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Financial spillover and global risk in a multi-region model of the world economy☆

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ABSTRACT

This paper estimates a three-region DSGE model (EA, US, RoW) with international financial linkages in the form of cross-border equity holding and allowing for region-specific as well as global financial shocks, which match empirical measures of financial tightness and global stock market valuation. Spillover from financial shocks increases with international financial integration and is practically zero under full home bias in normal times. The global risk captures international synchronisation of financial cycles. Spillover of financial shocks is amplified at the zero lower bound, at which investment risk takes on the characteristics of a general uncertainty shock. The model results suggest that integrated financial markets should provide a powerful motivation for international policy coordination to prevent financial turmoil.

1. Introduction

Growing interconnectedness in recent years and decades has increased the potential for spillover of economic developments across countries and continents. Examples include the global impact of commodity price shocks, the spread of financial crises, the effect of trade policies on trading partners, and the recent COVID-19 pandemics, which has disrupted value chains and transport around the globe. Economic spillover can be "smooth" (proportional), but at times also highly "disruptive" (discontinuous), adding to economic uncertainty. Trade effects of monetary and fiscal policy under "stable" import and export demand equations are examples of rather "smooth" (proportional) spillover. Banking crisis and financial panics, to the contrary, can be highly disruptive and can trigger contagion even in the absence of direct or indirect real or financial linkages between pairs of countries, associated, e.g., with changing investor "sentiments" or a re-assessment

☆ The views expressed in this paper are those of the authors only and should not be attributed to the European Commission.

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of financial risks ("wake-up calls", adjustment of credit ratings). Similarly, the COVID-19 pandemics has led to serial and increasingly dramatic forecast revisions in conjunction with a rising awareness for the sheer complexity of international linkages and interdependence.

The apparent importance of foreign factors for the business cycle of open economies contrasts with the difficulty that macroeconomic models and, notably, standard dynamic stochastic general equilibrium (DSGE) models have in generating and reproducing sizable spillover effects. In recent years, several studies have emphasised the fact that standard DSGE models are not able to endogenously reproduce observed degrees of global spillover (e.g. Alpanda and Aysun, 2014; Aysun, 2016; Bayoumi, 2016; Georgiadis and Jancokova, 2017; Justiniano and Preston, 2010). One reason for the failure of standard open-economy DSGE models to reproduce quantitatively plausible degrees of economic spillover is their predominant focus on bilateral trade in (final) goods and services, which often accounts for a rather small part of total output. On the contrary, financial globalisation and market exposure matter for international shock transmission, especially in periods of financial stress, but have not yet become standard elements of structural open-economy models beyond the common assumptions of perfect international financial markets or trade in one risk-free international bond.

The DSGE literature has put forward two types of model extensions to amplify international spillover through financial channels: (i) cross-country correlation of shocks, and (ii) endogenous international shock transmission via portfolio reallocation or financial frictions (e.g., constrained domestic or global banks, and leveraged investors). Within the first strand of this literature, Justiniano and Preston (2010) allow for the cross-country correlation of real and financial shocks (including global commodity prices, financial risk, and technological innovations), which strengthens the co-movement between Canada and the United States (US) in terms of output and inflation volatility in their model. Alpanda and Aysun (2014) show, in an estimated two-country model with the Euro Area (EA) and the US, that cross-border correlation of financial shocks considerably improves the model's ability to replicate international co-movement in macroeconomic time series. Similarly, Aysun (2016) demonstrates that an estimated EA-US two-country model with correlated demand and financial shocks can replicate the observed EA-US co-movement of economic activity, demand, and inflation.

Studies within the second strand of the spillover literature model portfolio decisions of international investors, or leveraged global actors (banks or investors) suddenly hit by a negative wealth shock that induces a tightening of credit supply or investment across countries and triggers strong co-movement in the cross section. Section 2 provides a short and selective overview of the respective literature on financial spillover channels in DSGE models together with some facts on international financial integration.

The empirical literature, e.g. Rose and Spiegel (2011), emphasises that models with financial linkages should be able to not only explain particular country cases in isolation, but also the varying severity of the global financial crisis across a larger sample of countries. The DSGE literature, to date, has focused on small models, notably two-country configurations, which do not lend themselves to broader comparisons of diverse experience with financial spillover in a cross-section of countries.

This paper contributes to the spillover literature along several dimensions: (i) We introduce financial spillover through cross-regional equity ownership (international equity portfolios), with equity valuation being affected by region-specific and a global investment risk shocks ('global risk appetite'); (ii) we analyse financial spillover in an estimated three-region DSGE model of the EA, the US, and the rest of the world (RoW); and (iii) we provide results on financial spillovers when the zero lower bound (ZLB) on monetary policy is occasionally binding.

Our model thus "combines" the two strands of financial spillover modelling mentioned above, i.e. structural channels (international equity portfolios) and internationally correlated shocks (global risk shock). It shows how spillover of region-specific shocks to investment risk strengthens with international equity diversification. It also replicates the observed co-movement of investment and real GDP growth across the three regions and finds that the global risk appetite shock has been more important than spillover of other regions' idiosyncratic risk shocks during the 2008–09 crisis, whereas the second recession (2012–13) in EA is rather associated with domestic risk factors. The estimated global risk shock tracks very closely the common component of three stock market indices, namely the S&P 500, the STOXX 600, and the MSCI global. Under the ZLB, (i) financial spillover amplifies in the absence of monetary stabilisation, and (ii) investment risk shock behaves like uncertainty shocks that dampen consumption and investment simultaneously.

Our results are in line with the empirical findings by Jordà et al. (2019), who document that the unprecedented surge in the synchronisation of financial cycles across countries has been driven primarily by global fluctuations in equity prices. Using credit, house price and equity price data for 17 advanced countries that spans over 150 years, they document that equity market co-movement has reached historical heights (Spearman correlation of 0.8), followed by credit market co-movement (correlation of 0.4). Jordà et al. (2019) attribute the increase in equity price synchronisation mostly to fluctuations in risk appetite, rather than to co-movement in dividends or risk-free rates. Fluctuations in the returns to risky assets are explained mainly by a global factor, related to risk aversion and market volatility measures (see also Miranda-Agrippino and Rey, 2015).

The remainder of the paper proceeds as follows. Section 2 provides some stylised facts on international financial integration and a brief overview over the literature on international financial linkages in DSGE models. Section 3 outlines the structure of our model. Section 4 describes the model solution and estimation methodology. Section 5 discusses posterior estimates and model fit. Section 6 assesses the role of international equity portfolios and global risk shocks for international spillover by inspecting impulse responses, cross-correlations, historical shock decompositions, and smoothed

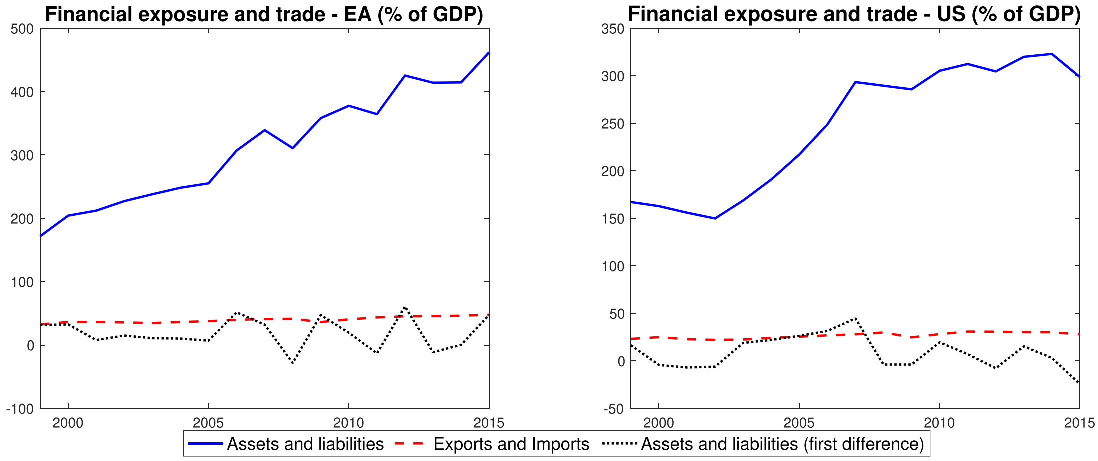

Fig. 1. EA and US financial exposure and trade openness. Source: Own calculations, based on Lane and Milesi-Ferretti (2018), BEA and Eurostat. EA trade in goods and services is total trade of EA Member States corrected by intra-EA trade.

estimates of the financial shocks. Section 7 presents results from the model with occasionally binding ZLB constraint. Section 8 summarises the paper and concludes.

2. International financial exposure and modelling approaches

Most open-economy DSGE models restrict international financial linkages to one internationally traded bond. Combined with the frequent assumption of zero net foreign assets (NFAs) in steady state, these models imply very little international financial exposure. Kollmann (2015) shows that the data rejects the incomplete market model with a single internationally traded bond. The data shows higher NFA volatility, which implies that the simple model underestimates cross-country wealth transfers.

The absence of sizable financial exposure in standard DSGE models also conflicts with data that shows large international asset and liability positions that make economies vulnerable to strong valuation effects in the wide sense of the term, including currency, default and liquidity risks. Fig. 1 shows total financial exposure, defined as the sum of foreign assets and foreign liabilities, relative to domestic GDP for the EA and the US, with data taken from the Lane and Milesi-Ferretti (2018) database, and trade openness, defined as the sum of exports and imports of goods and services over domestic GDP.

The comparison in Fig. 1 shows that financial exposure as the value of foreign assets and liabilities has approximately doubled in both regions between 1999 and 2015. Financial exposure is also much larger and has grown more strongly than trade openness over the past two decades. We show also the change in the sum of foreign assets and liabilities, which is more volatile than trade, but reaches comparable magnitudes in absolute terms.[1]

The disaggregation of EA and US financial exposure in Fig. 2 provides interesting additional information. The series show that firm ownership in form of *FDI* and *portfolio equity* has been the largest element in recent years, together accounting for half or more of total EA and US exposure in 2015. *Portfolio debt*, which in particular includes bonds, accounts for a much smaller portion, similarly to *other investment*, which includes deposits and loans. The residual *others* includes financial derivatives and foreign exchange reserves.

The literature on endogenous transmission channels broadly relies on two approaches to incorporate financial spillover in DSGE models, namely: (i) investors adjusting a portfolio of (imperfectly substitutable) domestic and foreign assets in response to shocks, or (ii) internationally operating investors or banks with financial constraints that tighten in response to capital losses (valuation losses, loan defaults) or bank runs.

Blanchard et al. (2005) is an example of the first (portfolio rebalancing) approach, introducing cross-border holding of domestic and foreign assets that are imperfect substitutes. The optimal portfolio allocation provides demand functions, where the demand for, and hence the value of, a particular asset varies with the expected (relative) return. Vogel (2010) applies the framework with a focus on cross-border firm ownership. Alpanda and Kabaca (2020), and Hohberger et al. (2019) focus on internationally traded government bonds in the analysis of quantitative easing policies in open economies. Benigno and Thoenissen (2008) introduce internationally traded domestic and foreign bonds as middle ground between the single internationally traded bond and the complete markets model, as the latter is also rejected by the data (e.g. Kollmann, 1995).

The second approach focuses on internationally operating and financially constrained investors and banks. Devereux and Yetman (2010) analyse the spillover from shocks to the real economy in the presence of leverage-constrained international investors. Kollmann et al. (2011) introduce a global bank with cross-border deposits and loans and a capital requirement

[1] Changes in the asset and liability position are due not only to financial (dis-)investment, but also to changes in the valuation of assets and liabilities.

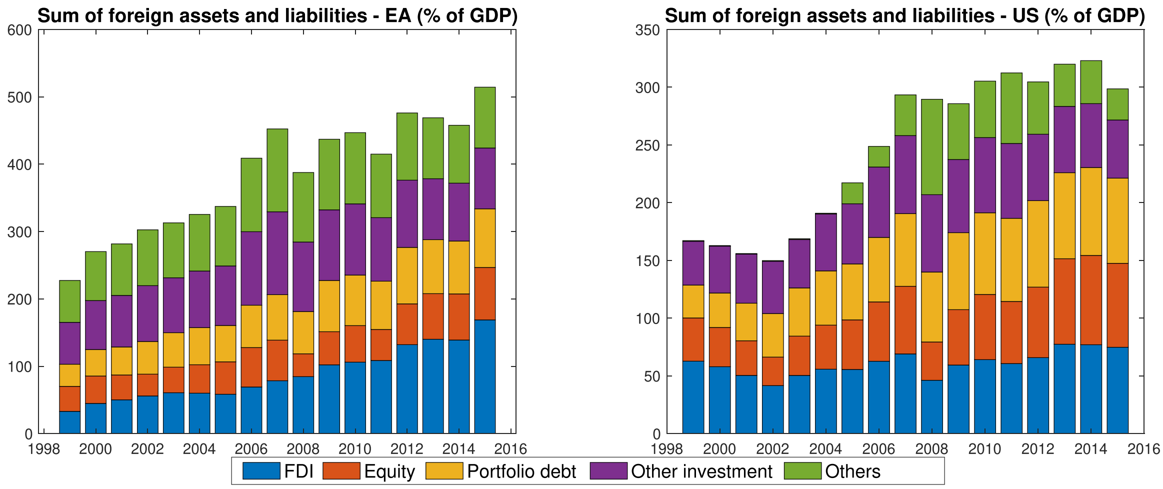

Fig. 2. EA and US financial exposure by classes of assets and liabilities. Source: Own calculations, based on Lane and Milesi-Ferretti (2018).

in a two-country model to generate an endogenous transmission of loan losses, leading to a simultaneous decline in economic activity in both regions. The estimated EA-US version by Kollmann et al. (2013) also finds positive co-movement in economic activity in response to financial shocks in the presence of internationally operating financial intermediaries with credit frictions. Similarly, Ueda (2012) builds a model with credit constraints and financial intermediaries that engage in cross-border borrowing and lending, where adverse shocks in one economy propagate to other countries and lead to synchronised cycles in goods, factor and financial markets. Alpanda and Aysun (2014) also introduce cross-border bank lending in an EA-US model and show that the channel strengthens spillover in economic activity.

The choice of modelling international financial linkages through cross-border equity holding associates our paper with the first group of models above, augmented by the global (i.e. internationally correlated) risk shock as mentioned in the introduction. The decomposition in Fig. 2 lends *prima facie* support to our choice to model financial exposure by cross-border firm ownership, i.e. FDI and international portfolio equity diversification, rather than by deposit and loan chains. The different channels may interact in the transmission of shocks, however. Valuation losses on an international equity or bond portfolio, e.g., may force banks to reduce loan supply to domestic or international lenders.[2]

3. The model

The model set-up builds on Giovannini et al. (2019) and features three regions: the Euro Area (EA), the United States (US), and the rest of the world (RoW). Given our focus on international financial spillovers, we extend the RoW block by physical capital. The regional blocks 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 US also feature a government sector.

We distinguish between two types of households in EA and US: Ricardian households, who are infinitely-lived and have access to financial markets, can smooth their consumption and own the firms (equity); liquidity-constrained households, who are without access to financial markets, consume their disposable wage and transfer income and do not hold any financial wealth. Both types of households provide labour services to domestic firms, at a common wage set by a labour union with monopoly power. The simplified RoW is inhabited only by Ricardian households that supply labour inelastically.

In the domestic production sector, monopolistically competitive firms produce a variety of differentiated intermediate goods, which are assembled by perfectly competitive firms into an aggregate domestic value added. In a final step, perfectly competitive firms produce total domestic output by combining domestic value added with industrial supplies (IS). RoW is the only producer of IS, consisting of energy (oil) and other commodities, in the model.

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

The EA and US fiscal authorities purchase final goods and make lump-sum transfers to households. Government expenditure is financed by issuing debt and levying distortionary taxes on labour, corporate profits, and consumption, as well as non-distortionary lump-sum taxes.

[2] It should also be mentioned that the EA and US series in Lane and Milesi-Ferretti (2018) are likely to exaggerate the growth of international FDI in recent years. The FDI data include increases in FDI that are linked to "financial engineering" of multinational corporations. See Lane and Milesi-Ferretti (2018) for further discussion.

The simplified RoW block does not comprise of a fiscal authority. The monetary authorities in the three regions set short-term nominal interest rates following a Taylor rule responding to inflation and the output gap.

The model description below focuses on the main features of the model. More details can be found in Appendix A.

3.1. 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 (1-ω_k^s) is liquidity-constrained (c) and consumes its entire disposable wage and transfer income in each period ("hand-to-mouth"). Household preferences are defined over consumption and leisure. Additionally, Ricardian utility depends on the beginning-of-period financial asset holdings.

3.1.1. 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.[3] Ricardian households have full access to financial markets, which allows them to accumulate wealth, $A_{j,k,t}$, consisting of domestic private risk-free bonds, $B_{j,k,t}^{rf}$, domestic government bonds, $B_{j,k,t}^G$, one internationally traded bond,[4] $B_{j,k,t}^W$, and internationally traded shares, $P_{l,k,t}^S S_{j,l,k,t}$, $\forall\ l \in \{EA, US, RoW\}$:

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

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 foreign shares are issued in foreign currency, hence financial wealth in domestic currency terms also depends on the nominal exchange rate $e_{l,k,t}$. We abstract from optimal portfolio choice and calibrate the portfolio weights ($s_{l,t}^S$) to observed sample means (see Table 1).

