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The Post-Crisis Slump in the Euro Area and the US: Evidence From an Estimated Three-Region DSGE Model

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The global financial crisis (2008-09) led to a sharp contraction in both Euro Area (EA) and US real activity, and was followed by a long-lasting slump. However, the post-crisis adjustment in the EA and the US shows striking differences—in particular, the EA slump has been markedly more protracted. We *estimate* a three-region (EA, US and Rest of World) New Keynesian DSGE model (using quarterly data for 1999-2014) to quantify the drivers of the divergent EA and US adjustment paths. Our results suggest that financial shocks were key drivers of the 2008-09 Great Recession, for both the EA and the US. The post-2009 slump in the EA mainly reflects a combination of adverse aggregate demand and supply shocks, in particular lower productivity growth, and persistent adverse shocks to capital investment, linked to the continuing poor health of the EA financial system. Adverse financial shocks were less persistent for the US. The financial shocks identified by the model are consistent with observed performance indicators of the EA and US banking systems.

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1. Introduction

The global financial crisis (2008-09) led to a sharp contraction in both Euro Area (EA) and US real activity, and was followed by a long-lasting slump. However, the post-crisis adjustment in the EA and the US shows striking differences. In particular, the EA slump has been markedly more protracted. As of this writing (2015), EA per capita real GDP remains below its pre-crisis peak. US per capita GDP only recovered to its pre-crisis peak in 2014 and remains noticeably below its pre-crisis trend. Private investment contracted less (as a share of GDP) in the EA than in the US, during the 2008-09 crisis, but in the aftermath of the crisis the EA investment share continued to trend down, while the US investment share began to recover in 2011. Also, post-crisis inflation has been lower in the EA than in the US. (See Section 2 for a detailed discussion of the EA and US post-crisis dynamics.)

There is a heated debate about the causes of these developments. Some commentators argue that the protracted EA slump reflects weak aggregate demand, driven i.a. by restrictive fiscal policy ('austerity'); see, e.g., IMF (2012), De Grauwe (2014) and Stiglitz (2015). Other analysts stress that rigidities in EA product and labor markets may have hampered the rebound of the EA economy, by slowing down sectoral redeployment and the adoption of new technologies (e.g., Fernald (2015)). Several commentators have also suggested that post-crisis deleveraging pressures and financial constraints have contributed to the persistent slump, especially in the EA (e.g., Rogoff (2015)). The supply of credit to the private sector may have been disrupted more persistently in the EA than in the US, due to the continuing poorer health of EA banks (OECD (2014)). EA banks rebuilt their capital much more gradually than US banks, after the crisis; in addition EA bank balance sheets were weakened by the sovereign debt crisis that erupted in 2010-11 (Acharya et al. (2015), Kalemli-Özcan et al. (2015)).

The contribution of this paper is to shed light on these issues and hypotheses using a state-of-the-art *estimated* dynamic stochastic general equilibrium (DSGE) model. So far, the debate on the EA post-crisis slump has often been polemical, with remarkably little use of evidence-based quantitative models. (Some recent research uses estimated DSGE models to analyze the dynamics of the US economy since the crisis; see discussion below.) The use of an *estimated* rich DSGE model allows us to recover the shocks that have driven the EA, US and ROW economies—and, hence, we can determine what shocks and transmission mechanisms mattered most and when.

In order to explain the striking post-crisis divergence between the EA and the US, we jointly model these two regions, as well as an aggregate of the Rest of the World (ROW), i.e. we consider a three-region model. The EA and US blocks of the model have the same structure, but parameters are allowed to differ across the blocks. The model is estimated using quarterly data for the period 1999q1-2014q4. In order to address the range of views about the post-crisis slump (see above), our model assumes a rich set of demand and supply shocks in goods, labor and asset markets, and it allows for nominal and real rigidities and financial frictions.

Our estimation results suggest that the persistent EA slump reflects a combination of adverse supply *and* demand shocks, in particular negative shocks to TFP growth and adverse shocks to production capital investment risk premia, linked to the continuing poor health of the EA banking system. Our empirical analysis suggests that fiscal policy (austerity) had a non-negligible impact, but was not the major factor delaying the recovery in the EA. EA real activity has benefited from noticeable *positive* factors during the aftermath of the crisis--however those positive influences were weaker than the adverse supply and demand shocks mentioned above. For example, our model estimates suggest that EA price mark-ups fell during and after the 2008-09 Great Recession, which was reflected in a rise in the EA wage share, and was a driver of low post-crisis EA inflation. An additional factor for low post-crisis inflation in the EA was weak private demand.

According to our estimates, the faster post-crisis rebound of the US economy largely reflects a steady fall in capital investment risk premia, linked to the faster improvement in the health of the US financial system. Furthermore, post-crisis TFP growth fell markedly less in the US than in the EA. In the aftermath of the crisis, US aggregate activity also benefited from more resilient private consumption demand, consistent with faster household deleveraging in the US (compared to the EA). According to our estimates, US fiscal policy was more stimulative than EA fiscal policy during the financial crisis. However, we also identify important factors that slowed down the recovery of the US economy; in particular, US price mark-ups rose during the post-crisis period, which had a negative influence on US output (and a positive effect on US inflation).

Our empirical estimates suggest that ROW real activity during the financial crisis had a noticeable stabilizing effect on EA and US GDP growth. Shock transmission between EA and the US has been weak.

As pointed out above, there is little empirical model-based research on the EA post-crisis slump. By contrast, several recent papers have studied the post-crisis dynamics of inflation and real activity in the US economy, using estimated *closed economy* DSGE models; see Christiano et al. (2015), Fratto and Uhlig (2015), Lindé et al. (2015) and Del Negro et al. (2015). Like Fratto and Uhlig (2015) and Lindé et al. (2015) we find that the zero-lower-bound (ZLB) was not a significant constraint for US and EA monetary policy during the 2008-09 Great Recession and its aftermath. We concur with Christiano et al. (2015) that financial shocks were the key driver of the Great Recession in the US; we find that those shocks matter a great deal for the persistence of the EA slump. A key contribution of our analysis of the US economy is that we model external (international) factors--we show that those factors play a non-negligible role for the US recovery.

As pointed out above, a central contribution of the paper here is the *estimation* of a large-scale multi-country model. By contrast most existing large multi-country models are *calibrated* (e.g., Coenen et al. (2010)). Jacob and Peersman (2012) and Kollmann (2013) have estimated two-country DSGE models, but those models are much more stylized than the structure here. The model here is closest to Kollmann, Ratto, Roeger in't Veld and Vogel (2015) who estimated a three-country model for Germany, the rest of the Euro Area and the ROW. That model has a detailed German block, and the focus is on developments in that country, while the blocks describing the other two regions are more stylized. By contrast, the model here treats the EA and US at the same level of disaggregation, in order to understand differences in adjustment across these two regions and in order to capture the interaction between these two regions.

Section 2 describes macroeconomic conditions in the EA, the US and ROW in the period 1999-2014. Section 3 gives an overview of the model. Section 4 discussed the econometric approach. Section 5 presents the empirical results. Section 6 concludes.

2. EA and US macroeconomic and financial conditions, 1999-2014

Figure 1 plots time series of key macroeconomic variables in the EA and the US in the period 1999-2014, i.e. since the launch of the Euro. Unless stated otherwise, the 'EA' data considered in this paper are aggregates for all countries that were members of the Euro Zone in 2015, less Lithuania (due to missing data).[1]

Panels a. and b. of Figure 1 show EA, US and ROW per capita real GDP (the series are normalized at 100 in 1999).[2] EA and US per capita output grew at roughly the same rate before

[1] Thus, the 'EA' aggregate pertains to these 18 countries: Belgium, Germany, Estonia, Ireland, Greece, Spain, France, Italy, Cyprus, Latvia, Luxemburg, Malta, Netherlands, Austria, Portugal, Slovenia, Slovakia, and Finland. In 1999-2014 the EA accounted on average for 74% of total GDP of all 28 current (2015) member countries of the European Union. This paper focuses on the EA instead of the EU, as EA countries have a common monetary policy.
[2] ROW is an aggregate of 58 countries, including non-EA EU member countries, countries that are neighbors of the EU, G7 countries excluding EA member states and the US, and emerging markets; see the Data Appendix.

the 2008-09 Great Recession. The EA recession started slightly later than the US recession, but both economies experienced approximately the same (relative) contraction, -5%, in 2008-09, and then began to recover at roughly the same rate. However, the EA recovery was short-lived. In 2010-11 the sovereign debt crisis erupted in EA periphery countries, and the trajectories of EA and US per capital GDP began to diverge: the EA experienced a recession in 2011- 2013, while US output growth returned to pre-crisis rates. EA per capita GDP in 2014 remained 3% below the pre-crisis peak of 2007, and 20% below a (log-)linear trend fitted to 1995-2007 per capita GDP. US real per capita GDP stayed below its pre-crisis peak until 2014, but remained about 10% below a (log-)linear trend fitted to 1995-2007 data. ROW per capita GDP growth has *markedly* exceeded EA and US growth, during the sample period (see Figure 1, Panel b.). ROW growth accelerated prior to the global crisis. In 2008-09 ROW growth fell sharply, but remained positive; strong ROW growth (4%-5% p.a.) resumed in 2010.

The EA-US divergence is also apparent in measured total factor productivity (TFP); see Figure 1, Panel i. EA TFP fell during the Great Recession, and has since then stagnated at a level below its pre-crisis peak. US TFP showed zero growth during the Great Recession, and then started to grow again.

The contraction of the employment rate during the Great Recession was much sharper in the US than in the EA (Panel e.). The US employment rate began to rebound in 2011, but has not yet reached pre-crisis levels, while EA employment continued to slide down after the crisis. The EA wage share (wage earnings/GDP ratio) trended downwards before 2007, and then experienced a marked increase (by close to 4 percentage points) during the Great Recession that has persisted to the end of the sample period (Panel f.). By contrast, the US wage share followed a downward trend throughout the sample period. Average inflation in 1999-2014 was lower in the EA than in the US (Panel k.). US and EA inflation fell during the financial crisis, and rose after the crisis, but stayed below pre-crisis levels.

The dynamics of the components of aggregate demand, too, differs noticeably across the EA and US. Panels c., d. and g. of Figure 1 show EA and US private consumption, private gross investment and net exports, in % of GDP (Y). (All ratios of variables to GDP discussed in the following paragraphs are ratios of nominal variables.) The EA consumption share (C/Y) fell slightly before the financial crisis, before rising somewhat during the crisis—overall the EA consumption share has been trendless. By contrast, the US consumption share increased steadily by 3.5 percentage points between 1999 and 2011, and then decreased slightly until 2014.

The private investment share (I/Y) contracted in both the EA and the US, during the 2008-09 recession. The EA investment share contracted less during the recession, but continued to trend down after 2009. By contrast, the US investment share began to rebound in 2011.

The post-crisis fall in aggregate demand was accompanied by a rise in the US and (especially) EA net exports/GDP ratios (Panel g.). The Euro appreciated steadily against the US dollar until 2008, but the Euro has depreciated by about 10% since then (Panel h.). The real effective exchange rate (REER) of the EA, too, appreciated until the crisis, and then depreciated mildly. The US effective REER depreciated steadily until 2011, and then appreciated slightly.

Finally, we note that the US primary government deficit rose more sharply than the EA government deficit during the 2008-09 recession, and remained greater than the EA deficit until 2012 (see Panel j.). This suggests that fiscal policy had a more aggressive countercyclical stance in the US than in the EA.

Key EA and US financial variables are plotted in Figure 2. In both regions the household debt/GDP ratio (see Panel a.) rose by roughly 1/3 between 1999 and the financial crisis; that ratio fell after the crisis—the reduction was more pronounced in the US. The debt of non-financial corporations rose more in the EA than in the US, before the financial crisis, and it remained high after the crisis (Panel b.).

