,t+1}}{e_{RoW,k,t}} - \left(\varepsilon^{bw}_{k,t} + \alpha^{bw_0}_k + \alpha^{bw_1}_k \frac{e_{RoW,k,t} B^W_{k,t}}{P^Y_{k,t} Y_{k,t}} \right)}{1 + \pi^{C,vat}_{k,t+1}} \right] \tag{A.5}$$

$\alpha^{bw1}_k \frac{e_{RoW,k,t} B^W_{k,t}}{P^Y_{k,t} Y_{k,t}}$ captures a debt-dependent country risk premium on net foreign asset holdings as external closure to ensure long-run stability (see Schmitt-Grohe and Uribe, 2003; Adolfson et al., 2008).

The optimality conditions are similar to standard Euler equations, but incorporate asset-specific risk premia similar to Vitek (2014, 2017), which depend on exogenous shocks ε^B_{kt}, ε^S_{kt}, $\varepsilon^b w_{kt}$. Combining the Euler equation for the risk-free bond (A.2) with (**??**), (2) and (A.5), we obtain the approximated following expressions:

$$i^G_{k,t} = i^{rf}_{k,t} + rprem^G_{k,t},$$

$$i^S_{k,t} = i^{rf}_{k,t} + rprem^S_{k,t},$$

$$E_t \left[\frac{e_{RoW,k,t+1}}{e_{RoW,k,t}} \right] i^W_{k,t} = i^{rf}_{k,t} + rprem^W_{k,t},$$

where $rprem^G_{k,t}$ and $rprem^W_{k,t}$ are risk premia on domestic government bonds and foreign bonds, respectively, and $rprem^S_{k,t}$ is a risk premium on domestic shares. This allows capturing both the international spillovers that occur via the financial market channel, and the financial frictions that have contributed to the financial crisis.[22]

Appendix A.2. Firms

Given the Lagrange multiplier associated with the technology constraint, μ^y, the FOCs with respect to labour, labour hoarding, capital, investment, and capacity utilisation are given by:

$$(1-\tau_k^K)\frac{W_{k,t}}{P_{k,t}^Y} = \alpha_k\left(\mu_{k,t}^y - \varepsilon_{k,t}^{ND}\right)\frac{Y_{k,t}}{N_{k,t}-FN_{k,t}} - \frac{\partial adj_{k,t}^N}{\partial N_{k,t}} + E_t\Big[\frac{1+\pi_{k,t+1}^Y}{1+i_{k,t+1}^s}\frac{\partial adj_{k,t+1}^N}{\partial N_{k,t}}\Big], \quad \text{(A.6)}$$

$$\begin{aligned}\mu_{k,t}^y\alpha_k\frac{Y_{k,t}}{N_{k,t}-FN_{k,t}} &= -\frac{Y_{k,t}}{Actr_{k,t}Pop_{k,t}}\Big(\gamma_k^{FN,1}+\gamma_k^{FN,2}\Big(\frac{FN_{k,t}}{Actr_{k,t}Pop_{k,t}}-\bar{FN}\Big)\Big)\\ &+ \frac{\partial adj_{k,t}^N}{\partial FN_{k,t}} - E_t\Big[\frac{1+\pi_{k,t+1}^Y}{1+i_{k,t+1}^s}\frac{\partial adj_{k,t+1}^N}{\partial FN_{k,t}}\Big], \quad \text{(A.7)}\end{aligned}$$

$$\begin{aligned}Q_{k,t} &= E_t\Bigg[\frac{1+\pi_{k,t+1}^Y}{1+i_{k,t+1}^s}\frac{P_{k,t+1}^I}{P_{k,t+1}^Y}\frac{P_{k,t}^Y}{P_{k,t}^I}\\ &\Bigg(\tau_k^K\delta_k - \frac{\partial adj_{k,t}^{CU}}{\partial K_{k,t-1}} + Q_{k,t+1}(1-\delta_k) + (1-\alpha_k)\mu_{k,t+1}^Y\frac{P_{k,t+1}^Y}{P_{k,t+1}^I}\frac{Y_{kt+1}}{K_{k,t}^{tot}}\Bigg)\Bigg], \quad \text{(A.8)}\end{aligned}$$

$$\begin{aligned}Q_{k,t} &= \Big[1+\gamma_k^{I,1}\Big(\frac{I_{k,t}}{K_{k,t-1}}-\delta_{k,t}^K\Big)+\gamma_k^{I,2}\frac{(I_{k,t}-I_{k,t-1}\exp(g_k^Y+g_k^{PI}))}{K_{k,t-1}}\Big]\\ &- E_t\Big[\frac{1+\pi_{k,t+1}^Y}{1+i_{k,t+1}^s}\frac{P_{k,t+1}^I}{P_{k,t+1}^Y}\frac{P_{k,t}^Y}{P_{k,t}^I}\exp(g_k^Y+g_k^{PI})\gamma_k^{I,2}\frac{(I_{k,t+1}-I_{k,t}\exp(g_k^Y+g_k^{PI}))}{K_{k,t}}\Big], \quad \text{(A.9)}\end{aligned}$$