Ricardian households derive utility from consumption, $C_{j,k,t}^s$, and incur disutility from labour, $N_{j,k,t}^s$, and from holding risky financial assets, $U_{j,k,t-1}^A$. The instantaneous utility function of savers, $u^s(.)$, is defined as:

$$u_{j,k,t}^s(C_{j,k,t}^s, N_{j,k,t}^s, \frac{U_{j,k,t-1}^A}{P_{k,t}^{C,vat}}) = \frac{1}{1-\theta_k}(C_{j,k,t}^s - h_k C_{k,t-1}^s)^{1-\theta_k} - \frac{\omega_k^N \varepsilon_{k,t}^U}{1+\theta_k^N}(C_{k,t})^{1-\theta_k}(N_{j,k,t}^s)^{(1+\theta_k^N)}$$
$$- (C_{j,k,t}^s - h_k C_{k,t-1}^s)^{-\theta_k} \frac{U_{j,k,t-1}^A}{P_{k,t}^{C,vat}},$$

where $C_{k,t}^s = \int_0^1 C_{j,k,t}^s dj$, h_k measures the strength of external habits in consumption, and ω_k^N indicates the disutility of labour, and $\varepsilon_{k,t}^U$ captures a labour supply shock. Aggregate consumption, $C_{k,t}$, in the second term of the right-hand side is introduced as normalisation to ensure a balanced steady-state growth path. The disutility of holding risky financial assets, $U_{j,k,t-1}^A$, takes the following form:

$$\begin{aligned} U_{j,k,t-1}^A &= \left(\alpha_k^{b_0} + \varepsilon_{k,t-1}^B\right) B_{j,k,t-1}^G + \left(\alpha_k^{bw_0} + \varepsilon_{k,t-1}^{bw}\right) e_{RoW,k,t} B_{j,k,t-1}^W \\ &+ \frac{\alpha_k^{bw_1}}{2} \frac{\left(e_{RoW,k,t-1} NFA_{k,t-1}\right)^2}{P_{k,t-1}^Y Y_{k,t-1}} + \sum_l s_{l,k}^S \left(\alpha_k^{S_0} + \varepsilon_{l,t-1}^S\right) e_{l,k,t} P_{l,k,t-1}^S S_{j,l,k,t-1}. \end{aligned}$$

Internationally traded bonds are subject to transaction costs which are a function of the average NFA position relative to GDP. The asset-specific risk premium depends on an asset specific exogenous shock $\varepsilon^x, x \in \{B, S, bw\}$, and an asset-specific intercept $\alpha^x, x \in \{b_0, S_0, bw_0\}$. By introducing a disutility of holding risky assets, the model captures the households' preference for safe assets, i.e. the risk-free short-term bonds, which generates an endogenous wedge between the returns on risky assets and safe bonds. A similar approach is used by Krishnamurthy and Vissing-Jorgensen (2012), Fisher (2015), Vitek (2014, 2017), and Albonico et al. (2019).[5]

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

[4] We assume without the loss of generality that the internationally traded bond is issued by RoW.

[5] Introducing risky assets in the utility function is along the lines of the money-in-utility approach by Sidrauski (1967), in which model agents derive utility from holding money. In our model, the disutility reflects the utility costs of holding risky assets as opposed to risk-free assets. An alternative approach would be to use transaction costs on risky assets, which, contrary to our preference-based approach, would need to enter the resource constraint of the economy.

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

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

where $P^{C,vat}_{k,t}$ is the private consumption deflator[6], $W_{k,t}$ 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 Eq. (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 and can be found in the A.1

3.1.2. Financial linkages

In light of the empirical evidence for increased global financial integration, discussed in Sections 1 and 2, we incorporate international financial linkages by allowing households to hold a portfolio of domestic and foreign corporate equity. The no-arbitrage condition determines the interest rate (Eq. 2), which depends on the risk perception of each region's households. A shift in EA household preferences towards holding risk-free bonds (i.e. upsurge in assets' riskiness), e.g., affects the return on equity also in other regions, in proportion to the respective foreign region's weight in the equity portfolio of EA households. The return on equity is, hence, determined by:

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

where $\lambda^S_{l,t}$ is the Lagrange multiplier, which is defined by Eq. (A.1) in Appendix A, $\alpha^{S_0}_k$ is a constant spread between the domestic risk-free bond and the risky corporate equity, and $\varepsilon^S_{l,t}$ captures a time-varying country-specific risk premium and a time-varying global risk shock, also labelled 'risk appetite'. The introduction of the latter is motivated by the empirical evidence in Jordà et al. (2019). The global shock affects the various regions proportionally to the estimated country-specific coefficient τ^{ra}_l. The risk premium on equity is defined as:

$$\varepsilon^S_{l,t} = \rho^S_l\varepsilon^S_{l,t-1} + \epsilon^S_{l,t} + \tau^{ra}_l(\varepsilon^{ra}_t - \rho^{ra}\varepsilon^{ra}_{t-1}), \quad \forall l \in \{EA, US, RoW\}$$

where $\varepsilon^S_{l,t}$ is the country-specific investment risk and $\epsilon^S_{l,t}$ its innovation, ε^{ra}_t is the global risk appetite shock, and τ^{ra}_l is the estimated country-specific impact of the global risk shock.

3.1.3. Liquidity-constrained households

Liquidity-constrained households do not have access to financial markets. Hence, the instantaneous utility function, $u^c(.)$, is:

$$u^c_{j,k,t}(C^c_{j,k,t}N^c_{j,k,t}) = \frac{1}{1-\theta_k}(C^c_{j,k,t} - h_kC^c_{k,t-1})^{1-\theta_k} - (C_{k,t})^{1-\theta_k}\frac{\omega^N_k\varepsilon^U_{k,t}}{1+\theta^N}(N^c_{j,k,t})^{1+\theta^N_k}.$$

In each time period, they consume their entire net disposable income, which consists of after-tax labour income and lump-sum transfers from the government:

$$(1+\tau^C_k)P^C_{k,t}C^c_{j,k,t} = (1-\tau^N_k)W_{k,t}N^c_{j,k,t} + T^c_{j,k,t} - tax^c_{j,k,t}.$$

3.1.4. Wage setting

Households provide differentiated labour services, $N^r_{j,k,t}$, with $r = \{s, c\}$, in a monopolistically competitive labour market. A labour union bundles labour hours provided by both types of domestic households proportionally into a homogeneous labour service and resells it to the firms that produce intermediate goods. Since both types of households face the same labour demand schedule, each household works the same number of hours as the average of the economy. The union maximises the weighted average of the discounted future stream of lifetime utility of its members with respect to the

[6] $P^{C,vat}_{k,t}$ 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).

wage, and subject to the weighted sum of their budget constraints, and to the intermediate-goods producing firms' demand for differentiated labour. Nominal rigidity in wage setting takes the form of adjustment costs for changing nominal wages. Additionally, we allow for real wage rigidity as in Blanchard and Galí (2007) and Coenen and Straub (2005). The wage rule is determined by equating the marginal disutility from working, $U^N_{k,t}$, which is identical for all households, to the weighted average of the marginal utility of consumption, $\lambda_{k,t}$, times the real wage adjusted for a wage mark-up:

$$\left[\frac{\mu^w_k U^N_{k,t}}{\lambda_{k,t}}\frac{P^{C,vat}_{k,t}}{P^Y_{k,t}}\right]^{1-\gamma^{wr}_k}\left[(1-\tau^N_k)\frac{W_{k,t-1}}{P^Y_{k,t-1}}\right]^{\gamma^{wr}_k} = (1-\tau^N_k)\frac{W_{k,t}}{P^Y_{k,t}}$$
$$+\gamma^w_k\left(\frac{W_{k,t}}{W_{k,t-1}}-1-(1-sfw_k)(\pi^Y_{k,t-1}-\bar{\pi})-\pi^w\right)\frac{W_{k,t}}{W_{k,t-1}}\frac{W_{k,t}}{P^Y_{k,t}}$$
$$-\gamma^w_k E_t\left[\tilde{\beta}_{k,t}\frac{\lambda_{k,t+1}}{\lambda_{k,t}}\frac{P^{C,vat}_{k,t}}{P^{C,vat}_{k,t+1}}\frac{N_{k,t+1}}{N_{k,t}}\left(\frac{W_{k,t+1}}{W_{k,t}}-1-(1-sfw_k)(\pi^Y_{k,t}-\bar{\pi})-\pi^w\right)\frac{W_{k,t+1}}{W_{k,t}}\frac{W_{k,t}}{P^Y_{k,t}}\right]+\frac{W_{k,t}}{P^Y_{k,t}}\varepsilon^U_{k,t},$$

where μ^w_k is the gross wage mark-up, γ^w_k and γ^{wr}_k represent the degree of nominal and real wage rigidity, respectively, sfw_k is the degree of forward-lookingness in the expectation formation by wage setters, and $\varepsilon^U_{k,t}$ captures a shock to the wage mark-up (labour supply shock). The marginal disutility from working is defined as: $U^N_{k,t} = \omega^N_k \varepsilon^U_{k,t}(C_{k,t})^{1-\theta_k}(N_{k,t})^{-\theta^N_k}$, and the weighted average of the marginal utility of consumption is given by:

$$\lambda_{k,t} = \omega^s_k(C^s_{k,t}-h_k C^s_{k,t-1})^{-\theta_k}+(1-\omega^s_k)(C^c_{k,t}-h_k C^c_{k,t-1})^{-\theta_k}.$$

3.2. Production sector

Total domestic output combines domestic value added and industrial supplies (IS). Value added is a bundle of differentiated goods produced by monopolistically competitive firms using capital and labour.

3.2.1. Total output demand

Perfectly competitive firms produce total output $O_{k,t}$ by combining the value added, $Y_{k,t}$, with (imported) industrial supplies, $IS_{k,t}$, using the following CES production function:

$$O_{k,t} = \left[\left(1-s^{IS}_k\exp(\varepsilon^{IS}_{k,t})\right)^{\frac{1}{\sigma^o_k}}(Y_{k,t})^{\frac{\sigma^o_{k-1}}{\sigma^o_k}}+\left(s^{IS}_k\exp\left(\varepsilon^{IS}_{k,t}\right)^{\frac{1}{\sigma^o_k}}(IS_{k,t})^{\frac{\sigma^o_{k-1}}{\sigma^o_k}}\right]^{\frac{\sigma^o_k}{\sigma^o_{k-1}}}, \tag{3}$$

where s^{IS}_k is the IS input share which is affected by the exogenous process $\varepsilon^{IS}_{k,t}$, and σ^o_k is the elasticity of substitution between factors. Each firm maximises its expected profits:

$$\max_{Y_{k,t},IS_{k,t}} P^O_{k,t}O_{k,t}-P^Y_{k,t}Y_{k,t}-P^{IS}_{k,t}IS_{k,t}$$

subject to the production function (3). The first order conditions for the demand for value added and industrial supplies are:

$$Y_{k,t} = \left(1-s^{IS}_k\varepsilon^{IS}_{k,t}\right)\left(\frac{P^Y_{k,t}}{P^O_{k,t}}\right)^{-\sigma^o_k}O_{k,t}, \tag{4}$$

$$IS_{k,t} = s^{IS}_k\varepsilon^{IS}_{k,t}\left(\frac{P^{IS}_{k,t}}{P^O_{k,t}}\right)^{-\sigma^o_k}O_{k,t}. \tag{5}$$

IS are assumed to be produced only by RoW. Thus, all commodities used by EA and US are imported from RoW and their price is taken as given:

$$P^{IS}_{k,t} = e_{RoW,k,t}P^{IS}_{RoW,k,t}+\tau^{IS}P^{Y0}_t,$$

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

$$P^O_{k,t} = \left[\left(1-s^{IS}_k\varepsilon^{IS}_{k,t}\right)\left(P^Y_{k,t}\right)^{\sigma^o_k-1}+s^{IS}_k\varepsilon^{IS}_{k,t}\left(P^{IS}_{k,t}\right)^{\sigma^o_k-1}\right]^{\frac{1}{1-\sigma^o_k}}.$$

3.2.2. Value added and intermediate goods producers

Value added, $Y_{k,t}$, is produced by perfectly competitive firms that combine a large number of differentiated goods, $Y_{i,k,t}$, produced by monopolistically competitive firms.

The differentiated goods are produced following a Cobb-Douglas production function, using total capital, $K^{tot}_{i,k,t-1}$, and labour, $N_{i,k,t}$:

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

where α_k is the steady-state labour share, $A^Y_{k,t}$ is an exogenous common labour-augmenting stochastic productivity scalar subject to trend and level shocks, and $CU_{i,k,t}$ and $FN_{i,k,t}$ are the firm-specific levels of capacity utilisation and labour hoarding.[7] $FC_{i,k}$ captures fixed costs 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 demand for firm-specific goods by the value-added bundlers, the technology constraint (6), and the law of motion of private capital, $K_{i,k,t} = I_{i,k,t} + (1-\delta_k)K_{i,k,t-1}$.[8] The period t profit of an intermediate goods producer i is:

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

where $I_{i,k,t}$ is the private physical investment at price $P^I_{i,k,t}$, τ^K is the corporate profit tax rate, and δ_k is the capital depreciation rate. Following Rotemberg (1982), firms face quadratic adjustment costs, $adj_{i,k,t}$, measured in terms of production input factors. Specifically, the adjustment costs are associated with the output price, $P^Y_{i,k,t}$, labour input, $N_{i,k,t}$, private investment, $I_{i,k,t}$, as well as capacity utilisation variation, $CU_{i,k,t}$, and labour hoarding, $FN_{i,k,t}$. The adjustment cost definitions and FOCs can be found in A.2.

3.3. Trade

Final good packagers combine domestic output and imports to serve the different sectors in the economy with components of aggregate demand. Imports are a bundle of imports of different origin and assembled by import retailers.

Final good packagers

The final aggregate-demand component goods are produced by perfectly competitive firms that combine 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:

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

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 $s^{M,\mathcal{D}}_k$ is a share of good-specific import demand components subject to a shock, $\varepsilon^M_{k,t}$. Demand for domestic output and imported goods is given by:

$$O^{\mathcal{D}}_{k,t} = \left(A^{p^{\mathcal{D}}}_{k,t}\right)^{\sigma^z_k-1}\left(1-\varepsilon^M_{k,t}s^{M,\mathcal{D}}_k\right)\left(\frac{P^O_{k,t}}{P^{\mathcal{D}}_{k,t}}\right)^{-\sigma^z_k}\mathcal{D}_{k,t},$$

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

The price deflator associated to the demand components is:

$$P^{\mathcal{D}}_{k,t} = \left(A^{p^{\mathcal{D}}}_{k,t}\right)^{-1}\left[\left(1-\varepsilon^M_{k,t}s^{M,\mathcal{D}}_k\right)\left(P^O_{k,t}\right)^{1-\sigma^z_k} + \varepsilon^M_{k,t}s^{M,\mathcal{D}}_k\left(P^M_{k,t}\right)^{1-\sigma^z_k}\right]^{\frac{1}{1-\sigma^z_k}}.$$

we define total imports excluding industrial supplies (non-IS imports) as:

$$M_{k,t} = M^C_{k,t} + M^I_{k,t} + M^G_{k,t} + M^{IG}_{k,t} + M^X_{k,t}.$$

[7] According to Burnside and Eichenbaum (1996), firms prefer not to lay off workers when demand is temporarily low, because firing and re-hiring workers may be more costly than hoarding them. The inclusion of labour hoarding, $FN_{i,k,t}$, improves the fit of working hours and better matches the observed co-movement between output and working hours.

[8] We assume the total number of shares to be normalised to $S^{tot}_{k,t} = 1$.

Import retailers

Final non-IS imports are produced by perfectly competitive firms, combining goods from the different foreign regions into an economy-specific final import good.

The associated demand for goods from country of origin l is:

$$M_{l,k,t} = s^M_{l,k,t}\left(\frac{P^M_{l,k,t}}{P^M_{k,t}}\right)^{-\sigma^{FM}_k} M_{k,t}\frac{size_k}{size_l},$$

and the import prices deflator is:

$$P^M_{k,t} = \left[\sum_l s^M_{l,k,t}(P^M_{l,k,t})^{1-\sigma^{FM}_k}\right]^{\frac{1}{1-\sigma^{FM}_k}},$$

where σ^{FM}_k is the price elasticity of demand for country l's goods, and $P^M_{l,k,t}$ is the price of its good. Since the good from country l is initially purchased at the export price of country l, $P^X_{l,t}$, the economy-specific import price is:

$$P^M_{l,k,t} = e_{l,k,t}P^X_{l,t}.$$

3.4. Fiscal policy

The government finances its consumption, $G_{k,t}$, investment, $I^G_{k,t}$, transfers, $T_{k,t}$, and the servicing of outstanding debt by issuing one-period bonds, $B^G_{k,t}$, and by collecting constant linear taxes on labour, τ^N_k, corporate profit, τ^K, and consumption, τ^C. It also levies lump-sum taxes, $tax_{k,t}$, that adjust according to a budget closure rule to ensure debt sustainability in the long run. Government expenditure, investment and transfers follow a feedback rule that matches them to data on discretionary fiscal effort, and their real levels grow proportionally to potential output growth. More detail on the fiscal block can be found in A.3.

3.5. Monetary policy

Monetary policy follows a Taylor-type rule that responds sluggishly to the annualised (CPI) inflation, $\pi^{c,vat,QA}_{k,t}$, and output gaps:[9]

$$\begin{aligned} i_{k,t} - \bar{i} = {} & \rho^i_k(i_{k,t-1} - \bar{i}) + (1-\rho^i_k)\Bigg[\eta^{i\pi}_k 0.25\left(\pi^{C,vat,QA}_{k,t} - \bar{\pi}^{C,vat,QA}_k\right) \\ & + \eta^{iy}_k\left(\log\left(0.25\sum_{r=1}^{4} Y_{k,t-r}\right) - \log\left(0.25\sum_{r=1}^{4} Y^{pot}_{k,t-r}\right)\right)\Bigg] + \varepsilon^i_{k,t}, \end{aligned} \tag{7}$$

where $\bar{i} = \bar{r} + \bar{\pi}^{Yobs}$ is the steady-state nominal interest rate, which equals the sum of the steady-state real interest rate and trend inflation. The policy parameters (ρ^i, $\eta^{i\pi}$, η^{iy}) capture interest rate inertia and the response to the annualised inflation and output gaps, respectively. The treatment of the ZLB environment will be explained in Section 7.