The global financial crisis triggered a sizable increase in EA and US non-performing loan (NPL) rates (defined as non-performing bank loans divided by outstanding loans), by about 5 percentage points (Panel c.). After 2009, the EA NPL rate continued to trend upwards (reaching more than 8% in 2014), while the US NPL rate fell steadily—however, the US NPL rate in 2014 (2%) remains above the pre-crisis NPL rate. The 2008-09 recession also triggered a persistent rise in EA and US bank loan rate spreads (Panel d.), as well as a tightening of bank lending standards (as measured by loan officer surveys); see Panels e. and f.[3] During the financial crisis, net credit tightening was stronger in the US than in the EA. However, US credit conditions loosened after 2009, while EA credit continued to tighten. Credit tightness at a given date can be measured by cumulated net credit tightening in preceding periods. Panel f. indicates that US credit tightness fell markedly after 2009, while EA credit tightness continued to increase after 2009.[4] More

[3]The bank loan rate spread is defined as the bank loan rate (to non-financial corporations) minus the money market rate.
[4]Net credit tightening in a given quarter is defined as the percentage of banks that report a tightening of lending standards minus the percentage of banks reporting a loosening of lending standards, in that quarter. EA and US net credit tightening data are available from 2003q1 and from 1999q1, respectively (sources: ECB Euro Area Bank Lending Survey; Federal Reserve Board Senior Loan Officer Opinion Survey on Bank Lending Practices). The

restricted bank credit in the EA is consistent with the NPL problem which plagues EA banks. Aiyar et al. (2015) identify various channels by which high NPL levels restrict the supply of credit; for example, bank profitability suffers because of higher provisions and monitoring costs, which makes it more difficult to raise equity and put resources into new lending. Aiyar et al. (2015) also provide evidence that banks with higher NPLs have higher funding costs.

The evidence in Figure 2 indicates thus that the health of the EA and US banking systems was damaged by the 2008-09 financial crisis; the state of the EA banking system continued to deteriorate after 2009, while the health of the US banking system improved steadily. This is consistent with the fact that policy measures relieving the banking sector from bad loans were pursued earlier and more aggressively in the US; as a result, US banks rebuilt their capital much faster than EA banks after 2008-09 (OECD (2014)). In addition EA bank balance sheets were weakened by the sovereign debt crisis that erupted in 2010-11 (Acharya et al. (2015), Kalemli-Özcan et al. (2015)).

3. Model description

We consider a three-region world consisting of the EA, US and ROW. The EA and US blocks of the model are rather detailed, while the ROW block is more stylized. The EA and US blocks assume two (representative) households, firms and a government. EA and US households provide labor services to domestic firms. One of the two households in each region has access to financial markets, and she owns her region's firms. The other household has no access to financial markets, does not own financial or physical capital, and each period consumes her disposable wage and transfer income. We refer to these agents as 'Ricardian' and 'hand-to-mouth' households, respectively. Final output in the EA and in the US is generated by perfectly competitive firms that combine domestic and imported intermediate inputs. Intermediates are produced by monopolistically competitive firms using local labor and capital. EA and US wage rates are set by monopolistic trade unions. Nominal intermediate goods prices and nominal wages are sticky. Governments purchase the local final good, make lump-sum transfers to local households, levy labor and consumption taxes and issue debt. All exogenous random variables in

(cumulative) US credit tightness series shown in Panel f. is normalized additively (subtraction of a constant) so that the normalized series equals zero in 2002q4.

the model follow independent autoregressive processes. We next present the key aspects of the EA model block. The US block has the same structure.[5]

3.1. EA households

A household's welfare depends on consumption and hours worked. EA household i=r,h (r : Ricardian, h: hand-to-mouth) has this period utility function:

$$U_t^i \equiv \tfrac{1}{1-\theta}(C_t^i - \eta^C C_{t-1}^i)^{1-\theta} - s_t^N (C_t^i)^{1-\theta} \tfrac{1}{1+\theta^N}(N_t^i - \eta^N N_{t-1}^i)^{1+\theta^N},$$

with $0<\theta,\theta^N,s_t^N$ and $0<\eta^C,\eta^N<1$. C_t^i and N_t^i are consumption and the labor hours of household i in period t, respectively. We assume (exogenous) habit persistence for consumption and labor hours.[6] s_t^N is a stationary exogenous shock to the disutility of labor. The subjective discount factor of EA households, $0<\beta_{t,t+1}<1$, too is an exogenous random variable. Date t expected life-time utility of EA household i, V_t^i, is defined by $V_t^i = U_t^i + E_t \beta_{t,t+1} V_{t+1}^i$.

The EA Ricardian household owns all domestic firms, and she holds domestic and foreign bonds. Her period t budget constraint is:

$$(1+\tau^C)P_t C_t^r + B_{t+1}^r = (1-\tau^N)W_t N_t^r + B_t^r(1+i_t^r) + div_t + T_t^r,$$

where P_t, W_t, div_t and T_t^r are the consumption price index, the nominal wage rate, dividends generated by domestic firms, and government transfers received by the Ricardian household. B_{t+1}^r denotes the Ricardian household's bond holdings at the end of period t, and i_t^r is the nominal return on the household's bond portfolio between periods t-1 and t.[7] τ^C and τ^N are (constant) consumption and labor tax rates, respectively.

The hand-to-mouth household does not trade in asset markets and simply consumes her disposable wage and transfer income. Her budget constraint is: $(1+\tau^C)P_t C_t^h = (1-\tau^N)W_t N_t^h + T_t^h$.

[5]Parameter values are allowed to differ across the EA and the US. The description here abstracts from factor adjustment costs and variable capacity utilization rates assumed in the estimated model. Also, we only present the main exogenous shocks. The detailed model is available in a Not-for-Publication Appendix. The EA and US blocks build on, but are considerably different than, the EU Commission's QUEST model of the EU economy; see Ratto et al., 2009; in't Veld et al. (2015), Kollmann et al. (2015).

[6]To allow for balanced growth, the disutility of labor features the multiplicative term $(C_t^h)^{1-\theta}$; this term is treated as exogenous by the household.

[7]The household can hold risk-free one-period bonds denominated in EA, US and ROW currency. The model assumes small convex costs to holding foreign-currency bonds; those costs are rebated to agents in a lump sum fashion. The bond-holding costs pin down the household's bond portfolio in the certainty equivalent (linear) model approximation used below.

3.2. EA firms

3.2.1. EA Intermediate goods producers

In the EA, there is a continuum of intermediate goods indexed by $j \in [0,1]$. Each good is produced by a single firm. As all EA intermediate goods firms face symmetric decision problems, they make identical choices. Firm *j* has technology $y_t^j = \Theta_t (N_t^j)^\alpha (K_t^j)^{1-\alpha}$, where y_t^j, N_t^j, K_t^j are the firm's output, labor input and capital stock, respectively. Total factor productivity (TFP) $\Theta_t > 0$ is exogenous and common to all EA intermediate goods producers. Productivity is driven by a transitory autoregressive component, and by a unit root component whose drift follows a persistent autoregressive process. The law of motion of firm *j*'s capital stock is $K_{t+1}^j = K_t^j(1-\delta) + I_t^j$, with $0<\delta<1$; I_t^j is gross investment. The period *t* dividend of intermediate good firm *j* is

$$div_t^j = p_t^j y_t - W_t N_t^j - p_t^K I_t^j - P_t \kappa_t^j,$$

where p_t^j and p_t^K denote the price charged by the firm and the prices of production capital, respectively. At *t*, each firm faces a downward sloping demand curve for her output, with exogenous price elasticity $\varepsilon_t > 1$ that equals the substitution elasticity between different intermediate good varieties (see below). The firm bears a real cost $\kappa_t^j \equiv \frac{1}{2}\gamma(p_t^j - (1+\pi)p_{t-1}^j)^2 / p_t^j$ of changing her price, where π is the steady state inflation rate.

Firm *j* maximizes the present value of dividends $V_t^j = div_t^j + E_t \rho_{t,t+1}^j \cdot (P_t/P_{t+1}) \cdot V_{t+1}^j$, where $\rho_{t,t+1}^j$ is a stochastic discount factor that is smaller than the intertemporal marginal rate of substitution of the domestic Ricardian household (denoted by $\rho_{t,t+1}^r$): $\rho_{t,t+1}^j = (1-z_t)\rho_{t,t+1}^r$, where $0 \le z_t < 1$ is an exogenous random variable. This is a short-cut for capturing financial frictions facing the firm; z_t can, e.g., be interpreted as a 'principal agent friction' between the owner and the management of the firm (Hall (2011)). [8] The firm's Euler equations for capital is

$$1 = (1-z_t) E_t \rho_{t,t+1}^r (P_t/P_{t+1}) \{(1-1/\varepsilon_{t+1}) p_{t+1}^j MPK_{t+1}^j / p_t^K + (1-\delta) p_{t+1}^K / p_t^K + \Psi_t^j\},$$

[8]Following Bernanke and Gertler (1999), one can also view z_t as a non-fundamental shock that generates an investment bubble, i.e. fluctuations in physical investment and in the price of capital that are not related to (conventional) fundamentals.

where $MPK^j_{t+1} \equiv \Theta_{t+1}\alpha(K^j_{t+1})^{\alpha-1}(N^j_{t+1})^{1-\alpha}$ is the date t+1 marginal product of capital. The term Ψ^j_t depends on the future marginal price-adjustment cost (Ψ^j_t is zero, in steady state). z_t drives a wedge between the risk-free interest rate and the firm's expected return on physical capital.[9] We thus refer to z_t as a (capital) 'investment risk-premium'.

Quadratic price adjustment costs imply that the inflation rate of local intermediates, $\pi_t \equiv \ln(p^j_t/p^j_{t-1})$ obeys an expectational Phillips curve, $\pi_t - \pi = \rho^j E_t(\pi_{t+1} - \pi) + \vartheta^j(p^j_t/MC_t - \frac{\varepsilon}{\varepsilon-1})$, up to a linear approximation. Here MC^j_t is the marginal cost of intermediate good firms and $\varepsilon/(\varepsilon-1)$ is the steady state mark-up factor. ρ^j is the steady state subjective discount factor of intermediate good firms, and ϑ^j is a coefficient that depends on the cost of changing prices.[10]

3.2.2. EA production of new capital goods

New production capital is generated using final output. Let $J_t = \Xi_t \cdot \xi(I_t)$ be the amounts of EA final output needed to produce I_t units of EA capital, respectively. ξ is an increasing, strictly convex function, while Ξ_t is an exogenous shock. The price of production capital is $p^K_t = \Xi_t \xi'(I_t) P_t$. The dividends of the investment good sector is $div^K_t = p^K_t I_t - P_t J_t$.

3.2.3. EA final good sector

The EA final good is produced using the technology $Y_t = ((s^d_t)^{1/\nu}(D_t)^{(\nu/(\nu-1))} + (1-s^d_t)^{1/\nu}(M_t)^{(\nu-1)/\nu})^{\nu/(\nu-1)}$, with $0.5 < s^d_t < 1$. $D_t = \{\int_0^1 (y^j_t)^{(\varepsilon_t-1)/\varepsilon_t} dj\}^{\varepsilon_t/(\varepsilon_t-1)}$ is an aggregate of the local intermediates, where $\varepsilon_t > 1$ is the exogenous substitution elasticity between varieties; M_t is a composite of intermediates imported from the US and the ROW. The home bias parameter s^d_t is an exogenous random variable. The price (=marginal cost) of the final good is $p_t = (s^d_t(p^i_t)^{1-\nu} + (1-s^d_t)(p^m_t)^{1-\nu})^{1/(1-\nu)}$, where p^m_t is the

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[9]The firm's Euler equation can be written as $1 = (1-z_t)E_t\rho^r_{t,t+1}(1+r^K_{t+1})$, where r^K_{t+1} is the firm's real return on physical capital between t and t+1. The Ricardian household's Euler equation for a nominal one-period risk-free bond with interest rate i_{t+1} is $1 = E_t\rho^r_{t,t+1}(P_t/P_{t+1})(1+i_{t+1})$. Thus, up to a (log-)linear approximation: $i_{t+1} - E_t \ln(P_{t+1}/P_t) \cong E_t r^K_{t+1} - z_t$.

[10]The model assumes that export prices are set in producer currency; this implies full pass through of nominal exchange rate changes to export prices expressed in buyer currency. The key results highlighted below are unaffected if instead price setting in buyer currency ('pricing to market') is assumed. This is due to the fact that foreign trade shares are low, for the EA and the US.

import price index. The final good is used for domestic private and government consumption, and for investment.

3.3. Wage setting in the EA

We assume an EA trade union that 'differentiates' homogenous EA labor hours provided by the two domestic households into imperfectly substitutable labor services; the union then offers those services to intermediate goods-producing firms--the labor input N_t in those firms' production functions is a CES aggregate of these differentiated labor services. The union set wage rates at a mark-up μ_t^W over the marginal rate of substitution between leisure and consumption. The wage mark-up is inversely related to the degree of substitution between labor varieties in production. We follow Blanchard and Gali (2007) and allow for real wage inertia; the current period real wage rate set by the union is a weighted average of the desired real wage and the past real wage: $W_t/P_t=((1+\mu_t^W)\cdot mrs_t)^{1-\xi}(W_{t-1}/P_{t-1})^{\xi}$, where mrs_t is a weighted average of the two households' marginal rates of substitution between consumption and leisure. The parameter ξ can be interpreted as an index of real wage rigidity. Real wage rigidity is crucial for capturing the high persistence of employment rate fluctuations in both the US and the EA.