$$\mu_{k,t}^y(1-\alpha_k)\frac{Y_{k,t}}{CU_{k,t}}\frac{P_{k,t}^Y}{P_{k,t}^I} = K_{k,t-1}^{tot}\Big[\gamma_k^{u,1}+\gamma_k^{u,2}(CU_{k,t}-1)\Big], \quad \text{(A.10)}$$

where $Q_{k,t} = \mu_{k,t}/\frac{P_{k,t}^I}{P_{k,t}^Y}$ represents Tobin's Q and $Actr_{k,t}Pop_{k,t}$ is the active labour force of the domestic country. Equations (A.6) and (A.7) characterise the optimal level of labour input, taking into account labour hoarding. While (A.6) equates the marginal cost of labour to its marginal productivity, equation (A.7) determines the optimal level of labour hoarding at the

[22]Observationally, this approach is equivalent to assuming exogenous risk premia as well as endogenous risk premia derived, e.g., in the spirit of Bernanke et al. (1996).

expense of the loss in the marginal productivity. Equation (A.8) and (A.9) define the Tobin's Q, which is equal to the replacement cost of capital (the relative price of capital). Finally, (A.10) describes capacity utilisation, where the left-hand side indicates the additional output produced while the right-hand side captures the costs of higher utilisation rate.

Given the Rotemberg set-up and imposing the price symmetry condition, $P^Y_{i,k,t} = P^Y_{k,t}$, the FOC with respect to $P^Y_{i,k,t}$ yields the New Keynesian Phillips curve:

$$\begin{aligned}\mu^y_{k,t}\sigma^Y_k &= (1-\tau^K_k)(\sigma^Y_k - 1) + \sigma^Y_k \gamma^P_k \frac{P^Y_{k,t}}{P^Y_{k,t-1}}\left(\pi^Y_{k,t} - \bar{\pi}\right) \\ &- \sigma^Y_k \gamma^P_k \left[\frac{1+\pi^Y_{k,t+1}}{1+i^s_{k,t+1}} \frac{P^Y_{k,t+1}}{P^Y_{k,t}} \frac{Y_{k,t+1}}{Y_{k,t}} \left(\pi^Y_{k,t+1} - \bar{\pi}\right)\right] + \sigma^Y_k \varepsilon^{\mu}_{k,t},\end{aligned}$$

where $\varepsilon^{\mu Y}_{k,t}$ is the inverse of the markup shock.

In order to allow firms to be less forward-looking in their price setting, we introduce a backward-looking term $\pi^\star_{k,t} = \rho^{\pi^\star}_k \bar{\pi} + (1-\rho^{\pi^\star}_k)(\pi^Y_{k,t-1})$, where $\bar{\pi}$ is the steady-state inflation. The final New Keynesian Phillips curve takes then the following form:

$$\begin{aligned}\mu^y_{k,t}\sigma^Y_k &= (1-\tau^K_k)(\sigma^Y_k - 1) + \sigma^Y_k \gamma^P_k \frac{P^Y_{k,t}}{P^Y_{k,t-1}}\left(\pi^Y_{k,t} - \bar{\pi}\right) \\ &- \sigma^Y_k \gamma^P_k \frac{1+\pi^Y_{k,t+1}}{1+i^s_{k,t+1}} \frac{P^Y_{k,t+1}}{P^Y_{k,t}} \frac{Y_{k,t+1}}{Y_{k,t}} \left[sfp_k\left(\pi^Y_{k,t+1} - \bar{\pi}\right) + (1-sfp_k)(\pi^\star_{k,t} - \bar{\pi})\right] \\ &+ \sigma^Y_k \varepsilon^{\mu Y}_{k,t},\end{aligned} \qquad (A.11)$$

where sfp_k is the share of forward-looking price setters.

Appendix B. Data source and transformations

B.1. Data sources

Data for the EA (quarterly national accounts, fiscal aggregates, quarterly interest and exchange rates) are taken from Eurostat. Corresponding data for the US come from the Bureau of Economic Analysis (BEA) and the Federal Reserve. EA and US imports of industrial supplies from RoW are based on BEA data and on Eurostat Comext data. RoW series are constructed on the basis of the IMF International Financial Statistics (IFS) and World Economic Outlook (WEO) databases.