3.6. Closing the economy

Market clearing requires that:

$$Y_{k,t}P^Y_{k,t} + \tau^{IS}IS_{k,t}P^{Y0}_t = P^C_{k,t}C_{k,t} + P^I_{k,t}I_{k,t} + P^{IG}_{k,t}IG_{k,t} + P^G_{k,t}G_{k,t} + TB_{k,t},$$

where the trade balance, $TB_{k,t}$, is defined as the difference between exports and (non-IS as well as IS) imports:

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

Domestic holding of the internationally traded bond, $B^W_{k,t}$, evolves according to:

$$e_{RoW,k,t}B^W_{k,t} = (1+i^{bw}_{t-1})e_{RoW,k,t}B^W_{k,t-1} + \sum_l e_{l,k,t}\Pi_{l,t}S_{l,t} - \sum_l \Pi_{k,t}S_{l,k,t} + TB_{k,t} + ITR_kP_{k,t}Y_{k,t},$$

where $e_{l,k,t}\Pi_{l,t}S_{l,t}$ are dividends on foreign equities l held by domestic country k, and $\Pi_{k,t}S_{l,k,t}$ are dividends on domestic equities held by foreign countries. ITR_k represents international transfers, which are calibrated to allow for a non-zero steady state of the trade balance.

[9] We define potential output, $Y^{pot}_{k,t}$, as the output level that prevails when labour input equals steady-state per-capita hours worked, the capital stock is utilised at full capacity, and TFP equals its trend component.

Table 1
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

The domestic economy's NFA position is:

$$NFA_{k,t} = e_{RoW,k,t}B^{W}_{k,t} + \sum_{l} e_{l,k,t}P^{S}_{l,t}S_{l,t} - \sum_{l} P^{S}_{k,t}S_{l,k,t}.$$

Finally, the NFA positions of all countries sum to zero:

$$\sum_{l} NFA_{l,t}size_{l} = 0.$$

3.7. Commodity supplier

In our model, RoW is the only provider of IS. A competitive sector in RoW provides two distinct IS goods (IS^{n}), i.e. oil (IS^{Oil}) and non-oil commodities (IS^{Com}), to domestic and foreign final output producers. The prices of IS goods are flexible. Normalised by the RoW GDP deflator, they are an increasing function of the demand for RoW IS in the three regions:

$$\ln\left(\frac{P^{n}_{RoW,t}}{P^{Y}_{RoW,t}}\right) = \eta\left(\sum_{l}\ln(IS^{n}_{l,t}) + \ln(IS^{n}_{RoW,t})\right) - \varepsilon^{n}_{t}, \quad \forall l \in \{EA, US\}$$

where ε^{n}_{t} is a disturbance that captures exogenous IS supply shocks. The parameter η is the inverse of the price elasticity of the demand for IS.

EA, US and RoW demand for IS is determined by final good producers in the respective regions and given by Eq. (5). Since we observe volumes and prices of IS imports by EA and US from RoW, we have EA and US IS-specific demand shocks. Empirically, the IS import price series for EA and US differ, but are highly positively correlated. To account for these differences, which may reflect different bundles of IS, we assume that competitive RoW IS exporters bundle oil and non-oil commodities into destination-specific IS aggregates. The respective IS bundle prices are given by:

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

$$P^{IS}_{RoW,RoW,t} = \left[s^{Oil}_{RoW}\left(P^{Oil}_{RoW,t}\right)^{1-\sigma^{IS}} + (1-s^{Oil}_{RoW})\left(P^{Com}_{RoW,t}\right)^{1-\sigma^{IS}}\right]^{\frac{1}{1-\sigma^{IS}}}.$$

4. Model solution and econometric approach

We solve the model by linearising it around its deterministic steady state. A subset of parameters is calibrated to match long-run properties, the remaining parameters are estimated using Bayesian methods.[10] 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 comes 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 61 observed series and contains 62 exogenous shocks. The list of observables can be found in Appendix F. The large number of shocks derives from the large number of observables used for estimation. Many shocks are needed to capture the key dynamic properties of the macroeconomic and financial data (see Kollmann et al., 2015).

We chose the values for the calibrated parameters such that the steady-state ratios of main spending aggregates and income shares to GDP in the model match the average historical ratios for the EA, US and RoW. The steady-state shares of the EA, the US, and the RoW in world GDP are 17%, 27%, and 56%, respectively. Trade-related parameters, notably the degree of openness, or preferences for imports, match the average import content of the demand components as computed by Bussière et al. (2013). Steady-state NFA positions of the three regions are set to zero. The EA, US, and RoW steady-state ratios of private consumption and investment to GDP are 56%, 68%, 72%, and 18%, 17%, 27%, respectively. Global trend GDP

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

[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 Euclidean slices. The slice sampler has been shown to be more efficient and to offer better mixing properties than the Metropolis-Hastings sampler (Calés et al., 2017). Similar Bayesian techniques are used by Giovannini et al. (2019) or Hohberger et al. (2019).

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

growth and trend inflation are 0.35% and 0.5% per quarter, respectively. The quarterly depreciation rate of capital is 1.4% in the EA, 1.6% in the US, and 1.5% in the RoW. We set the effective rate of time preferences to 0.25% per quarter. The steady-state shares of Ricardian households are 67% in the EA and 73% in the US, based on the survey in Dolls et al. (2012). Steady-state government debt to annual GDP is 74% in the EA and 78% in the US.[13] Table B.1 in Appendix B provides an overview of selected calibrated parameters. The weights of the respective regions in foreign equity portfolios average observed gross foreign holdings of equity, with data coming from the FinFlows dataset and covering 2001–2017.[14] Table 1 reports these numbers, whereby the weights in any given row represent equity held by the region displayed in the column relative to total equity issued by the country displayed in the row. The data suggest continued strong home bias in equity holding, with 3/4 of EA and US equity being held domestically.

5. Estimation results

This section summarises key results from model estimation. It presents selected parameter estimates, highlighting structural differences and similarities across the three regional blocks, and assesses the models ability to fit the data.

5.1. Posterior estimates

The posterior estimates for key model parameters for EA, US, and RoW, together with 90% highest posterior density (HPD) intervals, are reported in Table 2. The estimated monetary policy parameters suggest a stronger response to inflation in EA (1.33) compared to US (1.20) and RoW (1.14). RoW interest rate inertia (0.93) and the RoW response to output (0.39) are larger than the respective estimates for EA and US. Estimated habit persistence is high for all countries, implying a slow adjustment of consumption to changes in income. Estimated risk aversion is slightly higher in RoW and US compared to EA. The inverse of the labour supply elasticity is fairly similar, whereas the price elasticity of import demand is significantly higher in US. The price elasticity of industrial supplies 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).

Given the lack of labour market data for the RoW block, we abstract from various associated rigidities and assume households to supply labour inelastically. Focusing on the comparison of EA and US estimates, estimated price and nominal wage adjustment costs are slightly higher in EA, whereas real wage rigidity is high for both regions. Adjustment cost parameters for labour demand are rather similar (around 20), whereas adjustment costs for labour hoarding point to stronger rigidity in US (2.4) compared to EA (1.7). EA, US, and RoW face similar levels of capacity utilisation adjustment costs. Estimated investment adjustment costs are rather high, in particular for RoW, which is also driven by the fact that RoW investment data are available only at annual frequency. Estimates of EA and US investment adjustment costs are somewhat lower, with a slightly higher mode in EA (140) compared to (125). Selected posterior estimates of parameters driving the shock processes can be found in Table B2 in Appendix B.

The posterior estimates for global financial risk spillover (‘global risk appetite’) are well identified and particularly high in EA (2.80) and RoW (2.18). The coefficient for US (0.30) is positive but small in comparison, suggesting that global financial spillovers play a significant role for EA and RoW, but not for the US, where US-specific risk premia shocks dominate.[15]

5.2. Theoretical moments and model fit

In order to evaluate the capability of the model to fit the data, Table 3 compares sample and model-implied moments for a subset of key statistics. In particular, we focus on the volatility and persistence of real GDP, consumption, investment, employment, and the trade balance-to-GDP ratio, and on the cross-correlation of GDP with its main components. The estimated model tends to slightly overestimate the volatility of real variables in EA and US. However, the relative magnitudes seem to be preserved, notably the comparatively high volatility of investment growth, std(GI)/std(GY), which is in line with the data patterns.

First-order autocorrelation coefficients match the data fairly well in all three countries, except for the underprediction of the persistence of GDP growth in EA. The correlations between GDP growth and its components are fairly well captured in most cases. All three regional blocks replicate well the correlation between consumption, investment and (for EA and US) employment growth, on the one hand, and output growth, on the other hand. The trade balance is positively correlated with output in our model, which matches the data pattern only in RoW.

The last column in Table 3 reports the r^2 of the 1-year ahead forecast.[16] The 1-year ahead r^2 is positive for all three regions, indicating that the forecast errors from the model are not very large. Overall, the theoretical moments in Table 3 indicate the ability of the estimated structural model to replicate key features of the EA, US and RoW business cycles.

[13] The simplified RoW block abstracts from a fiscal sector and liquidity-constrained households.

[14] https://finflows.jrc.ec.europa.eu.

[15] Posterior distributions and information on the identification of the country-specific coefficients can be found in Fig. B.1 in Appendix B.

[16] 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, the definition implies that our r^2 has an upper bound at 1 and is unbounded from below. In the perfect case, where the model generates no forecast error, the r^2 is one, and r^2 declines monotonically as the forecast error increases. Since the volatility of the forecast error can exceed the volatility of the time series, r^2 can also become negative.

Table 2
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	0.85	0.80	0.93
			0.12	(0.78, 0.89)	(0.75, 0.85)	(0.92, 0.95)
Response to inflation	$\eta^{i,\phi}$	G	2.00	1.33	1.20	1.14
			0.40	(1.09, 1.76)	(1.07, 1.52)	(1.01, 1.41)
Response to GDP	$\eta^{i,y}$	G	0.20	0.08	0.09	0.39
			0.08	(0.05, 0.12)	(0.07, 0.11)	(0.28, 0.45)
		Preferences				
Consumption habit persistence	h	B	0.50	0.85	0.83	0.94
			0.10	(0.80, 0.91)	(0.74, 0.89)	(0.93, 0.97)
Risk aversion	θ	G	1.50	1.48	1.57	1.63
			0.20	(1.22, 1.81)	(1.29, 1.97)	(1.31, 2.13)
Inverse Frisch elasticity of labour supply	θ^N	G	2.50	2.12	1.94	2.50*
			0.50	(1.58, 2.84)	(1.55, 2.94)	
Import price elasticity	σ^z	G	2.00	1.27	1.99	1.21
			0.40	(1.11, 1.42)	(1.64, 2.84)	(1.11, 1.37)
Oil price elasticity	σ^o	G	0.50	0.02	0.03	0.01*
			0.20	(0.00, 0.06)	(0.01, 0.07)	
Share of forward-looking price setters	*sfp*	B	1.00	0.44	0.38	0.72
			0.50	(0.17, 0.90)	(0.14, 0.63)	(0.53, 0.89)
		Nominal and real frictions				
Price adjustment cost	γ^P	G	60	22.31	20.12	95.25
			40	(14.67, 35.70)	(13.42, 34.71)	(48.14, 133.20)
Nominal wage adjustment cost	γ^w	G	5.00	5.50	3.19	-
			2.00	(2.43, 7.33)	(1.45, 4.41)	
Real wage rigidity	γ^{wr}	B	0.50	0.98	0.98	-
			0.20	(0.97, 0.99)	(0.96, 0.98)	
Employment adjustment cost	γ^N	G	60	20.09	19.48	-
			40	(13.04, 40.04)	(11.53, 32.66)	
Labour hoarding quadratic adj cost	$\gamma^{FN,2}$	G	2.00	1.74	2.36	-
			0.50	(1.33, 2.20)	(2.01, 3.00)	
Capacity utilisation quadratic adj cost	$\gamma^{CU,2}$	G	0.003	0.004	0.004	0.005
			0.0012	(0.002, 0.006)	(0.002, 0.006)	(0.002, 0.008)
Investment adjustment cost	$\gamma^{I,2}$	G	60	140.16	125.09	258.63
			40	(92.07, 210.40)	(92.99, 176.83)	(174.07, 329.69)
		Global risk appetite				
Global financial risk coefficient	τ^{ra}	B	0	2.80	0.30	2.18
			2	(0.01, 4.17)	(-2.06, 2.64)	(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)-(7) show the mode and the 90% HPD intervals of the posterior distributions of EA, US, and RoW. *RoW labour market related coefficients and selected others are calibrated due to lack of data.

From an empirical point of view, it is important to mention that the data density in the model with financial linkages and a global financial shock is higher than in the model version without.[17]

6. Risk shocks and spillover in the estimated model

The section characterises the model's estimated investment risk shocks and their transmission to the domestic economy and foreign regions. It characterises the economies' dynamic response to investment risk and quantifies the latter's contribution to GDP growth in EA, US and RoW since the early 2000s. The section also compares the profile of the estimated shocks to empirical measures of financial constraints and financial risk to illustrate the empirical plausibility of the former.

6.1. Dynamic transmission of shocks

This subsection discusses the estimated dynamic effects of shocks to investment risk originating in EA, US, and RoW, and to global financial risk ('global risk appetite'). The transmission of these shocks to the domestic region and spillover to the foreign ones is displayed by impulse response functions (IRFs) in Figs. 3–6.[18] All shocks are harmonised to one

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

[18] The IRFs for standard supply shocks, e.g. TFP and price markup shocks, and standard demand shocks, e.g. private saving shocks, originating in EA and US are qualitatively very similar to those in standard DSGE models of similar structure (e.g. Kollmann et al., 2016).

Table 3
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 difference for the trade balance-to-GDP ratio and quarter-on-quarter growth rates for all other variables. Consumption and investment growth relate to the private sector only. The r2 is reported for the absolute nominal trade balance.

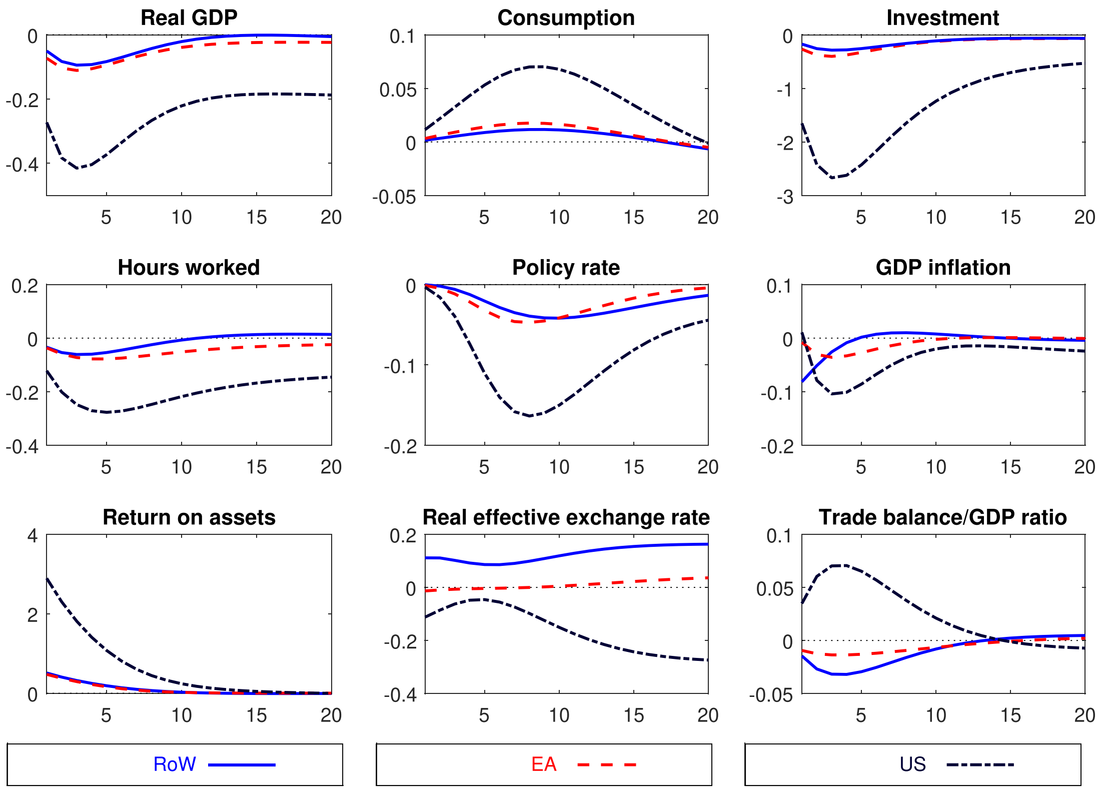

Fig. 3. Dynamic responses to a positive US investment risk premium shock. Note: The trade balance (normalised by GDP), inflation (p.a.) and interest rate (p.a.) responses are expressed as percentage-point deviations from steady state. All other responses are percent deviations from steady state. A fall in REER represents a real effective appreciation for the respective economy. The responses of RoW, EA and US variables are represented by continuous, dashed and dash-dotted lines, respectively.