3.4. EA monetary and fiscal policy

The EA monetary policy (nominal) interest rate i_{t+1} is set at date *t* by the EA central bank according to the interest rate feedback rule

$$i_{t+1}=(1-\rho^i)\bar{i}+\rho^i i_t+(1-\rho^i)[\eta^\pi\{\tfrac{1}{4}\ln(P_t/P_{t-4})-\pi\}+\eta^Y Y_t^{gap}]+\varepsilon_t^i,$$

where Y_t^{gap} is the EA output gap, i.e. the (relative) deviation of actual GDP from potential GDP.[11] ε_t^i is a white noise disturbance.

EA real government consumption, G_t, is set according to the following rule:

$$c_t^G-c^G=\rho^G(c_{t-1}^G-c^G)+\varepsilon_t^G,$$

where $c_t^G\equiv G_t/Y_t$ is government consumption normalized by GDP, while ε_t^G is a white noise shock. The model assumes government capital investment that raises private sector productivity (government investment follows a rule that is analogous to the government consumption rule).

[11] Date *t* potential GDP is defined as GDP that would obtain under full utilization of the date *t* capital stock and steady state hours worked, if TFP equaled its trend (unit root) component at *t*.

EA government transfers to households follow a feedback rule that links net transfers to the government budget deficit and to government debt:

$$\tau_t-\tau=\rho^{\tau}(\tau_{t-1}-\tau)+\eta^{def}(\Delta B^g_{t+1}/GDP^{nom}_t-def)+\eta^{B}(B^g_{t+1}/GDP^{nom}_t-b)+\varepsilon^{\tau}_t,$$

where $\tau_t \equiv T_t/GDP^{nom}_t$ are nominal net transfers (T_t), normalized by nominal GDP; B^g_{t+1} is EA nominal public debt. The EA government budget constraint is $B^g_{t+1}=(1+i_t)B^g_t-R^g_t+P_tG_t+T_t$, where R^g_t is nominal tax revenue.

3.5. The ROW block

The model of the ROW economy is a simplified structure with fewer shocks. Specifically, the ROW block consists of a New Keynesian Phillips curve, a budget constraint for the representative household, demand functions for domestic and imported goods (derived from CES consumption good aggregators), and a production technology that uses labor as the sole factor input. The ROW block abstracts from capital accumulation. In the ROW, there are shocks to labor productivity, mark-ups, the subjective discount rate, the relative preference for domestic vs. imported goods, and to monetary policy.

3.6. Exogenous shocks

The estimated model assumes 58 exogenous shocks. Other recent estimated DSGE models likewise assume many shocks (e.g., Kollmann et al. (2015)), as it appears that many shocks are needed to capture the key dynamic properties of macroeconomic and financial data. The large number of shocks is also dictated by the fact that we use a large number of observables (53) for estimation, to shed light on different potential causes of the post-crisis slump. Note that the number of shocks has to be at least as large as the number of observables to avoid stochastic singularity of the model.[12]

4. Model solution and econometric approach

We compute an approximate model solution by linearizing the model around its deterministic steady state. Following the recent literature that estimates DSGE models, we calibrate a subset of

[12]We follow the empirical DSGE literature (e.g. Lindé et al. (2015)), and select observables such that each shock has at least one associated observable that is strongly impacted by the shock (e.g. as we assume trade shocks, we use trade data to identify the trade shocks). The number of shocks exceeds the number of observables because we assume that TFP in each region is driven by a combination of transitory and permanent shocks. All shocks have a sufficiently distinct impact on observables so that shock identification is possible.

parameters to match long-run data properties, and we estimate the remaining parameters using Bayesian methods.[13] The observables employed in estimation are listed in the Data Appendix.[14] The estimation uses quarterly data for the period 1999q1- 2014q4.

We calibrate the model so that steady state ratios of main economic aggregates to GDP match average historical ratios for the EA and the US. The EA (US) steady state ratios of private consumption and investment to GDP are set to 56% (67%) and 19% (17%), respectively. The steady state shares of EA and US GDP in world GDP are 17% and 25%. The steady state trade share (0.5*(exports+imports)/GDP) is set at 18% in the EA and 13% in the US, and the quarterly depreciation rate of capital is 1.4% in the EA and 1.7% in the US. We set the steady state government debt/annual GDP ratio at 80% of GDP in the EA and 85% in the US. The EA and US steady state real GDP growth rate and inflation are set at 0.35% and 0.4% per quarter, respectively. We set the effective rate of time preferences to 0.25% per quarter.

5. Estimation results[15]

5.1. Posterior parameter estimates

The posterior estimates of key model parameters are reported in Table 1. (Estimates of other parameters can be found in the Not-for-Publication Appendix.) The steady state consumption share of the Ricardian household is estimated at 0.70 in the EA and 0.74 in the US. Estimated habit persistence in consumption is high in the EA (0.88) and the US (0.86), which indicates a sluggish adjustment of consumption to income shocks. The risk aversion coefficient is in the range of 1.4 in both regions. The parameter estimates suggest a slightly higher labor supply elasticity in the EA than in the US, while labor habit persistence is lower in the EA. Price elasticities of aggregate imports are sizable for the EA (4.3) and for the US (4.05). The elasticity of substitution between imports of different origins is lower, namely 1.06 between US and ROW goods for the EA and 0.28 between EA and ROW goods for the US (not shown in Table 1). The model estimates also suggest substantial nominal price and wage stickiness, and strong real wage

[13]We use the DYNARE software (Adjemian *et al.*, 2011) to solve the linearized model and to perform the estimation.
[14] The observables are not demeaned or detrended prior to estimation. The model is estimated on first differences of real GDP, real demand components and price indices, and on nominal ratios of aggregate demand components to GDP.
[15]The presentation of results below focuses on key parameter estimates, impulse responses and historical decomposition. Additional results can be found in the Not-for-publication Appendix. There, we i.a. report predicted business cycle statistics (standard deviations and cross-correlations of key macro variables) for the EA, US and ROW; these statistics are broadly consistent with empirical statistics. As a robustness check, we also estimated the model over a pre-crisis sub-sample (1999-2007); we find that parameter estimates are close to the ones obtained over the whole sample.

rigidity. Estimated price adjustment costs are lower in the EA, compared to the US, whereas wage stickiness is higher in the EA. Estimated monetary and fiscal policy parameters are quite similar across both regions. The estimated EA and US interest rate rules indicate a strong response of the policy rate to domestic inflation, and a weak response to domestic output. The fiscal feedback rules for government transfers exhibit very weak responses to public debt and deficit levels.[16] The estimates also suggest that most exogenous variables are highly serially correlated. The standard deviation of innovations to TFP, subjective discount factors, price and wage mark-ups and trade shares are sizable.

The model properties discussed in what follows are evaluated at the posterior mode of the model parameters.

5.2. Dynamic effects of shocks

Figure 3a-3h shows dynamic responses to shocks that matter most during and after the financial crisis. We begin by discussing effects of EA and US aggregate supply shocks (transitory and permanent TFP shocks), and then consider household saving shocks (modeled as shocks to the Ricardian household's subjective discount factor), as well as shocks to government consumption, and to investment risk premia. Finally, we discuss shocks to uncovered interest parity (between the EA/US and the ROW), shocks to ROW competitiveness, and shocks to ROW aggregate demand. In all cases, the effects of a separate one-time 1% (0.01) innovation to a single exogenous variable are reported.[17]

Predicted responses to transitory shocks to the level of TFP are standard, in the model here (see Figure 3a). A transitory positive region-specific TFP shock raises domestic GDP, consumption, investment and the real wage rate, and it lowers domestic inflation, and triggers a real exchange rate depreciation (represented in Figure 3 by a rise in the real exchange rate), which induces a substitution of imports by domestic goods, and hence (slightly) lowers foreign output. Price stickiness, consumption habit and investment adjustment costs dampen the expansion of

[16] In the estimated policy rule for the transfers/GDP ratio (see Sect. 3.4), the coefficient of the government debt/GDP ratio is small $\eta^B = -0.001$, but transfers are highly persistent, $\rho^\tau = 0.97$; thus a deviation of the debt/GDP ratio from target triggers a long-lasting adjustment of transfers. This ensures that debt/GDP converges to steady state in the long run, i.e. that the debt/GDP ratio is stationary. The long-run response coefficient of transfers to debt/GDP, $\eta^B/(1-\rho^\tau)$, exceeds (in absolute value) the steady state difference between the real interest rate and the real GDP growth rate. The negative feedback response of transfers to the public *deficit* ($\eta^{def} = -0.01$) also contributes to debt stabilization.

[17] In Figures 3a-3g, the sub-plots in the three left-most columns show responses to shocks originating in the EA; the sub-plots in the three right-most columns show responses to shocks originating in the US. Responses of EA [US] variables: continuous [dashed] lines.

aggregate demand, in the short term. This explains why output rises much less (in relative terms) than TFP, and why the transitory TFP shock *lowers* employment, on impact. The sluggish adjustment of aggregate demand also explains why a positive TFP shock raises the trade balance of the region that receives the shock.

A positive permanent TFP (growth rate) shock has a much stronger positive effect on domestic consumption, investment and output than a transitory shock (Figure 3b). The stronger effect on aggregate demand explains why permanent TFP shocks raise hours worked, and why these shocks raise domestic inflation in the short run.[18] The much stronger effect of a permanent TFP shock on aggregate demand also explains why that shock has a (slight) *positive* effect on foreign output.

These predicted responses suggest that transitory *negative* EA and US TFP shocks are not a good candidate for explaining the salient facts about the 2008-09 Great Recession and its aftermath. A transitory fall in TFP would raise inflation and employment and worsen the trade balance (which is inconsistent with the observed fall in inflation and employment and the rise in the EA and US trade balances after the 2008-09 recession). A *permanent* negative TFP shock could better explain the post-crisis data: such a shock is predicted by the model to lead to a persistent decline in output and employment and a temporary decrease in inflation (especially in the US). However, a permanent negative TFP shock fails to generate a strong decline in the investment/GDP ratio (as observed in the crisis and post-crisis data), or a trade balance improvement.

As shown in Figure 3c, a positive shock to private saving (a rise in the subjective discount factor) lowers domestic consumption. The shock triggers a fall in domestic and foreign GDP and inflation, it improves the trade balance, and it crowds *in* domestic and foreign investment. Thus, while positive private saving shocks might have driven the fall in inflation and the rise in trade balances during/after the crisis, those shocks fail to account for the slump in investment. Because of their predicted positive effect on investment, positive saving shocks likewise fail to generate a persistent decline in GDP growth.

Predicted responses to fiscal shocks are standard, in the model here. A rise in government purchases increases domestic output, and has a very small positive effect on foreign output

[18] The rise in US inflation is more persistent. The permanent US TFP shock boosts aggregate demand more than the EA shock. This reflects the fact that the US TFP growth rate is more persistent than EA TFP growth; see Table 2. Also, the estimated steady state consumption share of Ricardian (forward-looking) households is higher in the US than in the EA, and estimated consumption habit persistence is weaker in the US.

(Figure 3d). Domestic and foreign consumption and investment are crowded out by a rise in government purchases. Thus, fiscal *consolidation* is a possible candidate for explaining the post-crisis output slump. However, the model-predicted crowding *in* of consumption and investment generated by a fiscal consolidation seems inconsistent with the actual slump in consumption and investment.[19]

A rise in the investment risk premium is predicted to lower domestic investment, as well as domestic and foreign output (see Figure 3e). The fall in aggregate demand induced by the shock lowers labor demand, and thus employment and wages fall. In the short term, the shock lowers inflation. A positive investment risk premium shock generates responses that are consistent along several dimensions with the post-crisis experience: it induces a strong decline of investment relative to GDP; it also generates a highly persistent fall in GDP and a decline in inflation. However, private consumption is crowded in by a positive investment risk premium shock, which suggests that not all facts can be accounted for by this shock.[20]

Figure 3f shows dynamic responses to a shock to the interest parity condition between the Euro and the ROW currency, namely a fall in the risk premium on EA bonds (relative to ROW bonds). This shock appreciates the Euro on impact against the ROW currency, as well as against the US dollar. In response to this, the EA trade balance deteriorates. EA output falls, but EA consumption and investment rise. The Euro appreciation is also accompanied by a fall in EA inflation.