B.2. Constructing of data series for RoW variables

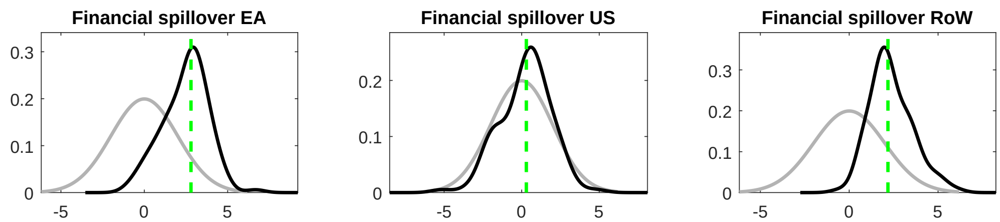
Series for GDP and prices in the RoW starting in 1999 are constructed on the basis of data for the following 58 countries: Albania, Algeria, Argentina, Armenia, Australia, Azerbaijan, Belarus, Brazil, Bulgaria, Canada, Chile, China, Colombia, Croatia, Czech Republic, Denmark, Egypt, Georgia, Hong Kong, Hungary, Iceland, India, Indonesia, Iran, Israel, Japan, Jordan, Korea, Lebanon, Libya, FYR Macedonia, Malaysia, Mexico, Moldova, Montenegro, Morocco, New Zealand, Nigeria, Norway, Philippines, Poland, Romania, Russia, Saudi Arabia, Serbia, Singapore, South Africa, Sweden, Switzerland, Syria, Taiwan, Thailand, Tunisia, Turkey, Ukraine, United Arab Emirates, United Kingdom, and Venezuela. The RoW data are annual data from the IMF International Financial Statistics (IFS) and World Economic Outlook (WEO) databases.

B.3. List of observables

The estimation uses the time series information for 60 endogenous variables and initial values for additional 4 variables. The observables are: Total factor productivity: EA,US; Population: EA, US, RoW; Labor force participation rate: EA,US; Net imports of industrial supplies (from RoW): EA,US; Price of imports of industrial supplies (from RoW): EA,US; Change in inventories (residually computed): EA,US; Trade balance of Services (residually computed as difference of trade balance of goods and services and trade balance of goods): EA,US; GDP deflator: EA, US, RoW; Real GDP: EA, US, RoW; CPI deflator (divided by GDP deflator): EA,US; Total investment (private+public) deflator (divided by GDP deflator): EA,US; Exports (goods) deflator (divided by GDP deflator): EA,US; Imports (goods) deflator (divided by GDP deflator): EA,US; Total Hours: EA,US; Nominal interest rate: EA,US, RoW; Government consumption (as a share of GDP): EA,US; Government investment (as a share of GDP): EA,US; Transfers (as a share of GDP): EA,US; Government debt (as a share of GDP), computed as cumulative sum of budget deficits: EA,US; Government investment deflator (divided by GDP deflator): EA,US; Government consumption deflator (divided by GDP deflator): EA,US; Private consumption (as a share of GDP): EA,US; Total investment, private and public (as a share of GDP): EA,US; Wage bill (as a share of GDP): EA,US; Exports (goods) (as a share of GDP): EA,US; Gov't interest payments (as a share of GDP): EA,US; Stock of physical capital (only initial value used): EA,US; Oil price (Brent) in US dollars; Nominal exchange rate Euro/Dollar; Nominal effective exchange rate, EA; Net Foreign Assets (as a share of GDP) (only initial value used): EA,US.

Appendix C. Estimation results

Figure C.1: Prior and posterior distribution of the global risk coefficients.



Note: All parameters (τ^{ra}) use the same prior distribution (grey). The dashed vertical line shows the mode, the black depicts the posterior distribution.

Table C.6: Historical sequence of occasionally binding regimes.

time	regime sequence	starting period of regime
2007Q1	0	1
2007Q2	0	1
2007Q3	0	1
2007Q4	0	1
2008Q1	0	1
2008Q2	0	1
2008Q3	0	1
2008Q4	0	1
2009Q1	0 1 0	1 6 10
2009Q2	0 1 0	1 4 9
2009Q3	0 1 0	1 3 8
2009Q4	0 1 0	1 3 7
2010Q1	0	1
2010Q2	0	1
2010Q3	0	1
2010Q4	0	1
2011Q1	0	1
2011Q2	0	1
2011Q3	0	1
2011Q4	0	1
2012Q1	0	1
2012Q2	0	1
2012Q3	0 1 0	1 7 10
2012Q4	0 1 0	1 6 11
2013Q1	0 1 0	1 4 12
2013Q2	0 1 0	1 4 10
2013Q3	0 1 0	1 3 10
2013Q4	0 1 0	1 3 10
2014Q1	0 1 0	1 3 10
2014Q2	0 1 0	1 3 10
2014Q3	0 1 0	1 2 9
2014Q4	1 0	1 9
2015Q1	1 0	1 9
2015Q2	1 0	1 8
2015Q3	1 0	1 6
2015Q4	1 0	1 6
2016Q1	1 0	1 6
2016Q2	1 0	1 5
2016Q3	1 0	1 5
2016Q4	1 0	1 3
2017Q1	1 0	1 3
2017Q2	1 0	1 3
2017Q3	1 0	1 3
2017Q4	1 0	1 3

Note: First column: [0] unconstrained; [0 1 0] indicates an unconstrained regime, but agents expect to be binding in the future; [1 0] indicates a constrained regime. Second column: [1 6 10] indicates an expected constrained regime starting in 6 periods ahead and last for additional 4 periods; [1 9] indicates a constrained regime with an expected duration of additional 9 periods.