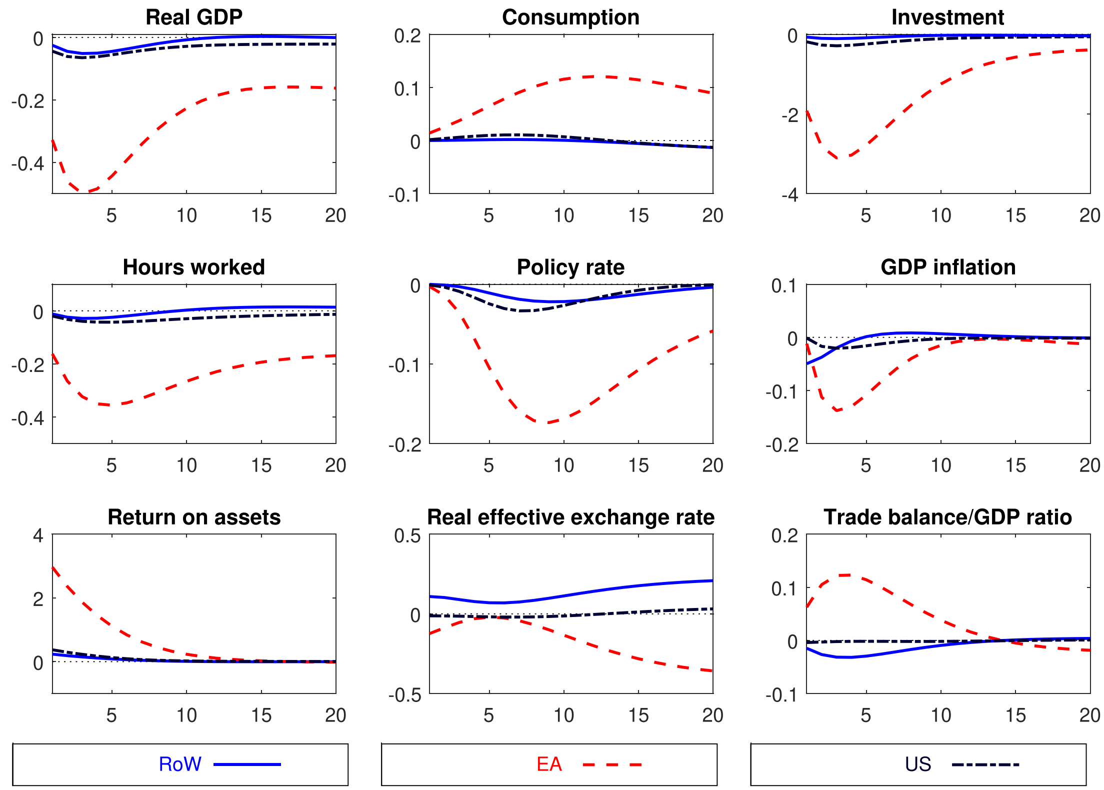

Fig. 4. Dynamic responses to a positive EA investment risk premium shock. Note: The trade balance (normalised by GDP), inflation (p.a.) and interest rate (p.a.) responses are expressed as percentage-point deviations from steady state. All other responses are percent deviations from steady state. A fall in the REER represents a real effective appreciation for the respective economy. The responses of RoW, EA and US variables are represented by continuous, dashed and dash-dotted lines, respectively.

standard deviation and use the same persistence for comparability. Each panel shows dynamic responses of real GDP, private consumption, private investment, total hours worked, the monetary policy rate, GDP inflation, the nominal return on equity, the real effective exchange rate (REER), and the trade balance-to-GDP ratio. Real variables are presented in percent deviations from their respective steady state, whereas GDP inflation, the policy 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 heightens the riskiness of domestic investments. US investment demand declines, and the (required) return on equity increases (Fig. 3). The associated fall in aggregate demand reduces labour demand, which leads to a decline in employment. Falling demand, employment and economic activity lower inflation. Private consumption is crowded in by a reduction in the policy rate. The US trade balance “improves” due to a decline in imports. The domestic transmission mechanism is similar for EA and RoW under the respective domestic investment risk shocks (Figs. 4 and 5).

Concerning spillover across regions, the IRFs suggest positive co-movement between US and EA in terms of GDP, investment and employment (Figs. 3 and 4). Spillover from US to EA (Fig. 3) is slightly more pronounced than vice versa (Fig. 4). An increase in RoW investment risk generates pronounced spillover to EA and US real GDP and employment (Fig. 5), which is plausible in light of the RoW region’s economic size and the negative repercussion on demand for EA and US output via the trade channel.

The negative spillover from increasing investment risk premia is dampened in “normal” times by accommodating monetary policy responses at the level of the receiving regional blocks. Given the synchronised decline of GDP and inflation, monetary authorities reduce the policy rates to dampen the decline in domestic economic activity. When monetary policy is constrained at the ZLB, however, spillover from foreign investment risk premia shocks to the domestic economy is amplified, as will be discussed in Section 7 below.

Fig. 6 displays the dynamic responses to an increase in global investment risk. The transmission of the global risk shock is similar to the transmission of the country-specific investment risk shocks above. The global shock affects all countries simultaneously, however, and differences across countries derive from the estimated region-specific weights with which the global risk shock enters regional investment decisions (Table 2). In line with the estimated coefficients for EA (2.8), US (0.3), and RoW (2.2), transmission to the US economy is the least pronounced (Fig. 6).

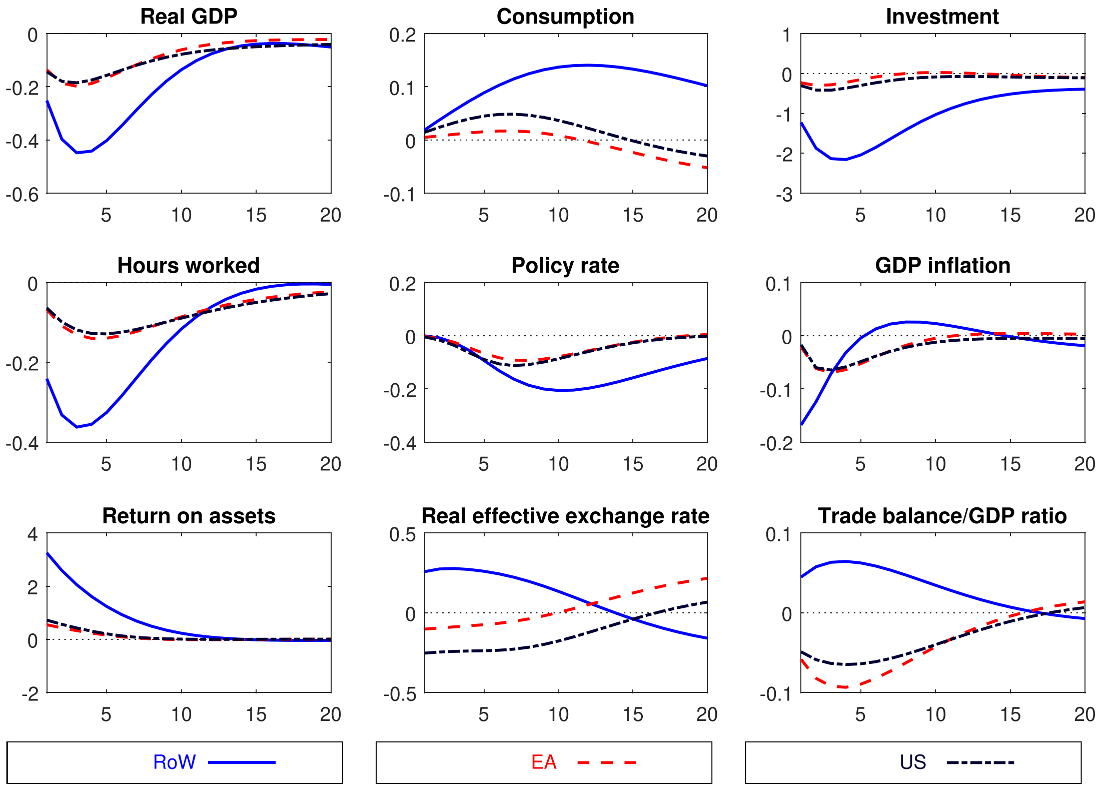

Fig. 5. Dynamic responses to a positive RoW investment risk premium shock. Note: The trade balance (normalised by GDP), inflation (p.a.) and interest rate (p.a.) responses are expressed as percentage-point deviations from steady state. All other responses are percent deviations from steady state. A fall in the REER represents a real effective appreciation for the respective economy. The responses of RoW, EA and US variables are represented by continuous, dashed and dash-dotted lines, respectively.

Table 4
Model implied cross-correlations of real GDP and investment growth.

	Data	Model		
		No financial linkages	Cross-border equity holding	All financial linkages
		GDP cross-correlation		
EA-US	0.51	0.23	0.31	0.27
EA-RoW	0.39	-0.10	-0.06	-0.08
US-RoW	0.49	-0.04	0.00	-0.01
		Investment cross-correlation		
EA-US	0.50	0.12	0.35	0.36
EA-RoW	0.42	0.03	0.24	0.33
US-RoW	0.36	0.03	0.28	0.32

Note: 'No financial linkages' refers to an estimated model version without cross-border equity holdings and global risk shock.

Overall, dynamic responses suggest that incorporating financial linkages through international equity portfolios increases spillover from idiosyncratic shocks to foreign investment risk. A model with full equity home bias, to the contrary, generates no relevant international co-movements in this case (see Fig. B.2 in Appendix B).

6.2. Cross-correlation

Comparing the model-implied correlation of quarterly GDP growth rates as well as investment growth rates across the three regions, the model with financial linkages, particularly the cross-border equity holdings, captures the international co-movements of GDP growth and investment growth better than an estimated model version without the international financial linkages (Table 4). Alternative models with cross-border linkages through internationally operating financial intermediaries or correlated shocks (e.g. Montinari and Stracca, 2016; Alpanda and Aysun, 2014) report similar results. The cross-correlations of investment growth in our model improve further with the introduction of the global financial risk shock and

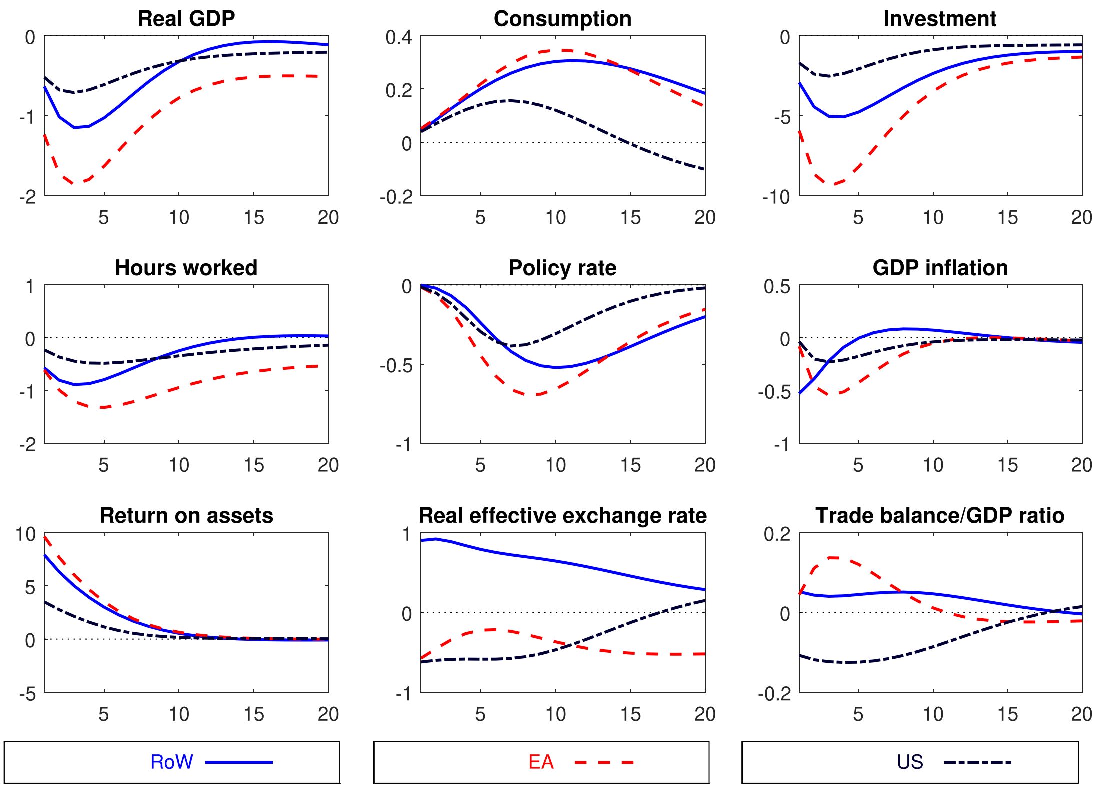

Fig. 6. Dynamic responses to a positive shock to global risk ('global risk appetite'). Note: The trade balance (normalised by GDP), inflation (p.a.) and interest rate (p.a.) responses are expressed as percentage-point deviations from steady state. All other responses are percent deviations from steady state. A fall in the REER represents a real effective appreciation for the respective economy. The responses of RoW, EA and US variables are represented by continuous, dashed and dash-dotted lines, respectively.

match the data fairly well. Although the model implied international co-movement also improves for GDP growth, gains are smaller.

6.3. Historical shock decomposition of real GDP growth

This subsection visualises the estimated contribution of different (groups of) shocks to historical real GDP growth data for the period 2000q1-2017q4. Figs. 7–9 display historical decomposition of the annual real GDP growth rates in each of the three model regions. In each subplot, the continuous black line represents the historical data, from which the steady-state growth (1.35% p.a.) has been subtracted. The vertical black bars display the contribution of the respective (group of) exogenous shocks to explaining the data, whereas stacked light bars summarise the contributions of all remaining shocks. Bars above the horizontal axis (steady state) represent positive shock contributions; bars below the horizontal axis show negative shock contributions. The sum of the contributions by all shocks equals the historical data.

We distinguish between the following groups of shocks: (1) Domestic demand shocks ('Demand');[19] (2) domestic supply shocks and shocks to TFP ('Supply'); (3) shocks to preferences for domestically produced versus foreign goods, shocks to export and import price mark-ups, and shocks to commodity demand and supply ('Trade shocks'); (4) shocks to the interest parity condition (exchange rate shocks) and to domestic monetary policy ('EXR and monetary policy'); (5) and (6) shocks originating in the respective foreign region; (7), (8) and (9) shocks to investment risk in US, EA, and RoW, respectively; (10) shocks to the global risk appetite; (11) other shocks and initial conditions.

Figs. 7 and 8 suggest that fluctuations in EA and US real GDP growth have been driven largely by domestic demand shocks, in particular household saving shocks, and shocks to the domestic investment risk premium. After the financial crisis of 2008-09, domestic demand and GDP have rebounded more quickly in the US compared to the EA, which has experienced a second recession in 2012–13. The contribution of domestic supply and TFP shocks to fluctuations in GDP growth has been rather small in EA and US compared to the influence of domestic demand disturbances.[20] Trade shocks have played

[19] The group of demand shocks and the groups of foreign shocks exclude the shocks to domestic and foreign investment risk premia, which are shown separately to highlight the cross-country spillovers.

[20] The dominant role of demand shocks in the decomposition of real GDP growth at annual or quarterly frequency is common in estimated New Keynesian (NK) DSGE models; see, e.g., Smets and Wouters (2005) for an early example, and Lindé et al. (2016) for a more recent survey. The finding contrasts with

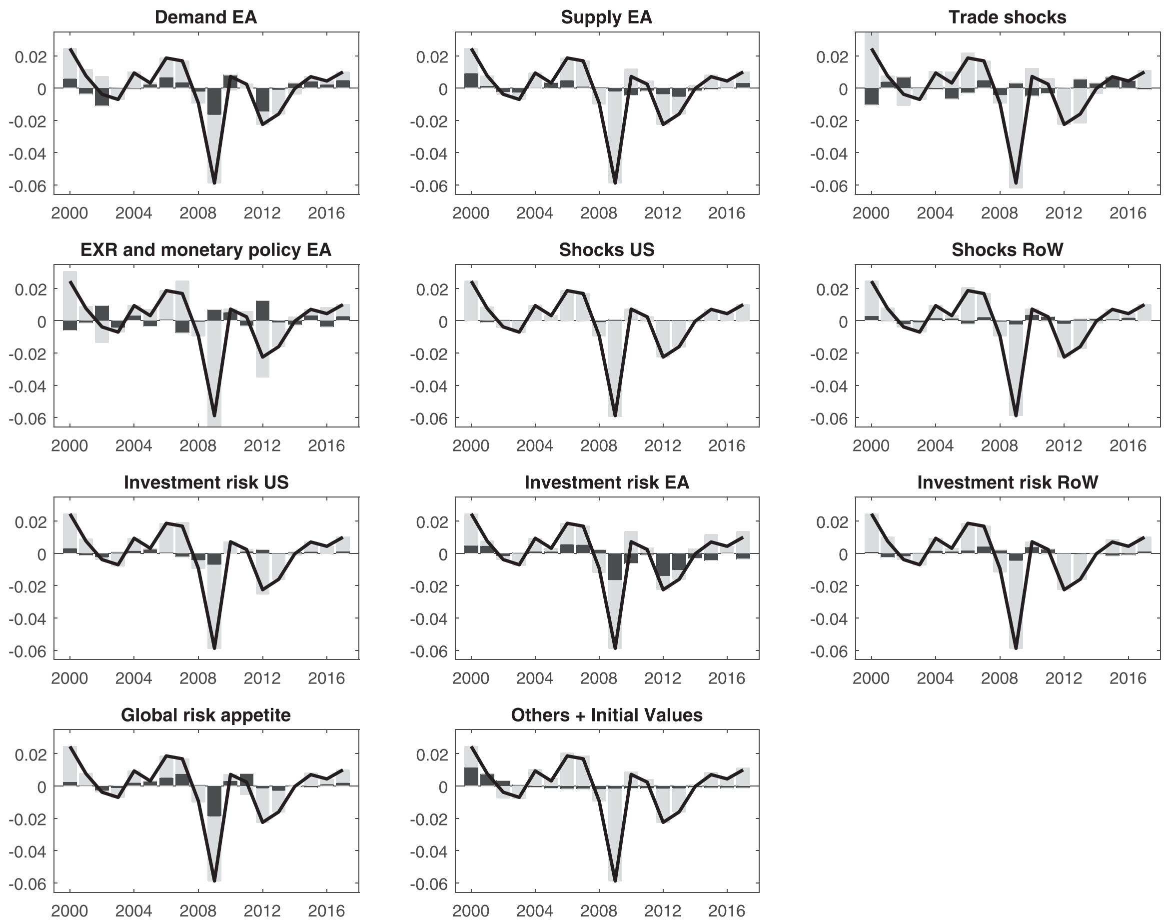

Fig. 7. Historical decomposition of real GDP growth in EA. Note: Annual real GDP growth is shown in percentage-point deviations from steady state, which is calibrated globally to 1.35% per year. 0.01 on the y-axis corresponds to 1 pp.

a stronger role in EA compared to US and contributed to the above-trend GDP growth during the post-crisis years, driven mainly by the positive growth contribution from falling oil and commodity prices (see Giovannini et al., 2019). Standard monetary policy has provided some additional stimulus in EA and US around the 2008–09 crisis, and euro depreciation (explained in the model by an increase in the risk premium on euro-denominated bonds) has strengthened EA GDP growth during the second recession in 2012–13.[21]

Strong RoW GDP growth has mainly been driven by persistent positive domestic supply shocks, according to our estimates (Fig. 9). The growth of RoW supply and real GDP has been interrupted in 2008–09, but recovered after 2010 at a somewhat slower pace. Domestic demand and investment shocks also played some role for RoW GDP growth fluctuations, whereas EA and US shocks had virtually no impact.