An increase in ROW export competitiveness in the EA (modeled as a fall in the export price mark-up charged by ROW producers in the EA) raises EA imports, and it boosts EA investment (see Figure 3g). EA inflation falls, the Euro depreciates, and EA output falls. (Analogous responses are generated by an increase in ROW export competitiveness in the US.)

Finally, Figure 3h shows dynamic responses to a positive private saving shock in the ROW (i.e. a negative ROW aggregate demand shock). That shock appreciates the EA and US real exchange rate, and it triggers a rise in EA and US consumption and investment, and a deterioration in these regions' trade balances.

[19] Interestingly, the fiscal multiplier is slightly higher in the US than in the EA; this is mainly a consequence of the stronger price rigidity in the US, and of the weaker inflation response in the estimated US monetary policy rule.

[20] Like for a positive private saving shock, the short term real wage response is positive in the EA while it turns negative immediately in the US. This is again a result of the price/wage adjustment speeds that differ across regions.

The results in this section suggest that a *combination* of various shocks is required to explain the major stylized facts of the EA and the US recovery. The next section disentangles the role of key shocks using estimated historical shock decompositions.

5.3. Decomposing EA and US historical time series, 1999-2014

To quantify the role of different shocks as drivers of endogenous variables in the period 1999-2014, we plot the estimated contribution of the different shocks to historical time series. Figure 4 shows historical decompositions of the following EA and US variables: the year-on-year growth rate of real GDP and of the GDP deflator, and the trade balance/GDP ratio. The continuous lines show historical series from which sample averages have been subtracted. The vertical black bars show the contribution of a different group of shocks (see below) to the data, while stacked light bars show the contribution of the remaining shocks. Bars above the horizontal axis represent positive shock contributions, while bars below the horizontal axis show negative contributions. The sum of all shock contributions equals the historical data.

The decompositions of EA variables in Figure 4 (see left-hand Panels) plot the contributions of the following (groups of) exogenous variables originating in the EA: (1) permanent and transitory shocks to EA TFP ('TFP EA'); (2) shocks to the EA investment risk premium; (3) EA price mark-up shocks; (4) EA wage mark-up shocks; (5) shocks to subjective discount factors of EA households ('Private saving shock EA'); (6) EA fiscal policy shocks (i.e. innovations to the fiscal policy decision rules); (7) EA monetary policy shocks; (8) interest parity shocks between the EA and the ROW ('Bond premium EA vs ROW'); (9) interest parity shocks between the US and the ROW ('Bond premium US vs ROW'); (10) shocks to the worldwide relative preference for EA-produced goods versus non-EA goods, and price mark-up shocks for exports and imports ('trade shocks'). In addition, we show contributions of all other non-trade related shocks that originate in the US ('Shocks US'), and of all non-trade-related shocks that originate in the ROW ('Shocks ROW'). The remaining shocks are less important than the shocks listed above, and are hence combined in a category labelled 'Others'.

Shock decompositions for US variables (see right-hand Panels in Fig. 4) use an analogous grouping of shocks.

The historical shock decompositions suggest that in the EA (and also in the US), the pre-crisis boom was largely driven by negative shocks to investment risk premia (see Figure 4a). Beginning in 2008, important adverse shocks occurred. Our estimates suggest that the EA growth slowdown in 2008-09 is largely due to: (i) an increase in the EA investment risk premium; (ii) a decline in EA TFP growth that represents a permanent level shift; (iii) negative trade shocks. ROW real activity during the 2008-09 financial crisis had a noticeable stabilizing effect on EA GDP growth. The crisis was followed in 2010 by a relatively rapid partial recovery due to a fall in risk premia (possibly linked to policy measures to stabilize the financial system). However, in 2011 the EA was hit by a further rise in the investment risk premium, with an adverse effect on investment and GDP. We interpret this second rise in the investment risk premium as a consequence of the sovereign debt crisis that weakened EA bank balance sheets, and thus reduced the supply of credit to the corporate sector and to households, which then lowered corporate investment and household (residential) investment. See Kalemli-Özcan et al. (2015) for micro evidence on this transmission channel of the sovereign debt crisis.

Shocks to EA price and wage mark-ups were less important for the post-2009 dynamics than TFP and investment risk premium shocks; overall, price mark-ups fell after 2009, which dampened the fall in GDP growth. In the EA, positive growth contributions from other sources were very limited after 2009. We identify a small increase in the external Euro risk premium that generated a modest growth impulse via Euro depreciation. Shocks originating in the US had a negligible effect on EA GDP growth.

Our estimates suggest that EA monetary policy shocks had a weak stabilizing effect on GDP growth until 2013. Note that we estimate a linearized version of the model in which the zero lower bound (ZLB) on the nominal policy interest rate is not imposed as a constraint on monetary policy. Estimated monetary policy shocks (disturbances to the interest rate rule) are positive in 2013-14, when the EA policy rate reached levels close to zero. This suggests that, in the EA, the ZLB was binding in 2013-14.[21]

We also find that EA fiscal policy shocks had a slight stimulative effect at the start of the Great Recession in 2008, and a slight contractionary effect before the start of the sovereign debt crisis. Thus, fiscal 'austerity' is not the main driver of the EA post-crisis slump.[22]

[21] The policy rate implied by the policy rule, without disturbance, is negative in 2013-14, so that a positive interest rate disturbance is needed to match the observed policy rate.

[22] The model includes shocks to public consumption, public investment and transfers (the estimation uses data on these variables, and on total fiscal revenue). By contrast, the model assumes constant consumption and income tax *rates* (and supposes that the residual variation in total fiscal revenue is due to a lump sum tax). The model might slightly underestimate the role of tighter fiscal policy for the EA slump, as the share of EA net social security contributions (equivalent to a labor tax) in GDP rose by 1 percentage point in 2007-14 (by contrast, EA direct and indirect tax revenues as a share of GDP staid roughly constant). The model predicts that a permanent labor tax rate increase of this size reduces the level of GDP by merely 0.05% on impact, and by 0.07% and 0.30% after 1 year and 10 years, respectively. That response is modest when compared to the effects of the key drivers of EA GDP identified in this paper (see text above).

The investment risk premium shock is not only important for explaining EA GDP growth, but is needed to explain the fluctuations in physical investment. The investment risk premium shock also helps to explain the dynamics of the EA trade balance before and after 2009 (see below). The adverse EA investment risk premium shocks during the crisis had a strong disinflationary effect (see Figure 4b), but that effect was largely offset by the fall in TFP; this explains the muted decline of EA inflation *during* the 2008-09 crisis. The persistently low post-crisis inflation rate is largely driven by a fall in price mark-ups, and by adverse saving and trade shocks (including oil prices). These effects were only partly offset by monetary policy. Fiscal policy was not a main driver of the persistent fall in post-crisis EA inflation.

The EA trade balance rose significantly and persistently in 2012, after having been stable since the beginning of the sample period. During the global 2008-09 crisis, the EA trade balance showed little change because of the simultaneous contraction of aggregate demand in the EA and in its trading partners (see Figure 4c). The weakness of EA aggregate demand after 2011, combined with the strong ROW recovery and the depreciation of the Euro (explained in the model by an increase in the risk premium on Euro-denominated bonds) then lead to a marked increase in the EA trade balance.

Investment risk premium shocks are even more dominant for US GDP growth than for EA growth (Figure 4a). Those shocks account almost fully for the 2008-09 output contraction. Importantly, the adverse investment risk premium shock was more short-lived in the US than in the EA. This is one of the key factors that explain the better post-crisis GDP performance of the US.

Figure 5 shows *smoothed estimates of EA and US investment risk premia* (see continuous lines). Both premia fell prior to the crisis, and rose sharply during the financial crisis--the estimated US investment risk premium rose more than the EA premium. In the aftermath of the financial crisis, the US investment risk premium fell gradually and steadily, but remained above its pre-crisis level. After the crisis, the estimated EA investment risk premium initially fell more than the US premium. However, the EA investment risk premium rose again sharply after the

The omission of the ZLB constraint too implies that our empirical analysis may understate the impact of fiscal shocks on real activity (see, e.g., Coenen et al. (2012), Farhi and Werning (2016)). In the Not-for-Publication Appendix, we study the impact of fiscal shocks in a model variant (solved using the Guerrieri and Iacoviello (2015) algorithm) in which the ZLB is imposed as an occasionally binding constraint on monetary policy. That analysis confirms that the ZLB was binding in the EA in 2013-14, and it finds that the effect of fiscal shocks to growth was slightly negative in 2013 and 2014 (accounting for 0.25% and 0.10% reductions in GDP growth in 2013 and 2014, respectively). Importantly, we find that imposing the ZLB constraint has a negligible effect on the response of the economy to TFP and investment risk premium shocks; it does not affect the result that these shocks were the most important driver of EA GDP growth during and after the financial crisis.

eruption of the sovereign debt crisis in 2011, and showed no sign of reverting to its pre-crisis level. It seems plausible that the different post-crisis paths of the EA and US investment risk premia are linked to the poorer health of the EA financial system that disrupted the supply of credit to the private sector more persistently in the EA than in the US (see discussion in Section 2). In fact, estimated investment risk premia are highly positively correlated with the indicators of intermediation frictions presented in Section 2. To illustrate this, Figure 5 also plots the cumulated net credit tightening series for the EA and the US (see dashed lines).[23] The correlations of the estimated EA investment risk premium with the EA cumulated net credit tightening series and with the EA bank loan rate spread are 0.78 and 0.89, respectively. For the estimated US investment risk premium, the corresponding correlations (with US credit tightness and the US loan rate spread) are 0.86 and 0.92, respectively. Note, especially, that the estimated investment risk premia match the fact that, during the financial crisis, the loan rate spread and credit tightness rose more sharply in the US than in the EA; the estimated premia also capture the steady improvement in US banking indicators after the crisis, and the deterioration in EA banking indicators after the outbreak of the sovereign debt crisis.

Positive private saving shocks and positive price mark-up shocks, too, contributed noticeably to the US output collapse in the 2008-09 crisis. The US private saving shock might be a proxy for the strong household debt deleveraging that began during the crisis (see Figure 2a).[24] Household saving shocks and adverse investment risk premium shocks contributed importantly to the drop in US inflation during the crisis (Figure 4b). However, the impact of these shocks on inflation was partly offset by a rise in US price mark-ups, together with countercyclical fiscal and monetary policy measures. In the aftermath of the crisis, inflation rebounded faster in the US than in the EA. The role of price mark-ups in muting the fall in US inflation during and after the crisis is consistent with the estimated DSGE model presented by Fratto and Uhlig (2014).

The US entered the financial crisis with a persistent trade deficit. Our historical decomposition suggests that the deficit was largely drive by positive ROW saving shocks, which is consistent with Bernanke's (2005) 'saving glut' hypothesis. In 2008, the US trade balance increased abruptly. This was largely driven by the positive US investment risk premium and saving shocks (Figure 4c). After 2009, the steady fall in the US investment risk premium lowered

[23] Empirical cumulated net credit tightening shown in Figure 5 are adjusted (using a linear transformation) so that the mean and standard deviation of the adjusted series equals the corresponding moments of the estimated investment risk premium.

[24] Albuquerque et al. (2014) document the rapid post-crisis adjustment of US household debt, and argue that it was completed in 2012.

the US trade balance; however, the US trade balance remained above its pre-crisis level, due to persistent positive US saving shocks and a strong recovery in ROW demand.

6. Conclusion

We have *estimated* a three-region (EA, US and Rest of World) New Keynesian DSGE model to quantify the drivers of the divergent EA and US adjustment paths during the aftermath of the global financial crisis. Our analysis reveals that the slow post-crisis recoveries in the US and EA have both common and idiosyncratic components. An important common feature is the strong rise in investment risk premia during the 2008-09 recession that put an end to a pre-crisis investment boom. The model-based estimates of investment risk premia are consistent with various performance indicators of the EA and US banking systems. An important additional contributing factor of the persistent post-2009 EA slump has been the slowdown of TFP growth. Private saving shocks and fiscal austerity are less important for explaining low EA growth according to our estimates; however, private saving shocks are important for the post-crisis slowdown of inflation.

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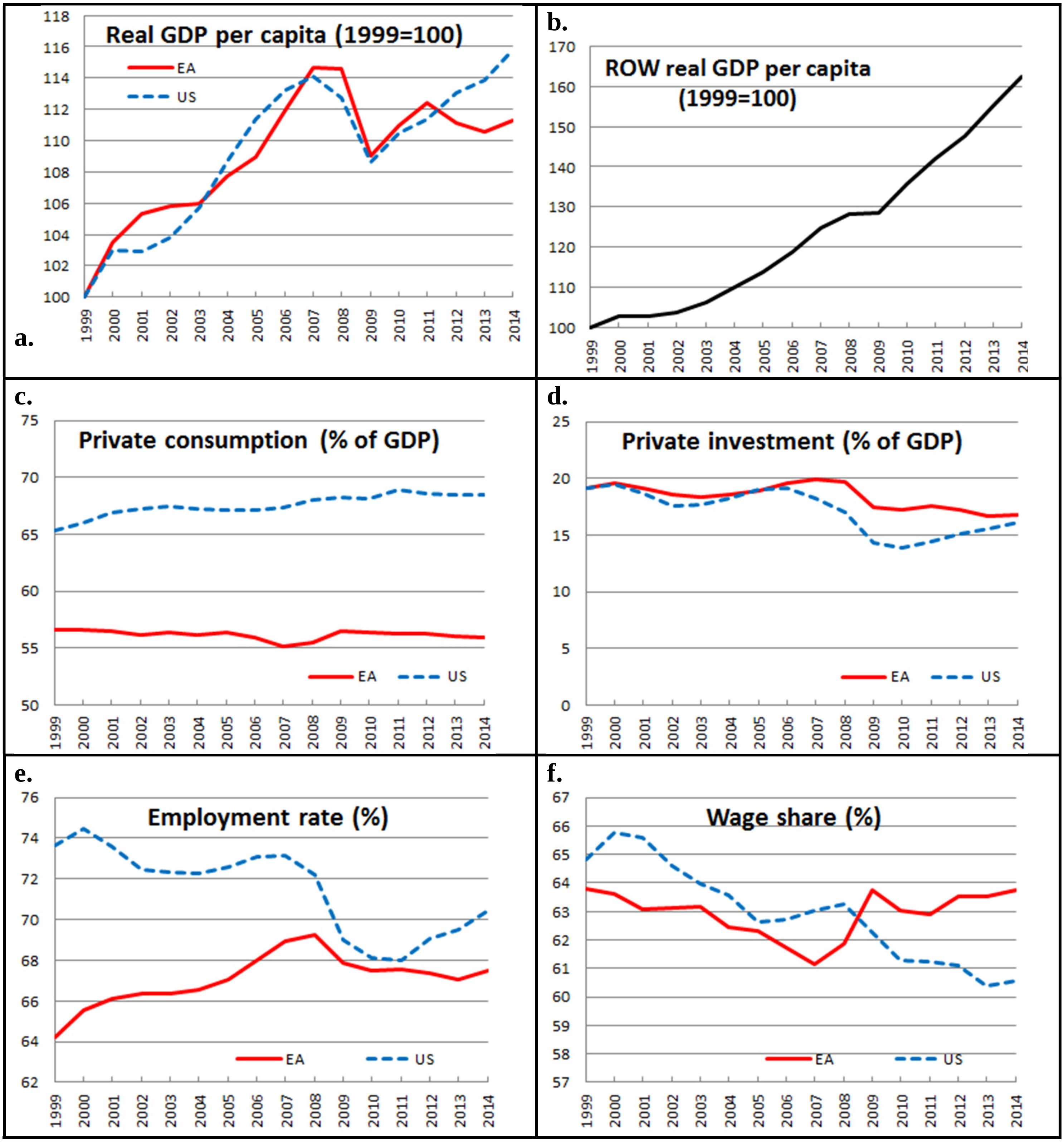
Table 1. Prior and posterior distributions of key estimated model parameters

	Posterior distributions				Prior distributions		
	EA		US				
	Mode	Std	Mode	Std	Distrib.	Mean	Std
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Preferences							
Consumption habit persistence	0.88	0.07	0.86	0.06	B	0.5	0.2
Labor habit persistence	0.38	3.13	0.85	0.10	B	0.5	0.2
Risk aversion	1.47	0.87	1.37	0.61	G	1.5	0.2
Labor supply elasticity	2.32	4.91	2.10	3.74	G	2.5	0.5
Import price elasticity	4.30	0.71	4.05	0.76	G	2	1
Steady state consumption share of Ricardian households							
	0.70	0.03	0.74	0.04	B	0.65	0.05
Nominal and real frictions							
Price adjustment cost	23.2	10.1	57.4	36.8	G	60	40
Nominal wage adj. cost	4.69	8.22	2.93	4.71	G	5	2
Real wage rigidity	0.97	0.06	0.96	0.05	B	0.5	0.2
Monetary policy							
Interest rate persistence	0.85	0.03	0.83	0.03	B	0.7	0.12
Response to inflation	2.23	0.56	1.76	0.24	B	2	0.4
Response to GDP	0.08	0.05	0.07	0.02	B	0.5	0.2
Fiscal policy							
Transfer persistence	0.97	0.05	0.96	0.07	B	0.7	0.1
Transfer response to deficit	-0.01	0.00	-0.01	0.01	B	-0.03	0.01
Transfer response to debt	-0.001	0.00	-0.001	0.00	B	-0.001	0.001
Gov. consumption persistence	0.95	0.01	0.95	0.02	B	0.7	0.1
Autocorrelations of forcing variables							
Temporary TFP	0.78	0.12	0.50	0.16	B	0.5	0.2
Permanent TFP growth	0.95	0.12	0.97	0.04	B	0.8	0.1
Subjective discount factor	0.80	0.10	0.79	0.08	B	0.5	0.2
Investment risk premium	0.94	0.05	0.96	0.03	B	0.5	0.2
Domestic price mark-up	0.24	0.15	0.76	0.12	B	0.5	0.2
Trade share	0.93	0.02	0.85	0.05	B	0.5	0.2
Export price mark-up	0.94	0.02	0.85	0.04	B	0.5	0.2
ROW export price mark-up	0.98	0.01	0.98	0.01	B	0.5	0.2
Standard deviations (%) of innovations to forcing variables							
Monetary policy	0.09	0.01	0.12	0.01	G	1.00	0.40
Gov. consumption	0.06	0.01	0.13	0.01	G	1.00	0.40
Gov. transfers	0.10	0.01	0.23	0.02	G	1.00	0.40
Temporary TFP	0.92	0.17	1.45	0.35	G	0.50	0.20
Permanent TFP growth	0.02	0.05	0.03	0.03	G	0.02	0.008
Subjective discount factor	0.96	0.92	1.19	0.91	G	0.10	0.40
Investment risk premium	0.18	0.09	0.16	0.08	G	1.00	0.40
Domestic price mark-up	3.65	1.55	3.80	2.93	G	2.00	0.80
Trade share	5.83	0.91	6.51	1.07	G	2.00	0.80
Export price mark-up	0.61	0.07	0.81	0.04	G	1.00	0.40
ROW export price mark-up	4.24	0.47	2.45	0.18	G	1.00	0.40

Notes: Cols. (1) lists model parameters. Cols. (2)-(3) and Cols. (4)-(5) show the mode and the standard deviation (Std) of the posterior distributions of EA parameters and of US parameters, respectively. Cols. (6) (labelled 'Distrib.') indicates the prior distribution function (B: Beta distribution; G: Gamma distribution). Identical priors are assumed for EA and US parameters.


a.
Real GDP per capita (1999=100)
EA
US
b.
ROW real GDP per capita
(1999=100)
c.
Private consumption (% of GDP)
EA
US
d.
Private investment (% of GDP)
EA
US
e.
Employment rate (%)
EA
US
f.
Wage share (%)
EA
US

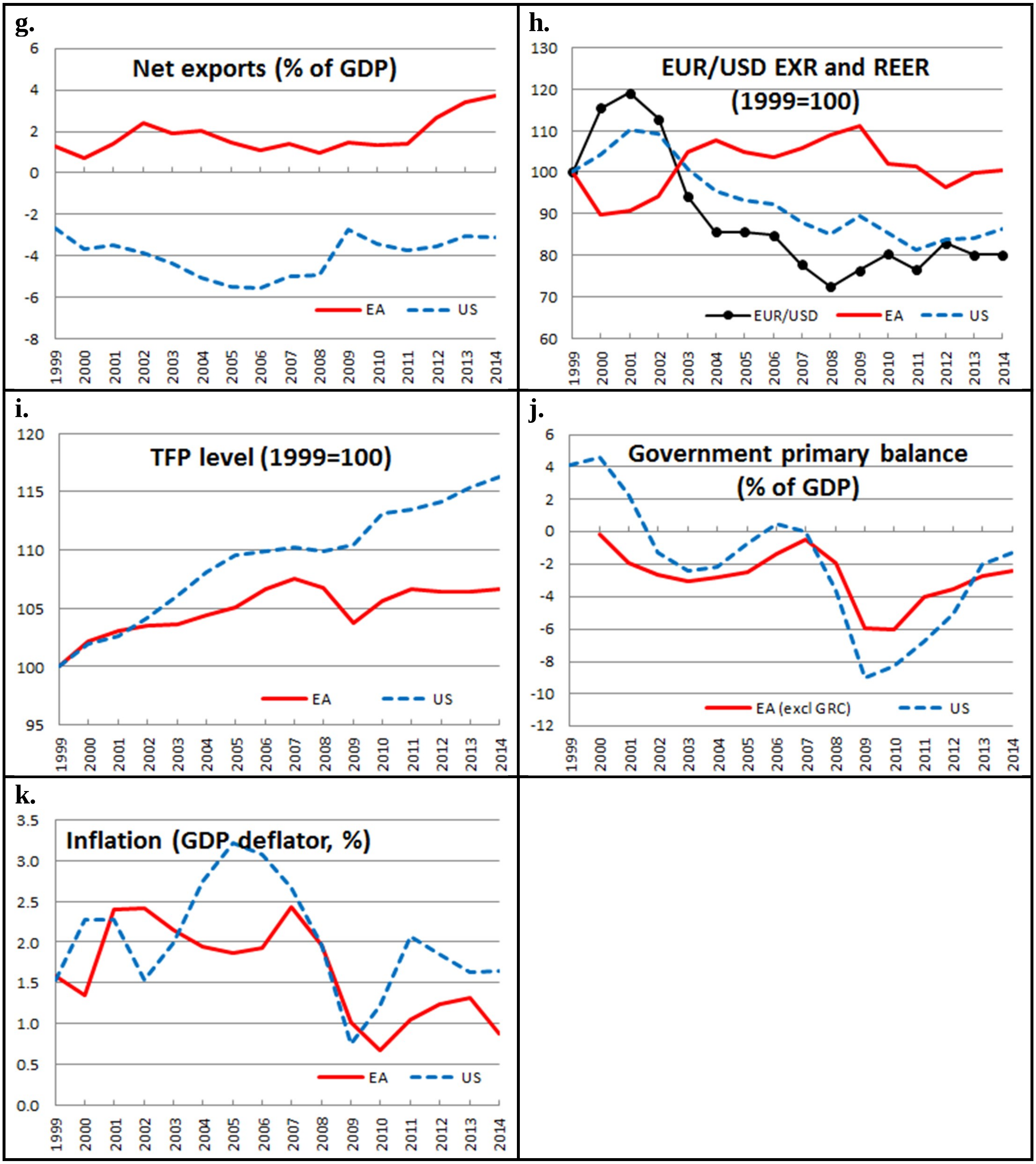


Figure 1. Macroeconomic conditions in the EA, US and ROW

Notes: The employment rate is total employment (persons) divided by the working-age (15-64) population. The wage share is compensation of employees adjusted for the imputed compensation of self-employed in per cent of GDP at factor costs. An increase in the EUR/USD exchange rate (Fig. 1.h) corresponds to a EUR depreciation against the USD; a REER increase corresponds to real effective appreciation in the respective region. REERs are based on CPIs and a group of 42 countries. The EA government balance excludes Greece due to missing data.