Overall, there is little evidence for sizable spillover of aggregate demand or supply shocks for all three regions. Only shocks originating in RoW had some positive impact on EA GDP growth in the recovery from the financial crisis. The estimates suggest that negative shocks to investment demand in US and RoW, i.e. an increase in region-specific risk premia, had noticeable negative spillover to EA GDP growth at the time of the 2008–09 crisis (Fig. 7).

Fig. 8 illustrates the dominant role of US investment risk premium shocks for US real GDP growth, where the risk increase and the decline in domestic consumption demand together almost fully explain the US output contraction in 2008–09. Financial spillovers from EA have contributed negatively in 2012–13 (up to 0.2 pp), whereas negative shocks to investment

the Real Business Cycle (RBC) literature that assigns a predominant role to supply shocks, notably TFP shocks, as drivers of economic fluctuations. RBC models are models of essentially frictionless economies with, in particular, fully flexible prices and wages. TFP and other supply shocks have strong effects and temporary demand shocks have little impact on real economic activity in such an environment in the short and medium term by construction. Price and wage stickiness is quantitatively important in our estimated model, which is a standard result of the large literature on estimated NK models.

[21] Since we do not impose a ZLB on the short-term nominal interest rate as constraint on monetary policy in the estimation, the (small) negative contributions of monetary shocks to EA GDP growth in 2013 and 2015 derive from a model-implied target policy rate ("shadow rate") below the observed policy rate, which has been restricted in practise by the ZLB. The gap between the actual rate and the target rate is filled by positive (contractionary) monetary policy shocks. Section 7 will compare the results to a scenario that accounts for the ZLB.

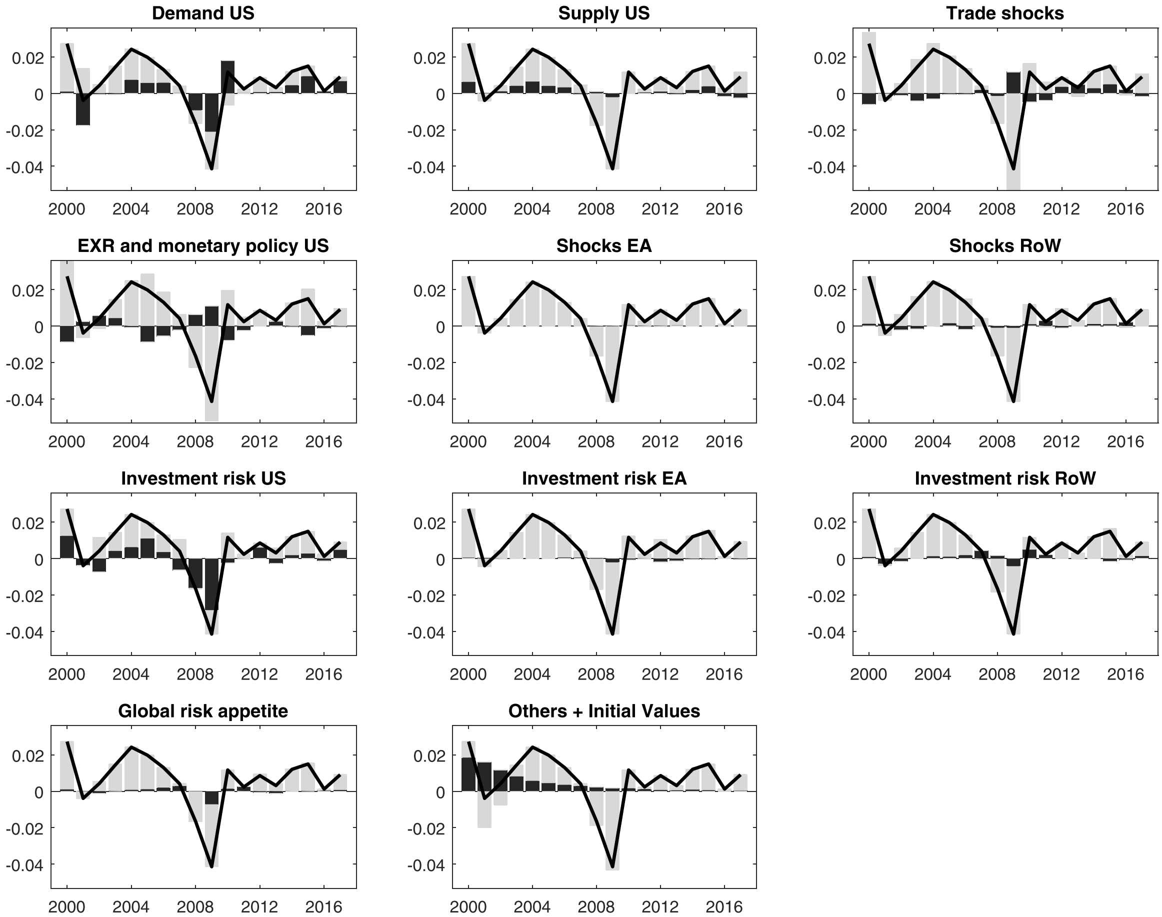

Fig. 8. Historical decomposition of real GDP growth in US. Note: Annual real GDP growth is shown in percentage-point deviations from steady state, which is calibrated globally to 1.35% per year. 0.01 on the y-axis corresponds to 1 pp.

risk in RoW have made positive contributions to US GDP growth in 2010 (0.5 pp), supporting the recovery from the financial crisis. The aggregate effect of foreign shocks on US GDP growth has been small compared to the estimated impact of domestic shocks, however.

The contribution of the global financial shock ('global risk appetite') to the three regions' GDP growth is of particular interest in our context. The estimates suggest that global risk appetite has played little role as driver of US GDP growth, but has been more important for EA and RoW. The negative contribution of (increasing) US investment risk to US GDP growth in Fig. 8 is compatible with the observation that the financial crisis has started in US. Global risk appetite was still contributing slightly on the positive side to US GDP growth in 2007. Positive global risk appetite has contributed more strongly to the pre-crisis boom in EA (up to 0.7 pp in 2007) until the reversal into negative global risk shocks in 2009 (Fig. 7). Global risk shocks played no relevant role for EA GDP growth during the sovereign debt crisis in 2012–13, which was instead characterised by strongly increasing EA investment risk, depressing EA GDP growth by as much as 1.4 pp in 2012.

6.4. Smoothed estimates of financial shocks

This subsection characterises the estimated regional and global investment risk premia shocks and compares them to empirical measures of financial tightening and corporate financing costs. The profiles of our estimates of investment risk premia shocks are similar to indicators of credit tightness in the EA and US economies (Fig. 10).[22]

Region-specific investment risk premia (solid lines) fell in both EA and US prior to 2007-08, and they rose sharply during the global financial crisis. In the aftermath of the financial crisis, the US investment risk premium has declined gradually

[22] Following Kollmann et al. (2016), we use net credit tightening as performance indicator, which is based on Fed and ECB bank surveys on the tightening in bank lending standards (per cent of banks that report a tightening in lending standards minus per cent of banks reporting loosening of standards). Credit tightness at a given date is measured by the cumulated net tightening in preceding periods. The EA series starts only in 2003q1. We do not have a comparable measure for RoW.

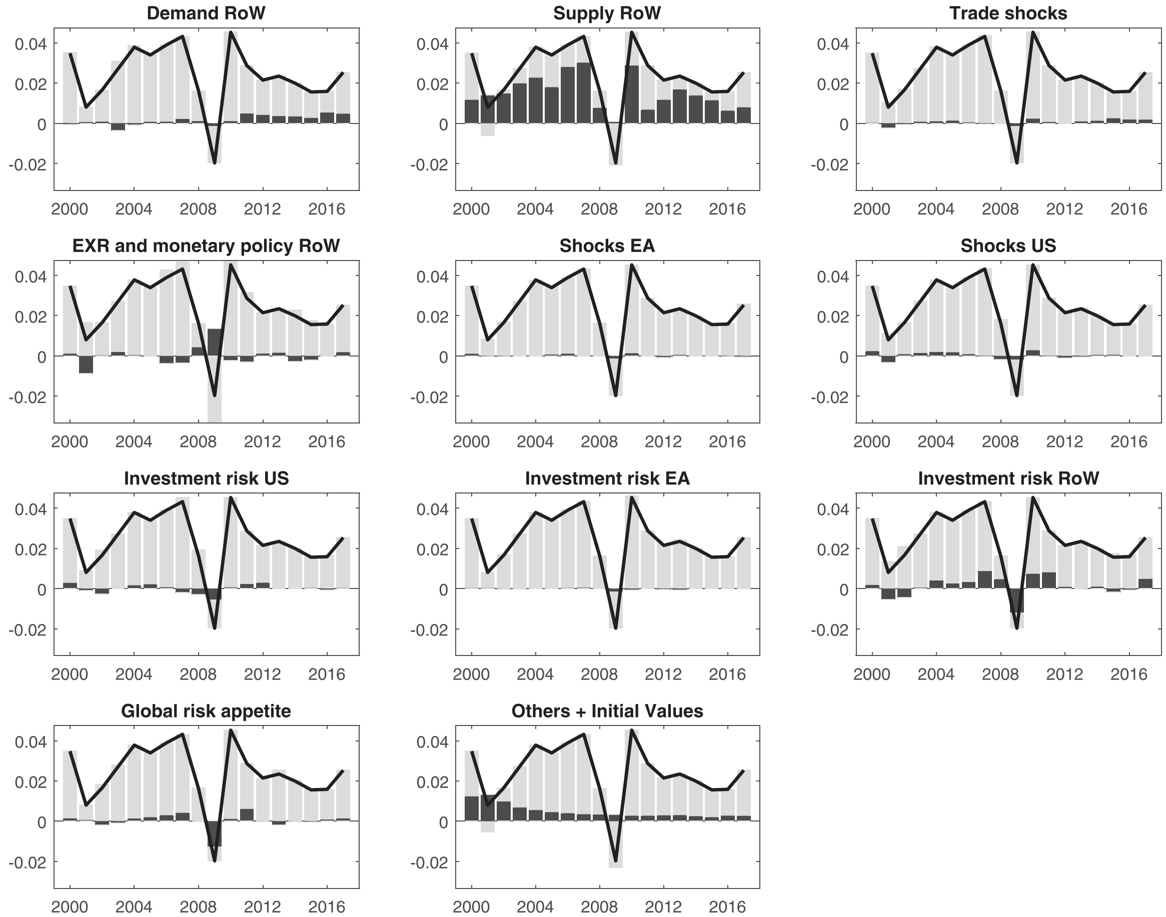

Fig. 9. Historical decomposition of real GDP growth in RoW. Note: Annual real GDP growth is shown in percentage-point deviations from steady state, which is calibrated globally to 1.35% per year. 0.01 on the y-axis corresponds to 1 pp.

and steadily towards its pre-crisis level. The estimated EA investment risk premium fell initially more strongly than the US premium after the financial crisis, but it rose again sharply during the sovereign debt crisis starting in 2011. It has fallen somewhat in recent years, but remains well above its pre-crisis level. Fig. 10 shows that the estimated investment risk premia strongly co-move with the sharp credit tightening during the financial crisis. The estimated premia also match the steady softening of US credit conditions after the crisis and the further tightening of lending standards in the EA with the sovereign debt crisis. The correlation coefficient for the co-movement between the estimated EA (US) investment risk premium shock and EA (US) cumulated net credit tightening is 0.86 (0.88).

Fig. 11 depicts the estimated region-specific investment risk premia and the region-specific impact of the global risk shock (dashed lines), where the latter is affected by the region-specific scalar τ_l^{ra}. Compared to EA and US, the decline of RoW investment risk premia prior to the financial crisis was more pronounced. RoW risk rose sharply during the financial crisis and declined sharply again after the crisis to around pre-crisis levels. Since then it has seen a steady increase back to early-2000s levels. The country-pair correlations of the estimated region-specific investment risk shocks are 0.52 for EA-US, 0.42 for EA-RoW, and -0.02 for US-RoW. Fig. 11 illustrates that high correlation of regional financial shocks arises primarily around periods of severe economic turmoil, notably the financial crisis in 2008–09. Restricting the sample, e.g., to the post-crisis period (2010–17) instead reduces the correlation coefficients to -0.58 for EA-US, 0.11 for EA-RoW, and -0.65 for US-RoW.

The general profile of the global risk shock (dashed line in Fig. 11) is by definition common across all three regions, but the contribution to aggregate risk in a particular region depends on the estimates of τ_l^{ra} reported in Table 2. The estimated global risk and the region-specific investment risk premia are positively correlated in EA (0.82) and RoW (0.84), but less related in the US case (0.42). Particularly striking is the time profile during the financial crisis. While global risk appetite was still positive in the beginning of 2008 (a negative contribution of the global factor to investment risk), positive shocks to US-specific risk already occurred in 2006q3 (see also Fig. 8). Given the pattern of the global risk shock, notably around the financial crisis 2008–09, Fig. 11 suggests that global shocks have been a major force behind the synchronisation of financial cycles across countries observed, e.g., by Miranda-Agrippino and Rey (2015) and Jordà et al. (2019).

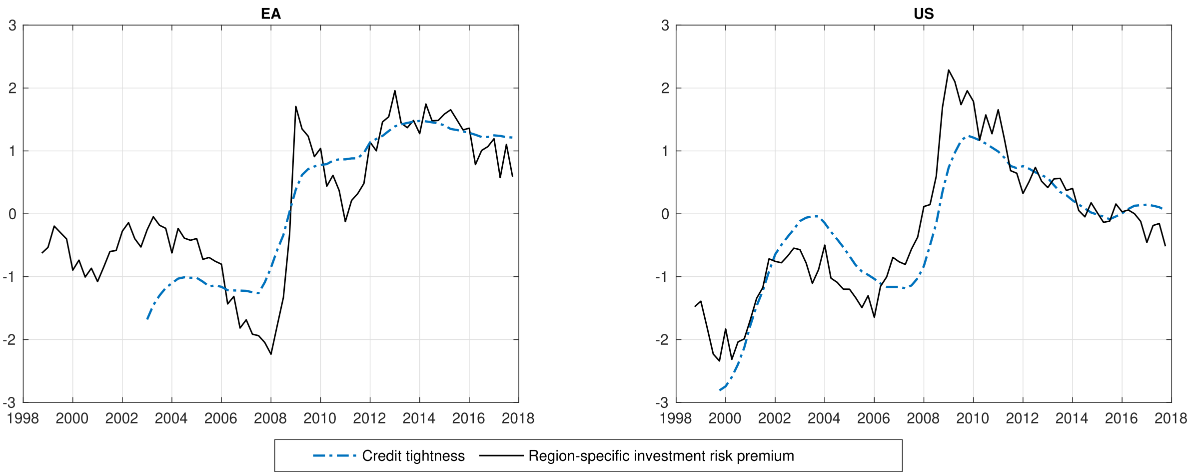

Fig. 10. Estimated region-specific investment risk premia and credit tightness. Note: Credit tightness (dashed) is adjusted (using a linear transformation) to align the mean and standard deviation of the adjusted series to the corresponding moments of the estimated investment risk premium shock.