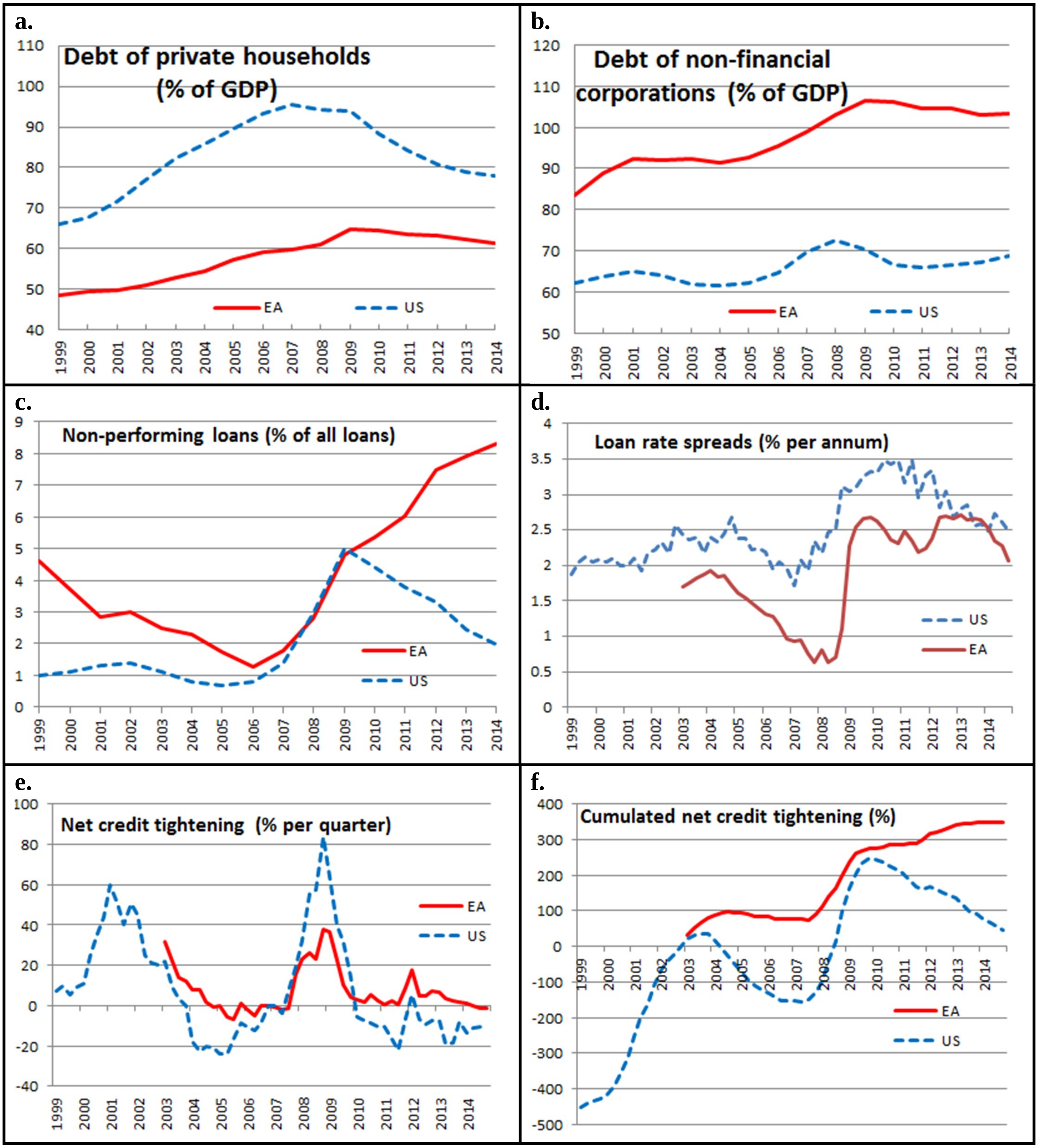


Figure 2. Financial indicators, EA and US.

Non-performing bank loans, bank loan rate spreads and net credit tightening for US pertain to commercial and industrial loans; the same variables for the EA pertain to loans to non-financial corporations. The non-performing loan rate (from World Bank Development indicators) is expressed as % of total outstanding loans. The loan rate spread is defined as the loan rate (to non-financial corporations) minus the money market rate. The net credit tightening measures are based on Fed & ECB bank surveys (percent of banks that report a tightening of lending standards minus percent of banks reporting loosening of standards); the EA series starts in 2003q1. The cumulated net credit tightening series for the US is (additively) normalized at zero for 2002q4.

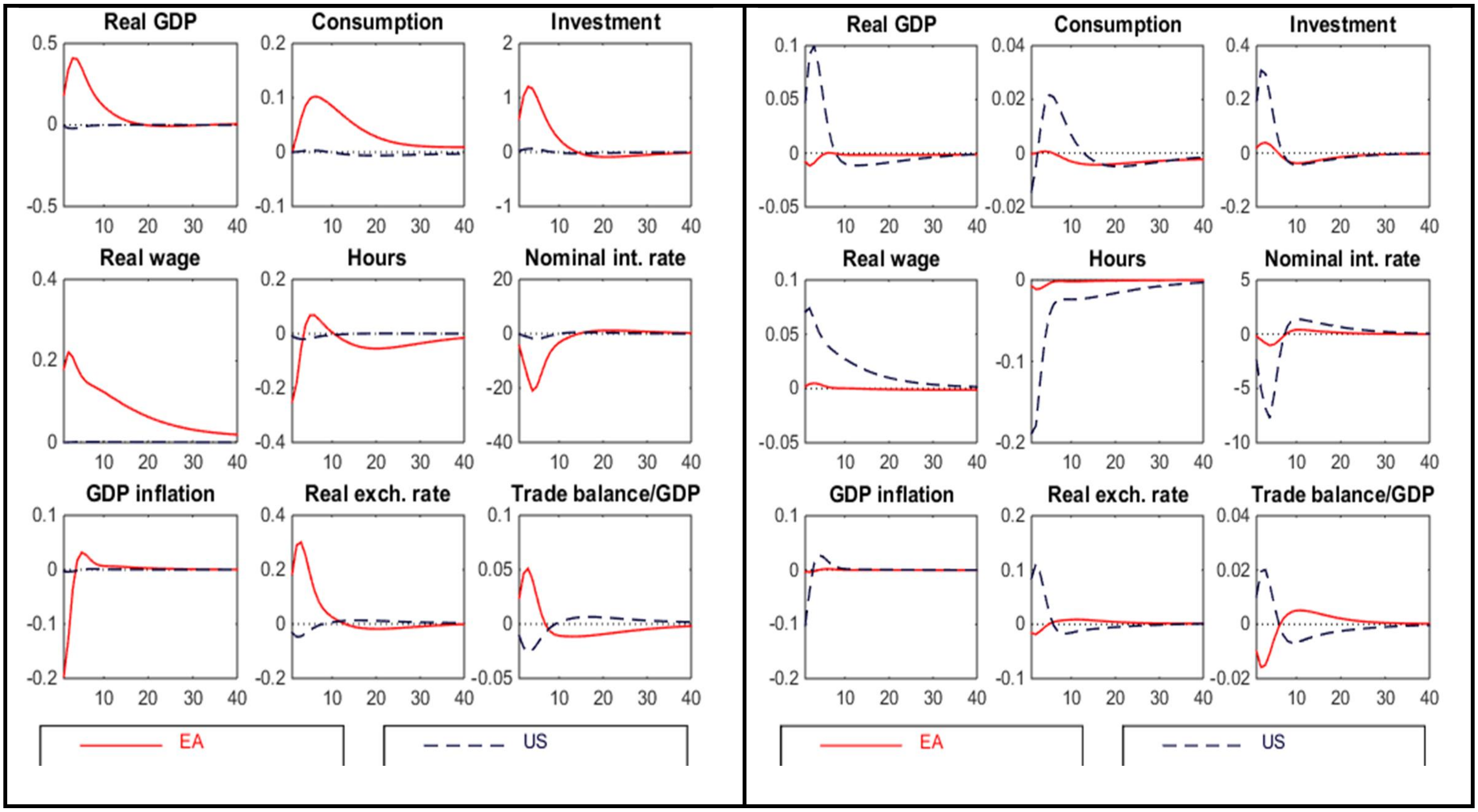


Fig. 3a. Dynamic responses to a transitory positive TFP shock in EA [US]: left [right] Panel

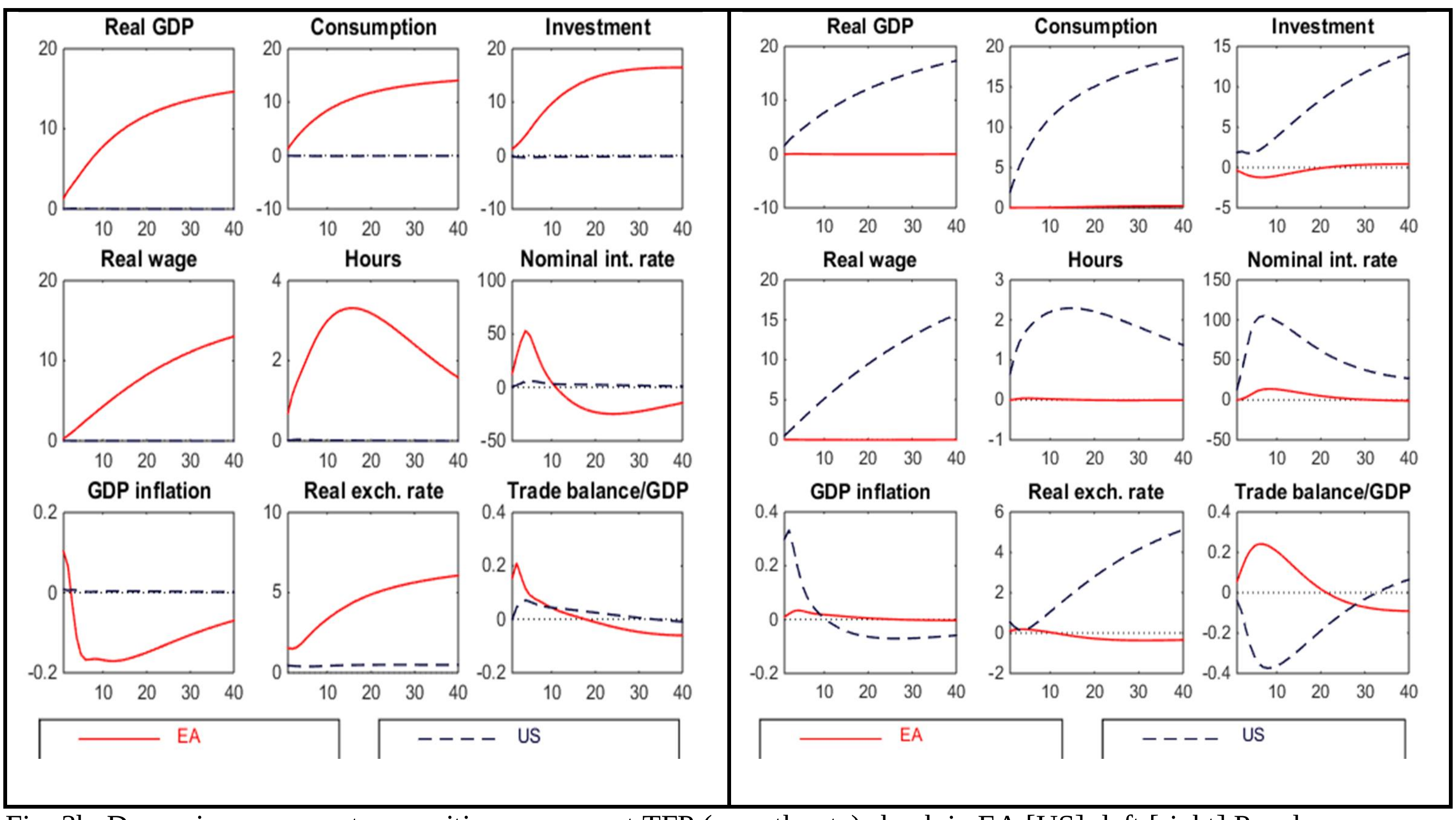


Fig. 3b. Dynamic responses to a positive permanent TFP (growth rate) shock in EA [US]: left [right] Panel

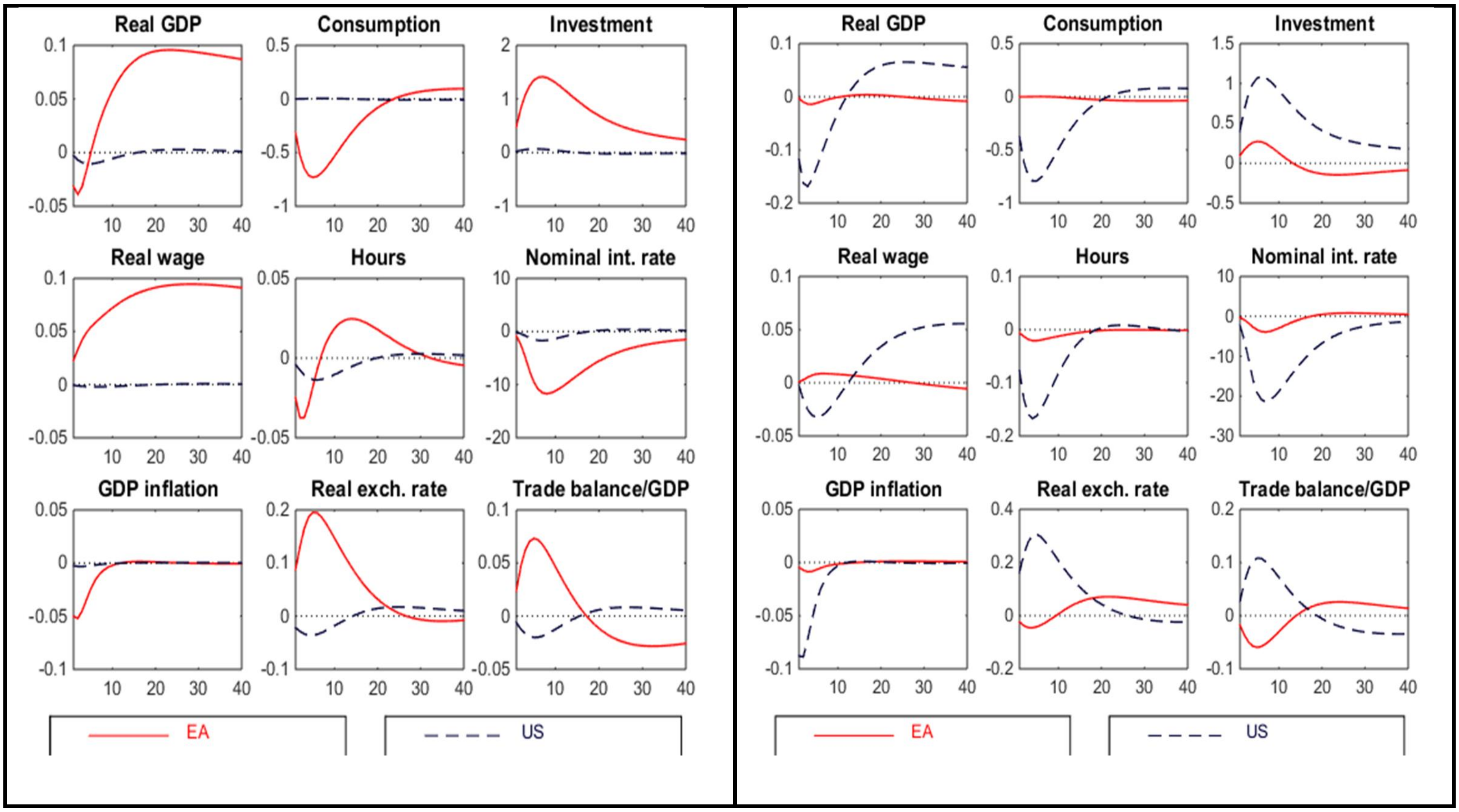


Fig. 3c. Dynamic responses to positive private saving shock in EA [US]: left [right] Panel

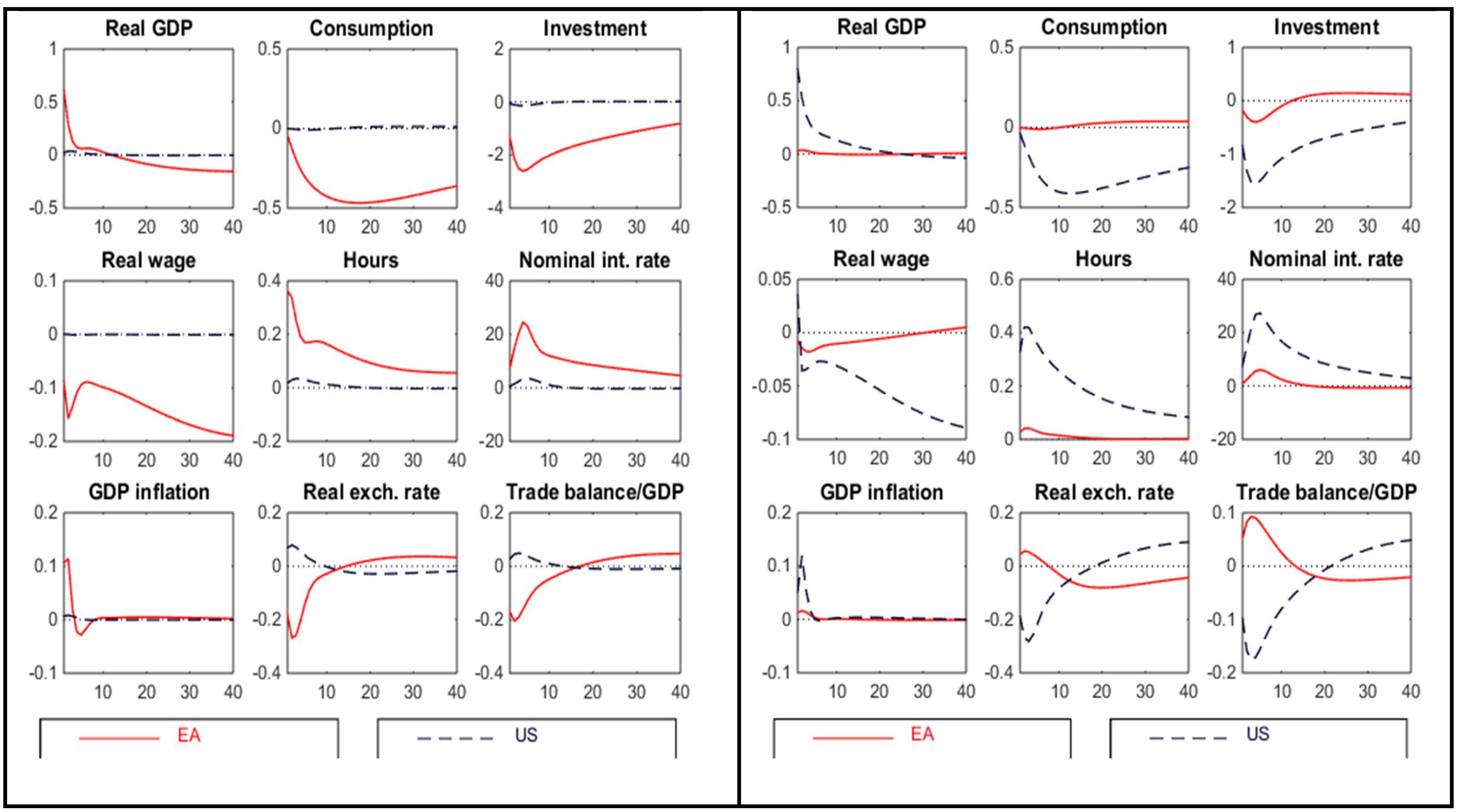


Fig. 3d. Dynamic responses to positive government purchases shock in EA [US]: left [right] Panel

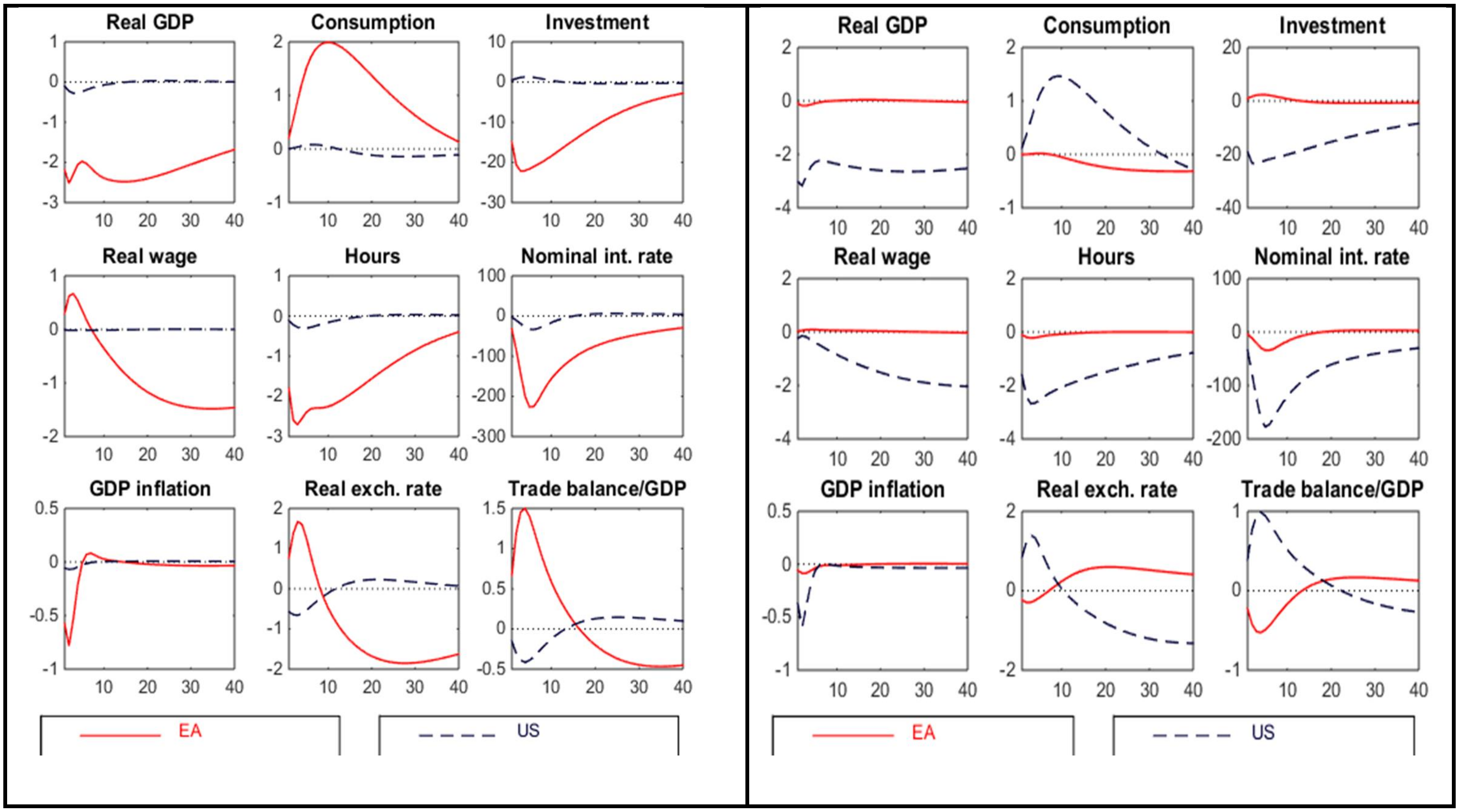


Fig. 3e. Dynamic responses to positive shock to investment risk premium in EA [US]: left [right] Panel