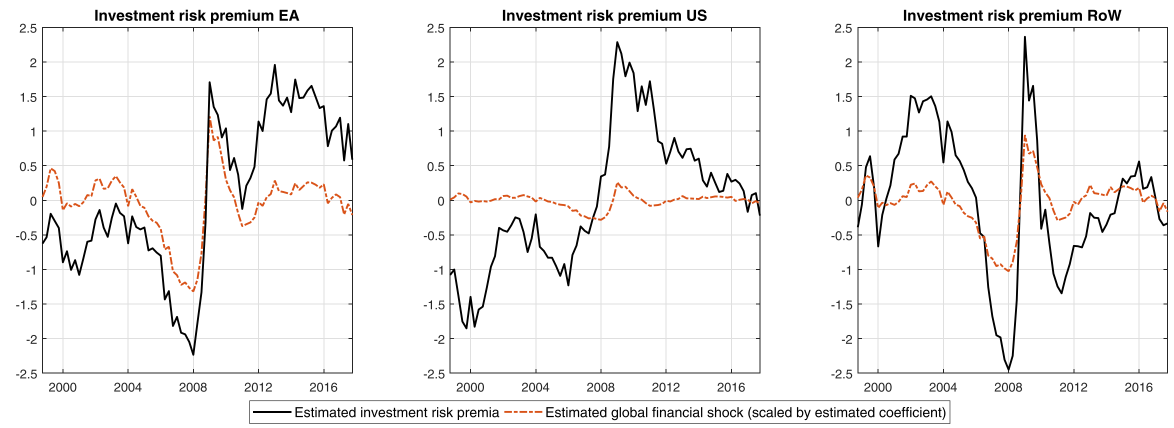

Fig. 11. Estimated investment risk premia and global financial shock. Note: The global financial shock (dashed line) is adjusted by the estimated country-specific coefficient (τ_k^{ra}). 1 on the y-axis corresponds to 1 percent.

Fig. 12 provides empirical motivation for the estimated global risk shock. It compares the estimated global risk series to the common factor (solid line) extracted from three stock indices: S&P 500, STOXX 600, and MSCI global. The three stock indices have been selected to capture market risk in equity holdings across the three regions of our model. We use principal component analysis (PCA) to extract the common global factor, i.e. a summary measure capturing the co-movement of the three stock indices.[23] As shown in Appendix A, the optimality condition of holding corporate equity can be approximated by the following expression:

$$i_{k,t}^{S} = i_{k,t}^{rf} + \sum_{l} s_l^S (rprem_{l,t}^S) + rprem_t^{ra}, \qquad \forall l \in \{EA, US, RoW\}.$$

The return on nominal shares is, hence, determined by the weighted country-specific premia, $rprem_{l,t}^S$, and a global risk premium, $rprem_t^{ra}$, over the risk free rate, i^{rf}. Fig. 12 shows that the model's estimated global risk shock closely tracks the common factor of the three indices. The correlation between the two series is 0.80. The global shock matches well the trough-peak-trough movement of the common factor around the financial crisis and follows relatively well the subsequent dynamics, with some divergence in 2016–18. Figure E1 in Appendix E compares the estimated global risk shock to alternative risk and uncertainty indicators.

7. Assessing financial spillovers in a ZLB environment

How does spillover from financial shocks change when we allow the ZLB on monetary policy to be occasionally binding? A binding ZLB implies that economic contraction with falling output and inflation rates, triggered, e.g., by positive shocks to

[23] Miranda-Agrippino and Rey (2015) use a similar approach to extract the common global factor of risky asset returns and show that the resulting series is a good approximation of other prominent indices.

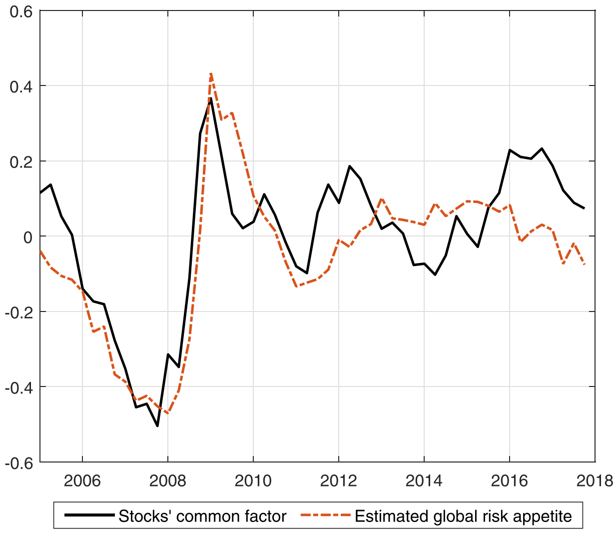

Fig. 12. Estimated global financial shock and common factor of market indices. Note: The global financial shock (dashed line) is compared with the extracted common factor from S&P 500, STOXX 600 and MSCI global indices (solid line). We linearly rescale the common factor so that the standard deviation matches the one of the estimated global shock. 1 on the y-axis corresponds to 1 percent.

investment risk, is not met by expansionary monetary policy to mitigate the decline in economic activity. Given empirical relevance for EA in recent years, we focus the discussion of the ZLB environment on the impact of financial shocks on EA real GDP growth.

We implement the ZLB as in Hohberger et al. (2019), following the algorithm by Giovannini and Ratto (2019), where the unconstrained nominal interest rate follows the Taylor-type rule of Eq. (7). Once the policy rate reaches the lower bound, it is constrained on the downside at $i^{LB}_{EA} = 0$. We use the piecewise linear solution approach (OccBin) of Guerrieri and Iacoviello (2015), which provides a sequence of smoothed variables and shocks consistent with the occasionally binding constraint in this situation.[24] The sequence of regimes, i.e. non-binding or binding ZLB, for EA and US is reported in Table B.3 in Appendix B.

7.1. Dynamic responses under ZLB

Based on the sequence of regimes in Table B.3, we obtain generalised impulse response functions (GIRFs) with a ZLB that is consistent with the estimated timing and duration of the ZLB regime in the estimated model. More precisely, we perform the following exercises: We use 2015q1 as starting point, a period in which the ZLB was binding for additional nine quarters in the EA according to the estimated model (see Table B.3). We remove the estimated positive shock to the investment risk in US and simulate the model with all remaining shocks. Then, we perform simulations adding the estimated US investment premium shock. The difference between the two scenarios provides the GIRFs under the ZLB for a positive shock to the investment risk in US (Fig. 13). We perform a similar exercise for the global risk shock (Fig. 14).

Fig. 13 presents the responses of US and EA variables to a positive shock to US investment risk in the environment described above. The shock is a (one standard-deviation) increase in US investment risk for comparability with the linear case in Fig. 3. Fig. 13 shows that the spillover from the US shock to EA amplifies when EA monetary policy is constrained and cannot react by monetary easing. The co-movement between US and EA real GDP and hours worked doubles compared to the linear (unconstrained) case. Under the ZLB there is no crowding-in of EA consumption that would follow from policy rate reductions in a non-ZLB environment.

Fig. 14 depicts the dynamic responses of EA variables to an increase in global financial risk, i.e. a fall in global risk appetite, and provides two valuable insights: First, the negative impact of the adverse global shock on EA variables is much more pronounced at the ZLB, due to the lack of offsetting monetary stimulus, and, second, the crowding-in of consumption changes into a crowding-out, driven by an increase in the real interest rate that follows from the fixed nominal rate in combination with price deflation. The results suggest that both shocks to investment risk under the ZLB mimic the dynamics of an uncertainty shock that lowers consumption and investment simultaneously.

7.2. Piecewise linear smoothed shock decomposition

This subsection presents an extension of the standard linear (additive) historical shock decomposition to occasionally binding constraints. We describe in Appendix C the piecewise linear approach in more detail.

[24] See Hohberger et al. (2019) for a detailed description of OccBin implementation in the model.

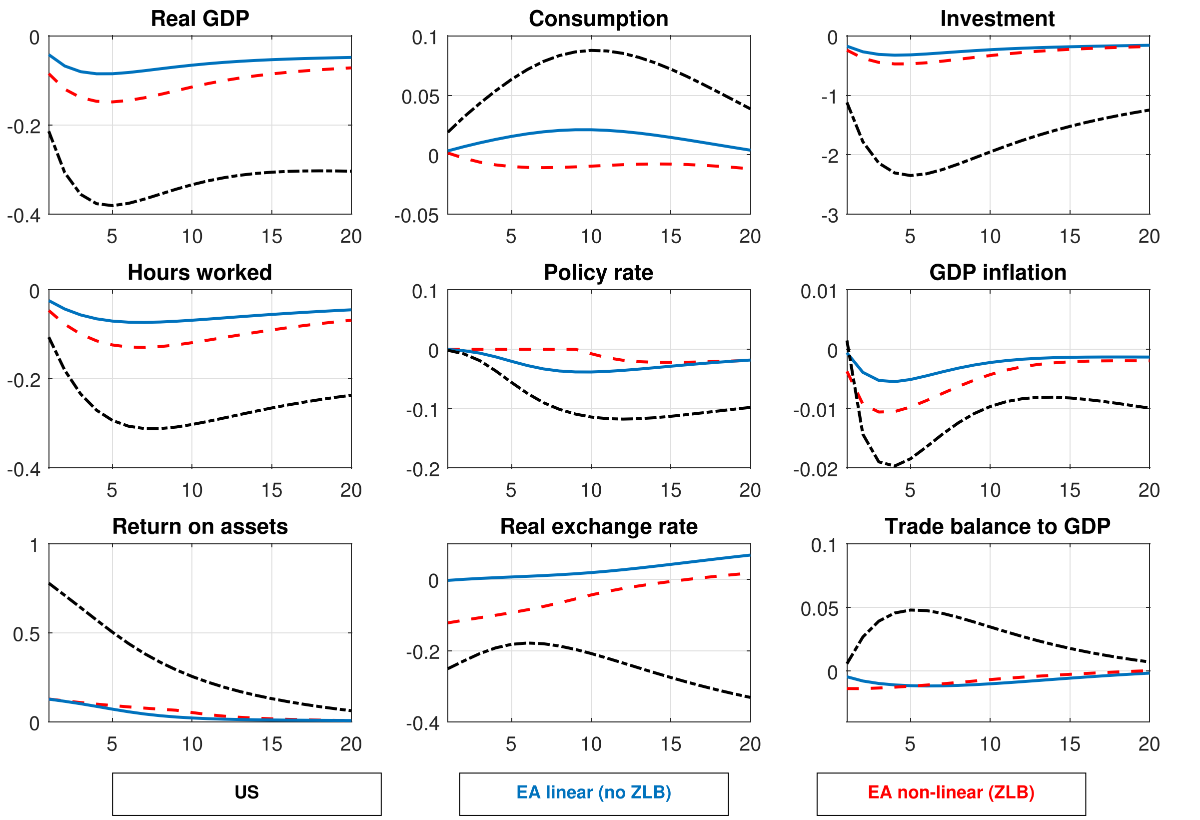

Fig. 13. Dynamic responses to an US investment risk premium shock under ZLB in EA. Note: The trade balance (normalised by GDP), inflation (p.a.) and interest rate (p.a.) responses are expressed as percentage-point deviations from steady state. All other responses are percent deviations from steady state. A fall in the REER represents an appreciation. The responses of US linear, EA linear (no ZLB), and EA non-linear (ZLB) are represented by dashed-dotted, continuous and dashed lines, respectively.

Fig. 15 compares the linear and the piecewise linear (allowing for the ZLB) shock decomposition for EA real GDP growth and shows that the ZLB constraint has amplified negative spillover from US investment risk shocks during the 2008–09 crisis and recession. More precisely, the negative contribution of US investment risk to EA growth in 2009 increases in absolute value from -0.7 pp to -1.0 pp when the ZLB is taken into consideration. The negative contributions of EA investment risk shocks, i.e. domestic investment risk, in the second recession also increases substantially, by -0.7 pp during 2012–15 on average, compared to the linear case. The differences between the ZLB and the linear decomposition with respect to the impact of global risk appetite shocks are marginal.

8. Conclusion

We have estimated a three-region DSGE model with the Euro Area (EA), the United States (US), and rest of the world (RoW) to analyse region-specific and global financial shocks and their spillovers in the presence of international financial integration. In particular, we have introduced international financial linkages via cross-border equity holding. The additional introduction of a global risk shock is motivated by recent empirical work that attributes the unprecedented synchronisation of financial cycles across countries to fluctuations in risk appetite and, in particular, a global risk factor.

Incorporating financial linkages through international equity portfolios increases spillover from idiosyncratic shocks to foreign investment risk. A model with full equity home bias, to the contrary, generates no relevant international spillover in this case. The augmented model is also able to reproduce the high correlation of investment and GDP growth between EA, US, and (less so for GDP) RoW observed in the data. The estimated risk shocks track empirical measures of financial tightness and stock market valuation. In particular, the estimated global financial risk shock is consistent with the common component of international stock market indices and plays a significant role in explaining co-movement during the 2008–09 crisis. Our estimation results also show that US investment risk rose before the deterioration of global risk appetite, i.e. the increase in global risk, prior to the 2008–09 financial crisis.

Allowing for a zero lower bound (ZLB) on short-term nominal interest rates in EA and US amplifies the international spillover from increasing regional and global investment risk on real GDP growth, when monetary policy is constrained and cannot mitigate the associated decline in economic activity. The international co-movement in economic activity increases

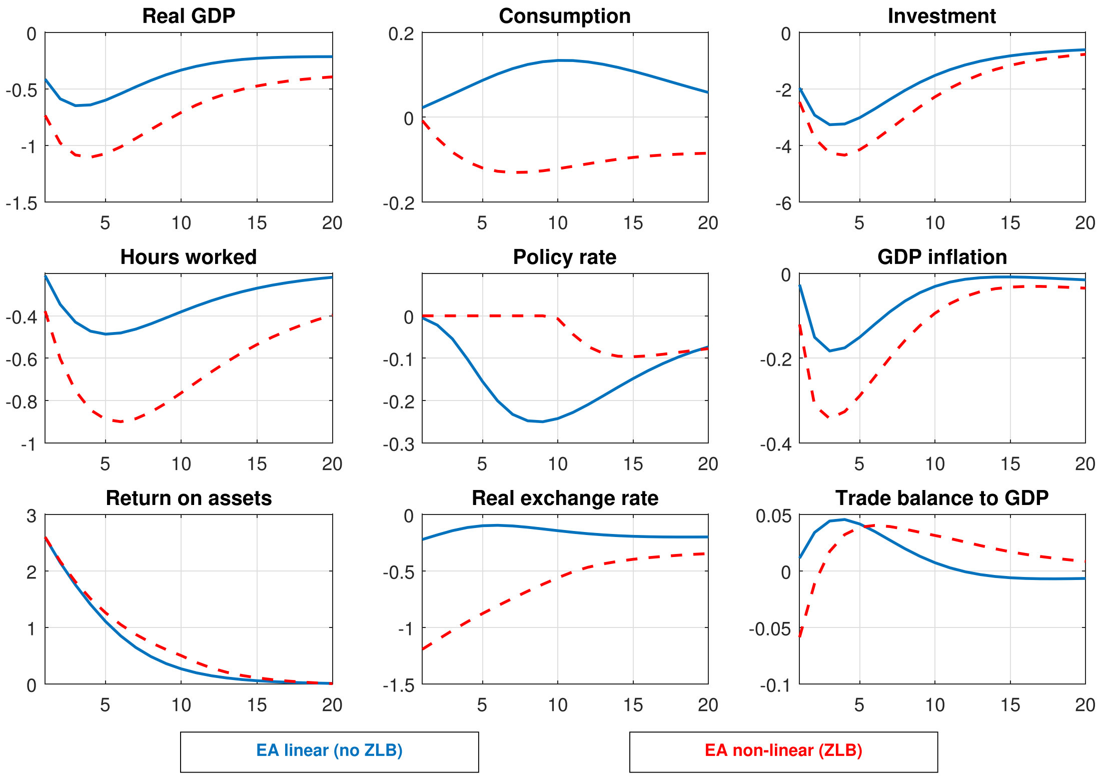

Fig. 14. Dynamic responses to a global risk appetite shock in EA under ZLB. Note: The trade balance (normalised by GDP), inflation (p.a.) and interest rate (p.a.) responses are expressed as percentage point deviations from steady state. All other responses are percent deviations from steady state. A fall in the REER represents an appreciation. The responses of EA linear (no ZLB) and EA non-linear (ZLB) are represented by continuous and dashed lines, respectively.

in this case. The transmission of the investment risk shock also changes at the ZLB, where it mimics a general uncertainty shock that dampens consumption and investment demand simultaneously.

The results have implications for economic policy. Growing international financial integration increases the spillover, i.e. externalities, from foreign and notably financial shocks. This should provide a stronger incentive for international policy coordination to prevent financial turmoil in integrated financial markets. Stronger spillover and economic contraction in response to risk shocks at the ZLB also underline the importance of non-standard monetary measures and fiscal tools to mimic the monetary policy of "normal" times.

Acknowledgements

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Appendix A. Model description

A1. Households

The Ricardian households (j) maximise the present value of the expected stream of future utility subject to Eq. (1). The resulting FOCs are:

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

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

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

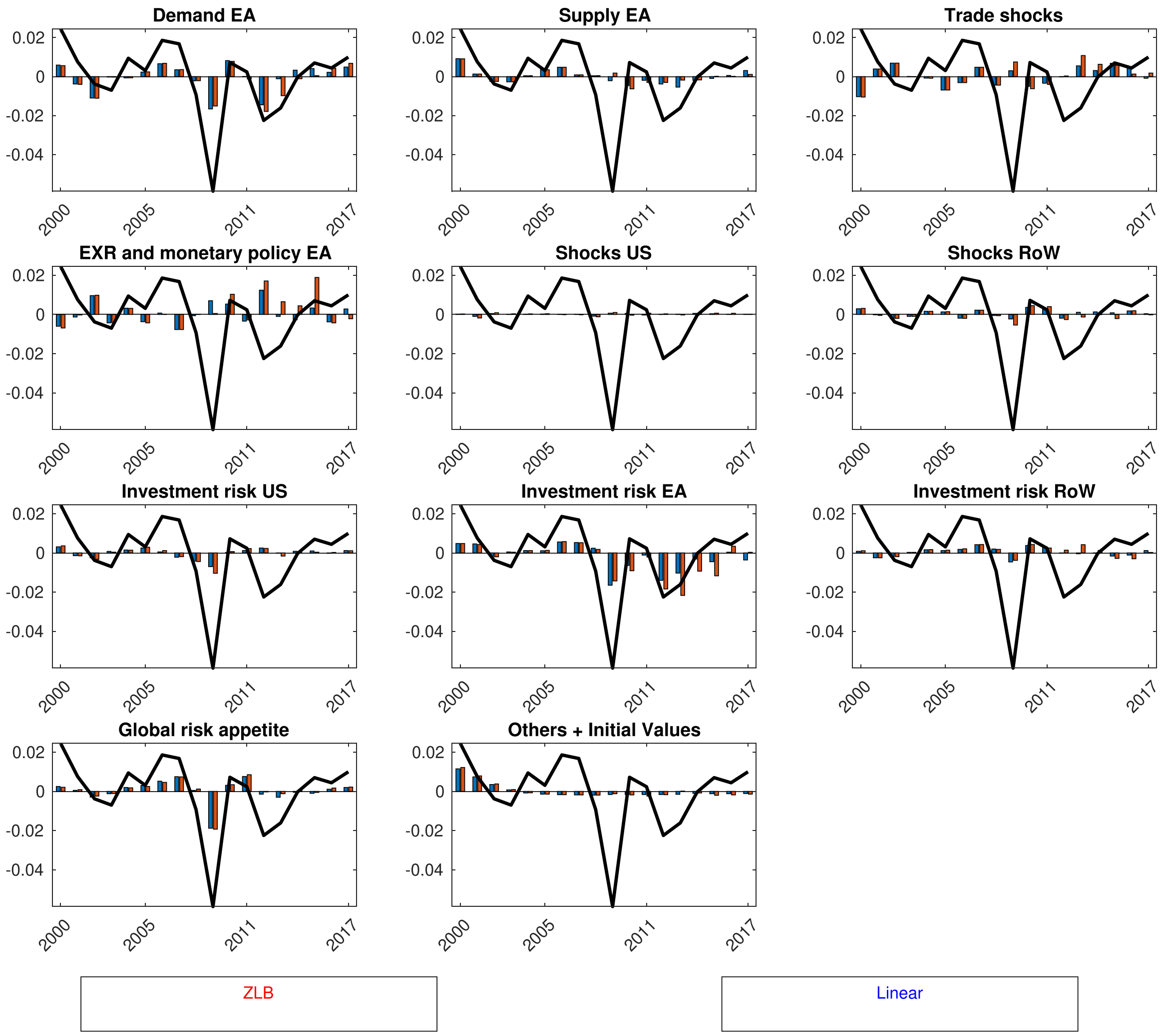

Fig. 15. Piecewise linear smoothed shock decomposition of EA real GDP growth. Note: Annual real GDP growth is shown in percentage-point deviations from steady state, which is calibrated to the mean over the sample period. 0.01 on the y-axis corresponds to 1 pp. Black solid lines are data.

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

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

where, $\alpha^{bw1}_k \frac{e_{RoW,k,t} NFA_{k,t}}{P^Y_{k,t} Y_{k,t}}$ 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 (A.3), (A.4) and (A.5), we obtain the following approximated expressions:

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

$$i^S_{k,t} = i^{rf}_{k,t} + \sum_l s^S_l (rprem^S_{l,t}) + rprem^{ra}_t, \qquad \forall l \in \{EA, US, RoW\},$$

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

where $rprem^G_{k,t}$ and $rprem^W_{k,t}$ are risk premia on domestic government bonds and foreign bonds, respectively, $rprem^S_{l,t}$ is the risk premium required by country l for holding equity issued by any country, and $rprem^{ra}_t$ is the global financial shock to the risk appetite.

A2. Firms

Following Rotemberg (1982), firms (i) face quadratic adjustment costs, $adj_{i,k,t}$, measured in terms of production input factors. Specifically, the adjustment costs are associated with the output price, $P^Y_{i,k,t}$, labour input, $N_{i,k,t}$, the capital stock, $K_{i,k,t-1,}$ and investment, $I_{i,k,t}$, as well as capacity utilisation variation, $CU_{i,k,t}$, and labour hoarding, $FN_{i,k,t}$:

$$adj^{P^Y}_{i,k,t} = \sigma^Y_k \frac{\gamma^P_k}{2} Y_{k,t}\left[\frac{P^Y_{i,k,t}}{P^Y_{i,k,t-1}} - \exp(\bar{\pi})\right]^2,$$

$$adj^N_{i,k,t} = \frac{\gamma^N_k}{2} Y_{k,t}\left[\frac{N_{i,k,t} - FN_{i,k,t}}{N_{i,k,t-1} - FN_{i,k,t-1}} - \exp(g^{pop})\right]^2,$$

$$adj^I_{i,k,t} = \frac{P^I_{k,t}}{P^Y_{k,t}}\left[\frac{\gamma^{I,1}_k}{2} K_{k,t-1}\left(\frac{I_{i,k,t}}{K_{k,t-1}} - \delta^K_{k,t}\right)^2 + \frac{\gamma^{I,2}_k}{2}\frac{\left(I_{i,k,t} - I_{i,k,t-1}\exp\left(g^Y + g^{P^I}_k\right)\right)^2}{K_{k,t-1}}\right],$$

$$adj^{CU}_{i,k,t} = \frac{P^I_{k,t}}{P^Y_{k,t}} K^{tot}_{i,k,t-1}\left[\gamma^{CU,1}_k (CU_{i,k,t} - 1) + \frac{\gamma^{CU,2}_k}{2}(CU_{i,k,t} - 1)^2\right],$$

$$adj^{FN}_{i,k,t} = Y_t\left[\gamma^{FN,1}_k\left(\frac{FN_{i,k,t}}{Actr_{k,t}Pop_{k,t}} - \bar{FN}\right) + \frac{\gamma^{FN,2}_k}{2}\left(\frac{FN_{i,k,t}}{Actr_{k,t}Pop_{k,t}} - \bar{FN}\right)^2\right],$$

where σ^Y_k represents the inverse of the steady state gross price markup on differentiated goods, γ-s capture the degree of adjustment costs, $\bar{\pi}$, g^{pop}, g^Y, $g^{P^I}_k$ are the global steady-state growth rates of output price, population, GDP and country-specific investment price deflators, respectively. $Actr_{k,t}Pop_{k,t}$ is the labour force, and $\bar{FN}$ is the steady-state labour hoarding. $\delta^K_{k,t} \neq \delta_k$ is a function of the depreciation rate adjusted for the capital trend in order to have zero adjustment costs on the trend-path.[25]

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:

$$(1-\tau^K_k)\frac{W_{k,t}}{P^Y_{k,t}} = \alpha_k\left(\mu^y_{k,t} - \varepsilon^{ND}_{k,t}\right)\frac{Y_{k,t}}{N_{k,t} - FN_{k,t}} - \frac{\partial adj^N_{k,t}}{\partial N_{k,t}} + E_t\left[\frac{1+\pi^Y_{k,t+1}}{1+i^s_{k,t+1}}\frac{\partial adj^N_{k,t+1}}{\partial N_{k,t}}\right], \tag{A.6}$$

$$\begin{aligned}\mu^y_{k,t}\alpha_k\frac{Y_{k,t}}{N_{k,t} - FN_{k,t}} &= -\frac{Y_{k,t}}{Actr_{k,t}Pop_{k,t}}\left(\gamma^{FN,1}_k + \gamma^{FN,2}_k\left(\frac{FN_{k,t}}{Actr_{k,t}Pop_{k,t}} - \bar{FN}\right)\right)\\ &\quad + \frac{\partial adj^N_{k,t}}{\partial FN_{k,t}} - E_t\left[\frac{1+\pi^Y_{k,t+1}}{1+i^s_{k,t+1}}\frac{\partial adj^N_{k,t+1}}{\partial FN_{k,t}}\right],\end{aligned} \tag{A.7}$$

$$Q_{k,t} = E_t\left[\frac{1+\pi^Y_{k,t+1}}{1+i^s_{k,t+1}}\frac{P^I_{k,t+1}}{P^Y_{k,t+1}}\frac{P^Y_{k,t}}{P^I_{k,t}}\left(\tau^K_k\delta_k - \frac{\partial adj^{CU}_{k,t}}{\partial K_{k,t-1}} + Q_{k,t+1}(1-\delta_k) + (1-\alpha_k)\mu^Y_{k,t+1}\frac{P^Y_{k,t+1}}{P^I_{k,t+1}}\frac{Y_{kt+1}}{K^{tot}_{k,t}}\right)\right], \tag{A.8}$$

$$\begin{aligned}Q_{k,t} &= \left[1 + \gamma^{I,1}_k\left(\frac{I_{k,t}}{K_{k,t-1}} - \delta^K_{k,t}\right) + \gamma^{I,2}_k\frac{\left(I_{k,t} - I_{k,t-1}\exp\left(g^Y + g^{P^I}_k\right)\right)}{K_{k,t-1}}\right]\\ &\quad - E_t\left[\frac{1+\pi^Y_{k,t+1}}{1+i^s_{k,t+1}}\frac{P^I_{k,t+1}}{P^Y_{k,t+1}}\frac{P^Y_{k,t}}{P^I_{k,t}}\exp\left(g^Y + g^{P^I}_k\right)\gamma^{I,2}_k\frac{\left(I_{k,t+1} - I_{k,t}\exp\left(g^Y + g^{P^I}_k\right)\right)}{K_{k,t}}\right],\end{aligned} \tag{A.9}$$

$$\mu^y_{k,t}(1-\alpha_k)\frac{Y_{k,t}}{CU_{k,t}}\frac{P^Y_{k,t}}{P^I_{k,t}} = K^{tot}_{k,t-1}\left[\gamma^{u,1}_k + \gamma^{u,2}_k(CU_{k,t} - 1)\right], \tag{A.10}$$

[25] We specify $\delta^K_{k,t} = exp(g^{\bar{Y}} + GAPI0) - (1-\delta_k)$, where $g^{\bar{Y}}$ and $GAPI0$ are the global GDP trend and the investment-specific technology growth, respectively, so that $\frac{I}{K} - \delta^k \neq 0$ along the trend path.

where $Q_{k,t} = \mu_{k,t}/\frac{P^I_{k,t}}{P^Y_{k,t}}$ represents Tobin's Q and $Actr_{k,t}Pop_{k,t}$ is the labour force of the domestic country. Eqs. (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, Eq. (A.7) determines the optimal level of labour hoarding at the expense of the loss in the marginal productivity. Note that for the limit $\gamma_k^{FN,2} \to \infty$, firms simply have a constant overhead labour $(\frac{FN_{k,t}}{Actr_{k,t}Pop_{k,t}} = \bar{FN})$. Eqs. (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:

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

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:

$$\begin{aligned}\mu^y_{k,t}\sigma^Y_k &= (1-\tau^K_k)(\sigma^Y_k - 1) + \sigma^Y_k \gamma^P_k \frac{P^Y_{k,t}}{P^Y_{k,t-1}}\left(\pi^Y_{k,t} - \bar{\pi}\right) \\ &\quad - \sigma^Y_k \gamma^P_k E_t\left[\frac{1+\pi^Y_{k,t+1}}{1+i^s_{k,t+1}} \frac{P^Y_{k,t+1}}{P^Y_{k,t}} \frac{Y_{k,t+1}}{Y_{k,t}}\left(sfp_k(\pi^Y_{k,t+1} - \bar{\pi}) + (1-sfp_k)(\pi^\star_{k,t} - \bar{\pi})\right)\right] \\ &\quad + \sigma^Y_k \varepsilon^{\mu Y}_{k,t},\end{aligned} \tag{A.12}$$

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

A3. Fiscal policy

The government finances its consumption, $G_{k,t}$, investment, $I^G_{k,t}$, transfers, $T_{k,t}$, and the servicing of the outstanding debt by issuing one-period bonds, $B^G_{k,t}$, and collecting constant linear taxes on labour, τ^N_k, corporate profit, τ^K and consumption, τ^C.

$$B^G_{k,t} = (1+i^G_{k,t-1})B^G_{k,t-1} - R^G_{k,t} + P^G_{k,t}G_{k,t} + P^{IG}_{k,t}I^G_{k,t} + T_{k,t}P^Y_{k,t},$$

where nominal government revenues, R^G, are defined as:

$$\begin{aligned}R^G_{k,t} &\equiv \tau^K\left(P^Y_{k,t}Y_{k,t} - W_{k,t}N_{k,t} - P^I_{k,t}\delta_k K_{k,t-1}\right) + \tau^N_k W_{k,t}N_{k,t} + \tau^C P^C_{k,t}C_{k,t} \\ &\quad + \tau^{IS}P^{Y0}_t IS_t + tax_{k,t}P^Y_{k,t}Y_{k,t}.\end{aligned}$$

Excise duties on IS imports from RoW, $\tau^{IS}P^{Y0}_t IS_t$, are assumed to be exogenously determined. To close the government budget constraint, lump sum taxes, $tax_{k,t}$, adjust residually as follows:

$$\begin{aligned}tax_{k,t} &= \rho_\tau tax_{k,t-1} + \eta^{deft}_k\left(\frac{\Delta B^G_{k,t-1}}{Y_{k,t-1}P^Y_{k,t-1}} - DEFTAR_k\right) \\ &\quad + \eta^{BT}_k\left(\frac{B^G_{k,t-1}}{Y_{k,t-1}P^Y_{k,t-1}} - BTAR_k\right) + \varepsilon^{tax}_{k,t},\end{aligned}$$

where $DEFTAR_k$ and $BTAR_k$ are the targets on government deficit and government debt, respectively, and $\varepsilon^{tax}_{k,t}$ captures a shock.

The model uses a measure of discretionary fiscal effort (DFE), such that government consumption, investment and transfers increase proportionally to the growth of potential output plus an idiosyncratic shock (ε^G, ε^{IG} and ε^T) that follows an AR(1) process.

Appendix B. Additional results

Table B1
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
Degree of openness	s^M	0.18	0.13	0.10
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 labour	ω^N	8.09	8.25	79.61
Production				
Cobb-Douglas labour 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 utilisation adj. costs	$\gamma^{CU,1}$	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

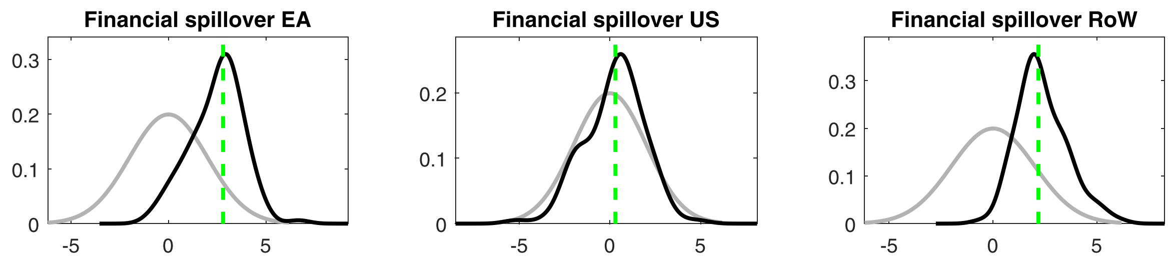

Fig. B1. Prior and posterior distribution of global risk coefficients. Note: All parameters (τ^{ra}) use the same prior distribution (grey). The dashed vertical line shows the mode, the black depicts the posterior distribution.

Table B2
Selected estimated exogenous shock processes.

		Prior distribution		Posterior distribution		
		Distr	Mean St.Dev	EA	US	RoW
Autocorrelations of forcing variables						
Subjective discount factor	ρ^{UC}	**Beta**	0.50	0.81	0.85	0.83
			0.20	(0.76, 0.91)	(0.75, 0.89)	(0.74, 0.93)
Investment risk premium	ρ^S	**Beta**	0.85	0.93	0.95	0.94
			0.05	(0.90, 0.96)	(0.89, 0.95)	(0.90, 0.97)
Price mark-up	ρ^{MUY}	**Beta**	0.50	-	-	0.98
			0.20			(0.97, 0.99)
Labour demand	ρ^{ND}	**Beta**	0.50	0.87	0.91	-
			0.20	(0.78, 0.93)	(0.86, 0.94)	
Trade share	ρ^M	**Beta**	0.50	0.98	0.98	0.98
			0.20	(0.97, 0.99)	(0.95, 0.99)	(0.98, 0.99)
International bond preference	ρ^{BW}	**Beta**	0.50	0.86	0.58	-
			0.20	(0.82, 0.97)	(0.50, 0.70)	
Global risk appetite	ρ^{ra}	**Beta**	0.50	0.83		
			0.20	(0.65, 0.91)		
Standard deviations (%) of innovations to forcing variables						
Subjective discount factor	ε^{UC}	**Gamma**	1.00	1.11	0.97	1.58
			0.40	(0.49, 1.49)	(0.49, 1.63)	(0.65, 2.91)
Investment risk premium	ε^S	**Gamma**	0.10	0.27	0.30	0.20
			0.04	(0.11, 0.33)	(0.07, 0.33)	(0.08, 0.27)

(*continued on next page*)

Table B2 (*continued*)

		Prior distribution		Posterior distribution		
		Distr	Mean St.Dev	EA	US	RoW
Price mark-up	ε^{MUY}	**Gamma**	2.00	3.40	3.62	2.57
			0.80	(2.51, 6.07)	(2.40, 5.91)	(1.92, 3.45)
Labour demand	ε^{ND}	**Gamma**	1.00	0.57	1.48	-
			0.40	(0.43, 0.71)	(1.34, 1.81)	
Trade share	ε^{M}	**Gamma**	1.00	2.04	2.50	1.53
			0.40	(1.73, 2.32)	(2.10, 2.97)	(1.37, 1.75)
International bond preference	ε^{BW}	**Gamma**	1.00	0.28	0.58	-
			0.40	(0.12, 0.40)	(0.39, 0.68)	
Global risk appetite	ε^{ra}	**Gamma**	0.10	0.12		
			0.04	(0.07, 0.21)		
Temporary TFP level	$\varepsilon^{L\bar{A}Y}$	**Gamma**	0.10	0.01	0.01	-
			0.04	(0.01, 0.02)	(0.00, 0.01)	
Labour supply	ε^{U}	**Gamma**	1.00	1.15	2.04	-
			0.40	(0.62, 1.66)	(1.04, 2.57)	
Monetary policy	ε^{i}	**Gamma**	1.00	0.10	0.11	0.07
			0.40	(0.09, 0.12)	(0.10, 0.13)	(0.06, 0.08)

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)-(7) show the mode and the 90% HPD intervals of the posterior distributions of EA, US, and RoW.

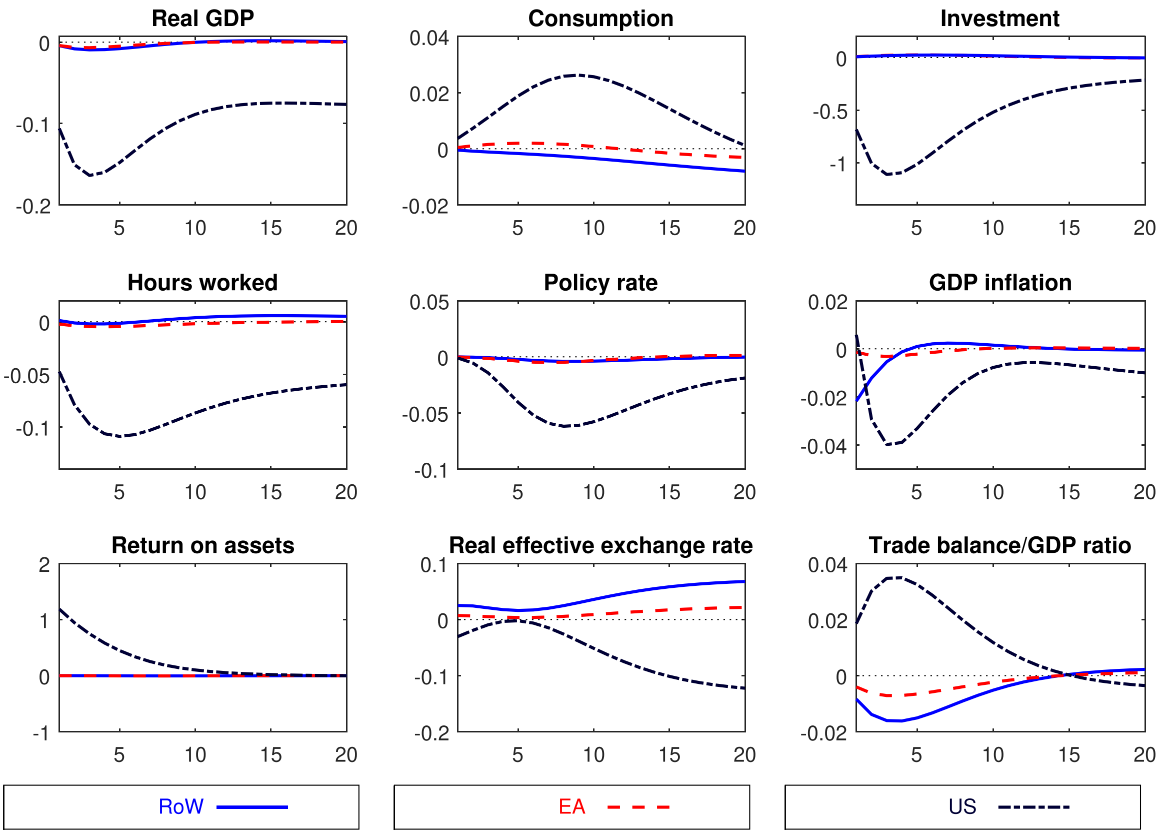

Fig. B2. Dynamic responses to a positive US investment risk premium shock in a model without cross-border equity holdings. Note: The trade balance (normalised by GDP), inflation (p.a.) and interest rate (p.a.) responses are expressed as percentage-point deviations from steady state. All other responses are percent deviations from steady state. A fall in the REER represents a real effective appreciation for the respective economy. The responses of RoW, EA and US variables are represented by continuous, dashed and dash-dotted lines, respectively.

Table B3
Historical sequence of occasionally binding regimes.

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

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.

Appendix C. Piecewise linear smoothed shock decomposition

This appendix describes an extension of the standard linear (additive) historical shock decomposition to occasionally binding constraints. The piecewise linear smoother provides an estimate of the historical sequence of regimes, i.e. identifies periods in which the ZLB has been binding, and in which, hence, the dynamic transmission of shocks differs from "normal" times, and periods in which it has not been binding (Table B.3). The sequence of regimes triggers a sequence of state space matrices:

$$y_t = C(t) + T(t)y_{t-1} + R(t)\epsilon_t,$$

where y are endogenous variables in deviation from steady state, ε are the smoothed shocks, and $C(t)$ is a constant which is triggered by the ZLB regime. While $C = 0$ in normal times, the constant is triggered by the fact that, under the ZLB regime, the Taylor rule becomes $i_{EA} = i_{EA}^{LB}$ and violates the steady state solution as $i_{EA}^{LB} < \bar{i}$.

The smoothed shock decomposition is performed similarly to the usual linear case: Given the smoothed series of regimes, the shocks are propagated individually through the sequence of state space matrices T and R. The array C is, instead, treated

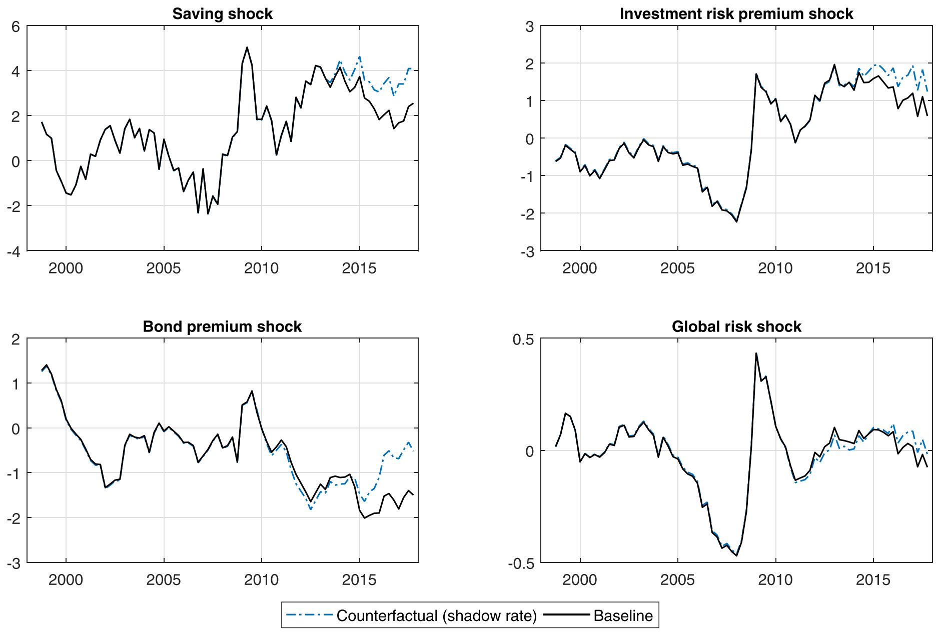

Fig. D1. Comparison of smoothed shocks in EA. Note: 1 on the y-axis corresponds to 1 percent.

as an additional 'exogenous' process, the regime effect. A similar procedure of shock decomposition is applied, for example, in the RISE Toolbox by Junior Maih.[26]

In this paper, we make a further step. The regime effect results from the interaction of all shocks hitting the system simultaneously, for all times $<= t$. Hence, we can assume that such a regime effect is also a function of the model shocks. This allows us to compute, at each time point and for each y_j of interest, the absolute value of the contribution of each shock ε_i onto variable y_j:

$$w_{j,i}(t) = |y_j(e_i, t)|,$$

which provides a set of weights that can be used to apportion the regime affect among all shocks in the model. The intuition behind this procedure is the following: If a shock is relevant for y at a given point in time t, it will also be relevant in triggering the regime effect. For example, if it is an expansionary shock, it would contribute to mitigate the duration of the constrained regime and vice versa. By doing so, we obtain a historical shock decomposition in terms of the usual model shocks, which also includes the regime effect (see Fig. 15).

Appendix D. Sensitivity analysis – observing shadow rates

This section provides a sensitivity check related to our monetary policy (Taylor rule) specification, unconventional monetary policy measures, and implications for financial markets, particularly for the estimated global risk shock.

As mentioned in Section 5, the model is solved and estimated using a first-order approximation around its deterministic steady state. Hence, we do not account for occasionally binding constraints during the estimation process, but impose an ex post evaluation of an effective zero lower bound by using the Occbin smoother described in Section 7.

Given our rich set of observed time series and estimated shocks, the estimation results are able to capture key dynamic properties of macroeconomic and financial data and should, hence, implicitly gather also the effects of unconventional monetary policy measures via domestic demand shocks (saving and investment risk) and exchange rate depreciation.

We perform the following counterfactual to provide some robustness analysis regarding the modelling of monetary policy: (i) We take the shadow rate data for the ECB policy rate and the US federal funds rate from Wu and Xia (2017) and Wu and Xia (2016), respectively. (ii) Instead of observing the policy rates, we observe the shadow rates for EA and US interest rates and re-run the Kalman filter to obtain smoothed estimates that back out a realisation of smoothed shocks consistent with the shadow rates. (iii) Since the monetary policy shock needs to adjust to match the shadow rates (i.e. more expansionary shocks that proxy the contribution of unconventional policies), it removes the expansionary component of unconventional policy from the saving, investment, and exchange rate shocks. The newly obtained series of smoothed shocks (saving, investment, exchange rate) in the counterfactual indicate, how these shocks would have evolved in the benchmark model without unconventional monetary policy.

Fig. D.1 provides a comparison of smoothed shocks between the counterfactual (observing the shadow rates) and our benchmark results. It depicts that with the beginning of large-scale unconventional monetary policy measures in 2015,

[26] https://github.com/jmaih/RISE_toolbox.

Table D1
Comparison of annual shock decomposition of EA GDP growth.

Year	Data	Saving		Investment		Global risk		Others	
		Benchmark	CF	Benchmark	CF	Benchmark	CF	Benchmark	CF
2008	-0.9	-0.2	-0.2	0.2	0.2	0.0	0.0	-1.0	-1.0
2009	-5.9	-1.7	-1.7	-1.7	-1.7	-1.9	-1.9	-0.7	-0.7
2010	0.7	0.8	0.8	-0.6	-0.6	0.3	0.3	0.2	0.2
2011	0.2	0.0	0.0	-0.1	-0.1	0.8	0.8	-0.4	-0.4
2012	-2.3	-1.4	-1.4	-1.4	-1.4	-0.1	-0.1	0.7	0.7
2013	-1.6	-0.1	-0.1	-1.0	-1.1	-0.3	-0.3	-0.2	-0.1
2014	0.0	0.3	0.2	-0.3	-0.5	0.0	-0.1	0.0	0.4
2015	0.7	0.4	0.2	-0.5	-0.8	-0.1	-0.2	0.9	1.5
2016	0.4	0.2	0.0	0.0	-0.3	0.1	0.0	0.1	0.7
2017	1.0	0.5	0.3	-0.4	-0.7	0.2	0.1	0.7	1.3

Note: Numerical values for the benchmark and the counterfactual are expressed in percentage-point (pp) deviations from the sample mean of EA GDP growth (1.3%). The four different groups of shocks in each scenario (Benchmark and CF) add up to the data (Column 2); a value of 1 corresponds to 1pp.

savings, investment risk, and the bond premium would have been higher in the counterfactual scenario, suggesting that our benchmark results capture implicitly the demand-driven boost in consumption (decrease in savings), investment (decrease in investment risk), and net exports (depreciation of the real exchange rate) stemming from unconventional monetary policy at the effective lower bound. The global risk shock, however, seems to be less affected during this period.

In order to highlight the impact of the counterfactual on annual EA GDP growth, Table D.1 provides a comparison of our benchmark model with the counterfactual. It supports the hypothesis that our benchmark model implicitly captures unconventional monetary policy measures by the ECB, notably through a bigger positive contribution of consumption (reduced savings) and investment demand, compared to the counterfactual (CF) scenario. Global risk sentiment seems to be less affected, but still contributes on average 0.1 pp more in the benchmark compared to the counterfactual. In terms of shock aggregation, the implicit proxy for unconventional policy, i.e. the less contractionary Taylor rule shock under the shadow rate specification, is captured by a bigger positive contribution of 'Others' in the counterfactual. The qualitative and quantitative findings of this comparison are comparable with the results in Hohberger et al. (2019).

Appendix E. Alternative risk indicators

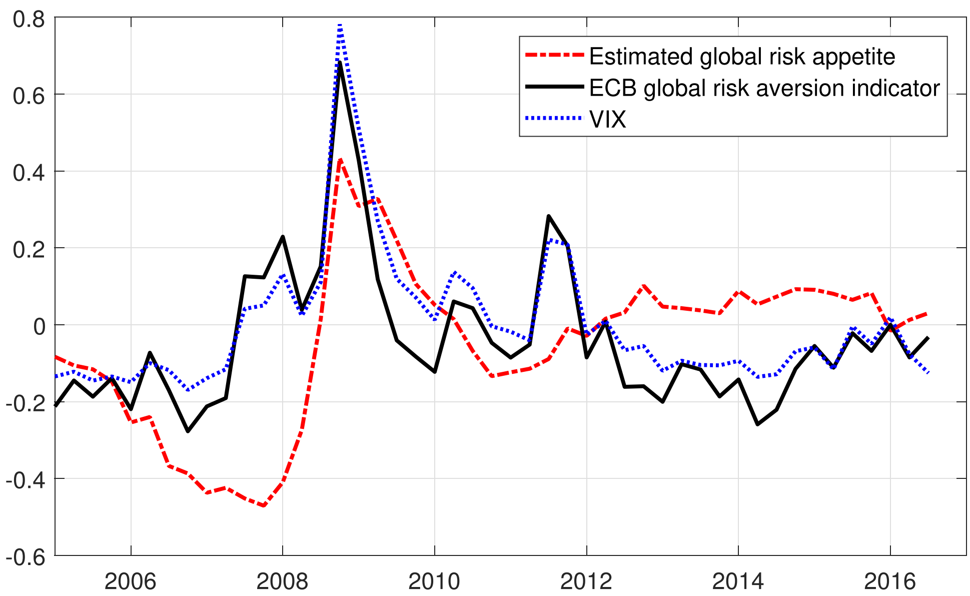

Fig. E1. Comparison of estimated global risk with alternative empirical indicators. Source: Federal Reserve Economic data (VIX) and ECB. All indices are normalised to have the same standard deviation. Data is shown based on the availability of the time span of the series.

Table F1
Observed times series.

Euro Area	US	RoW
Real GDP	Real GDP	Real GDP
TFP trend	TFP trend	GDP trend
Hours worked	Hours worked	Nominal interest rate
Nominal wage share to GDP	Nominal wage share to GDP	GDP deflator
Nominal interest rate	Nominal interest rate	Total investment to GDP
Net IS import share to GDP	Net IS import share to GDP	Population
Price of IS imports (from RoW)	Price of IS imports (from RoW)	
Government transfers to GDP	Government transfers to GDP	
Government debt to GDP	Government debt to GDP	
Gov. interest payments to GDP	Gov. interest payments to GDP	
Gov. consumption to GDP	Gov. consumption to GDP	
Gov. investment to GDP	Gov. investment to GDP	
Total investment to GDP	Total investment to GDP	
Private consumption to GDP	Private consumption to GDP	
Nominal exports to GDP	Nominal exports to GDP	
Nominal imports to GDP	Nominal imports to GDP	
Nominal effective exchange rate	Nominal exchange rate Euro/USD	
GDP deflator	GDP deflator	
Gov. consumption to GDP deflator	Gov. consumption to GDP deflator	
Gov. investment to GDP deflator	Gov. investment to GDP deflator	
Private consumption to GDP deflator	Private consumption to GDP deflator	
Total investment to GDP deflator	Total investment to GDP deflator	
Nominal import to GDP deflator	Nominal import to GDP deflator	
Nominal exports to GDP deflator	Nominal exports to GDP deflator	
Nominal trade balance to GDP	Nominal trade balance to GDP	
Active population rate	Active population rate	
Population	Population	
	Oil price (Brent) in USD	

Appendix F. Data source and transformations

F1. Data sources

Data for the EA (quarterly national accounts, fiscal aggregates, quarterly interest and exchange rates) are taken from Eurostat. The 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.

F2. Constructing of data series for RoW variables

Series for GDP, investment, prices and interest rates in 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.

F3. List of observables

The estimation uses the time series information for 61 endogenous variables. We additionally observe the first quarter of the capital stock and the net international investment position for EA and US to initialise the starting point. Table F.1 lists the observed time series. We apply logarithmic transformations to all observables, with the exception of the trade balance-to-GDP ratio, the oil price (Brent), the IS import share to GDP, the price of IS imports, and nominal interest rates. GDP deflators and relative prices of demand components are computed as the ratios of the current-price value to the chain-indexed volume series.

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