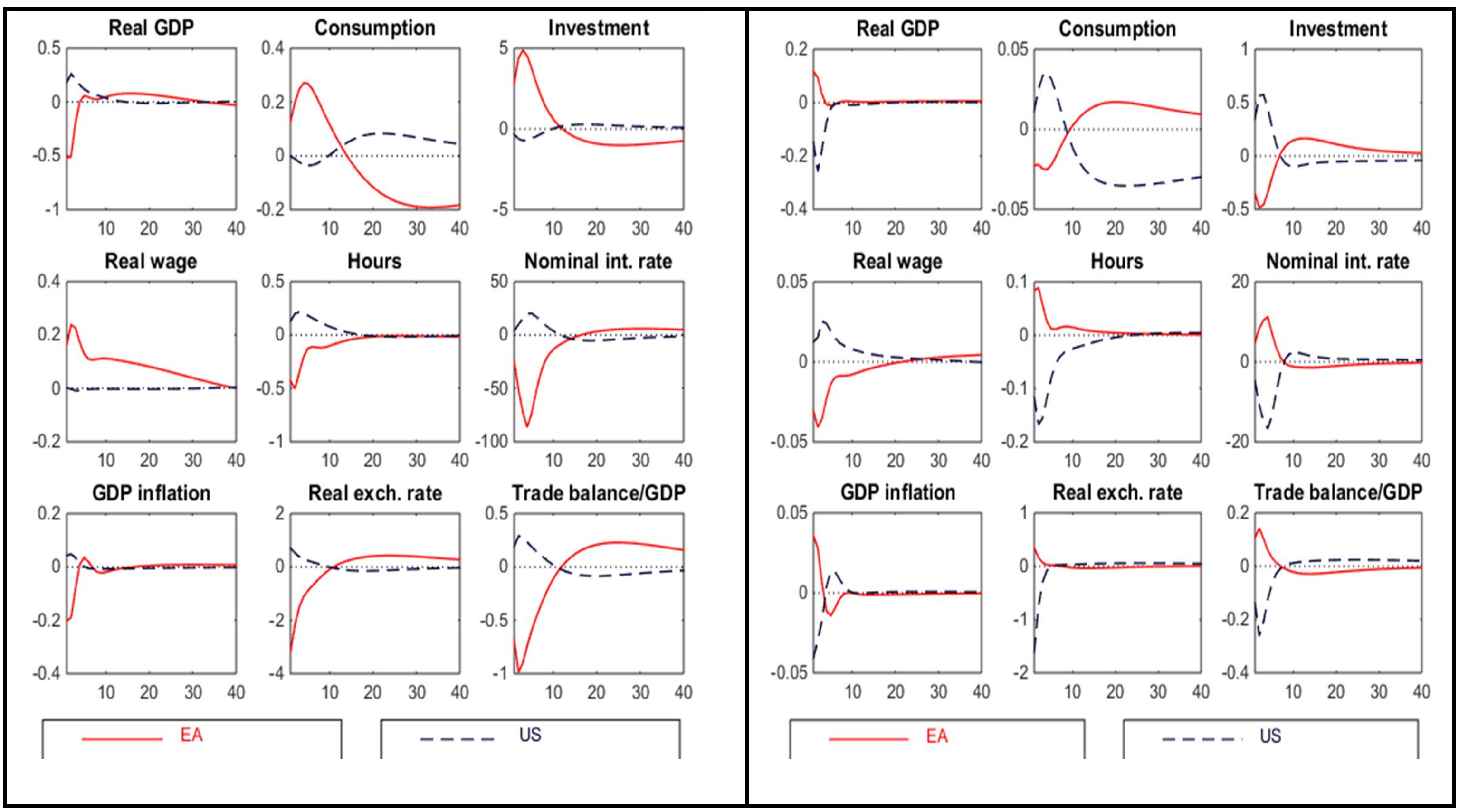


Fig. 3f. Dynamic responses to UIP shock between the EA [US] and the ROW: left [right] Panel

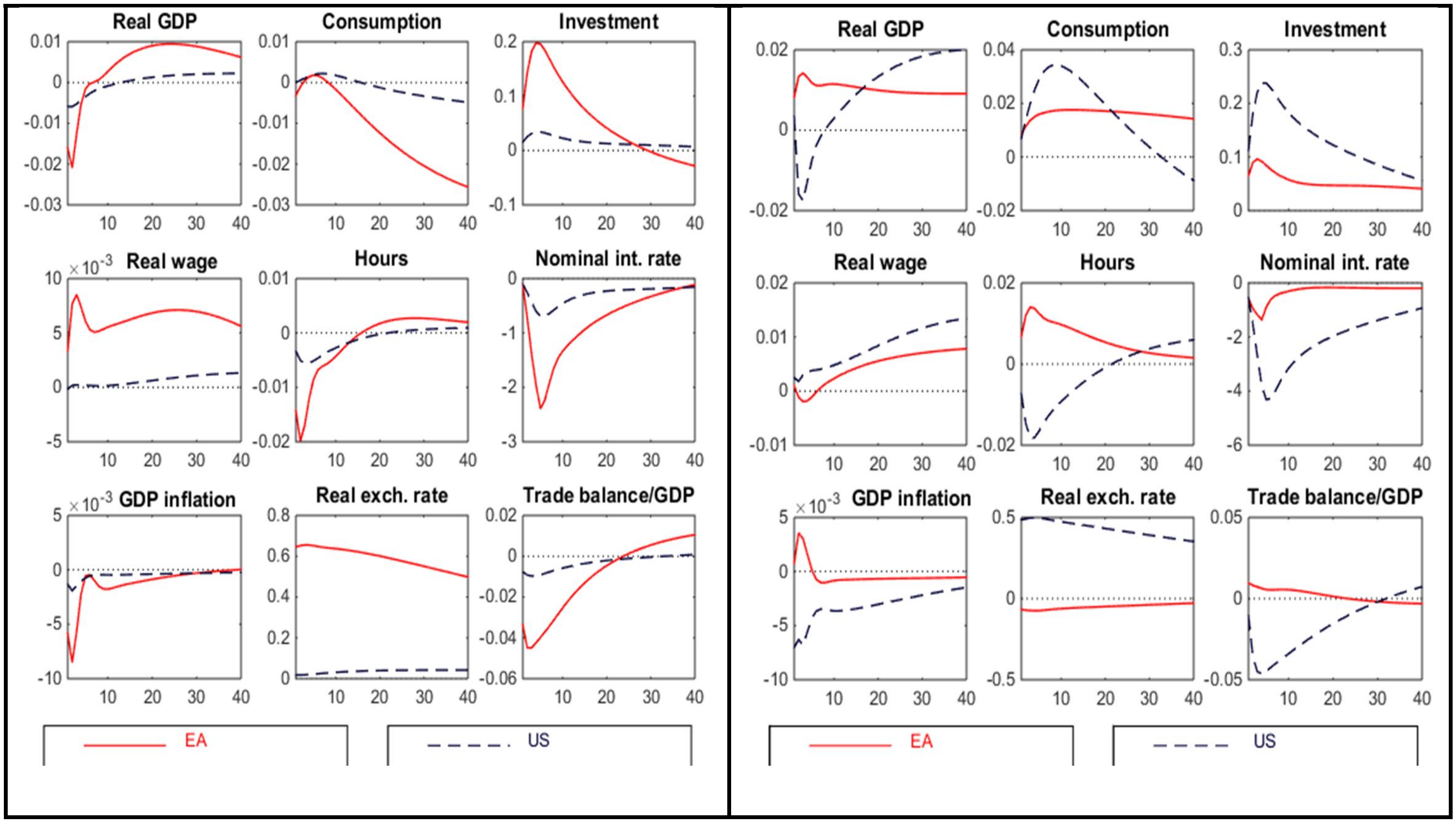


Fig. 3g. Dynamic responses to positive shock to ROW export competitiveness w.r.t. EA [US]: left [right] Panel

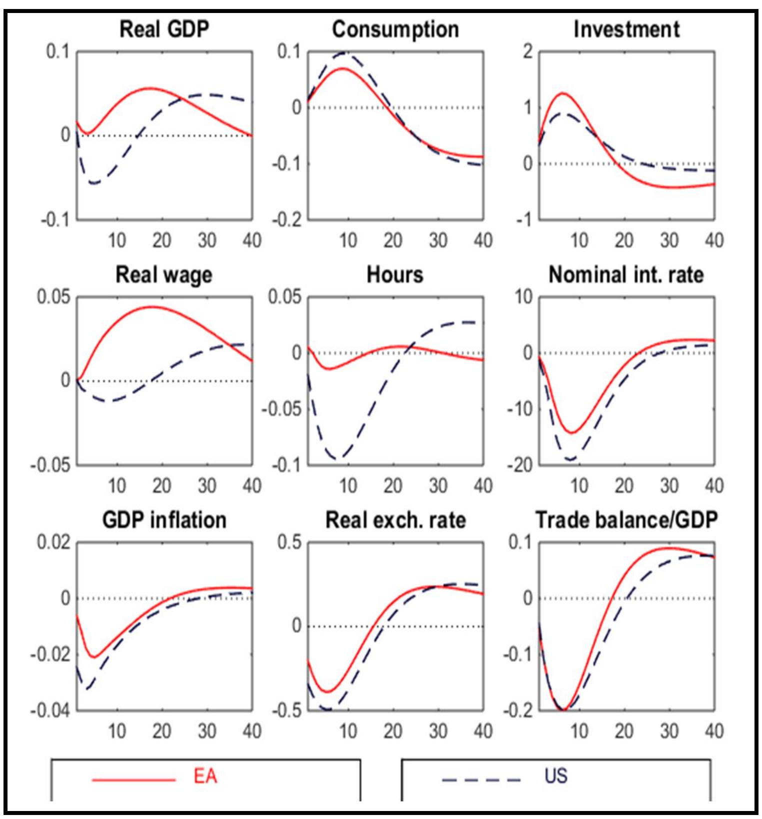


Fig. 3h. Dynamic responses to positive private saving shock in ROW

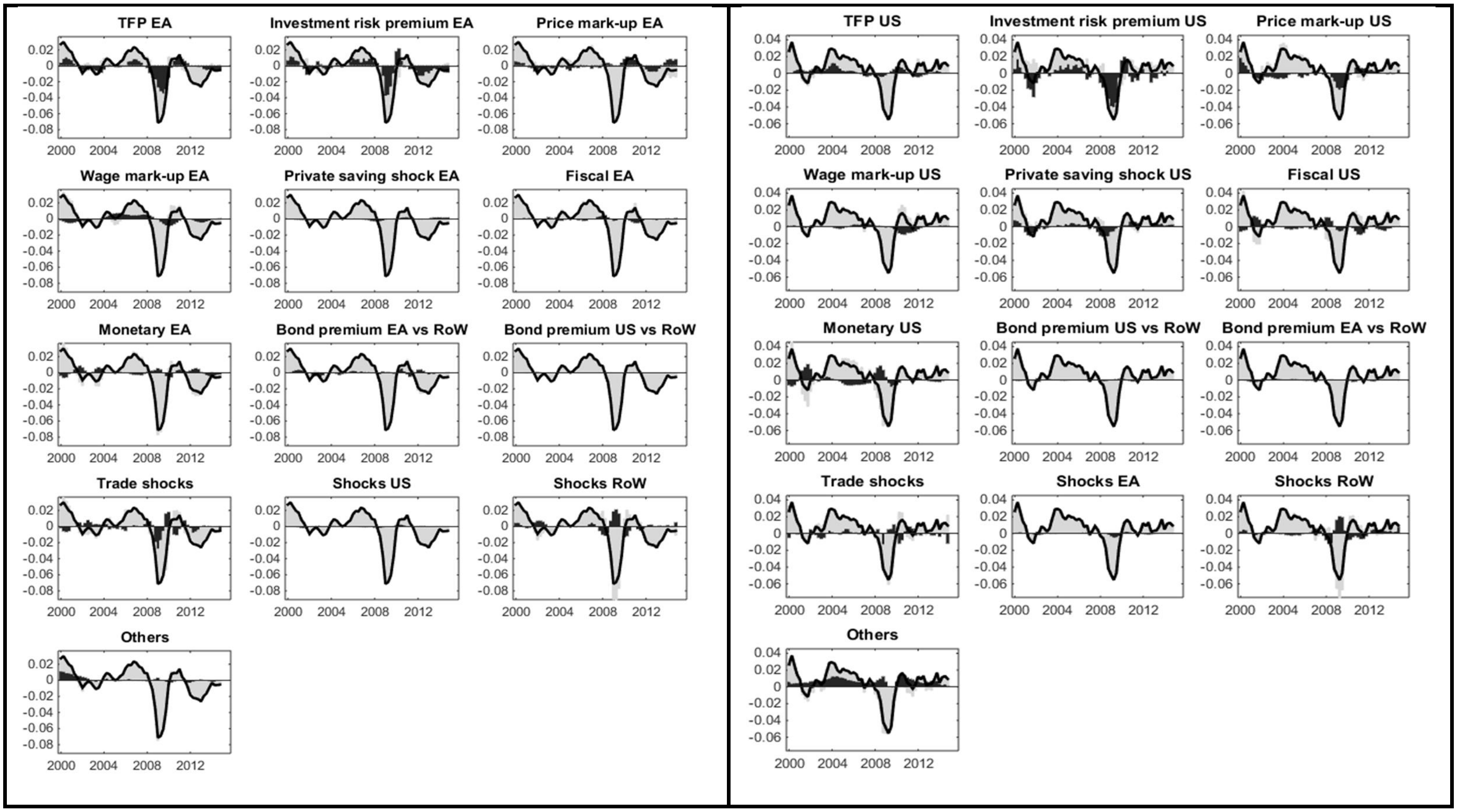


Fig. 4a. Historical decompositions of real GDP growth rate (year-on-year) in EA [US]: left [right] Panel

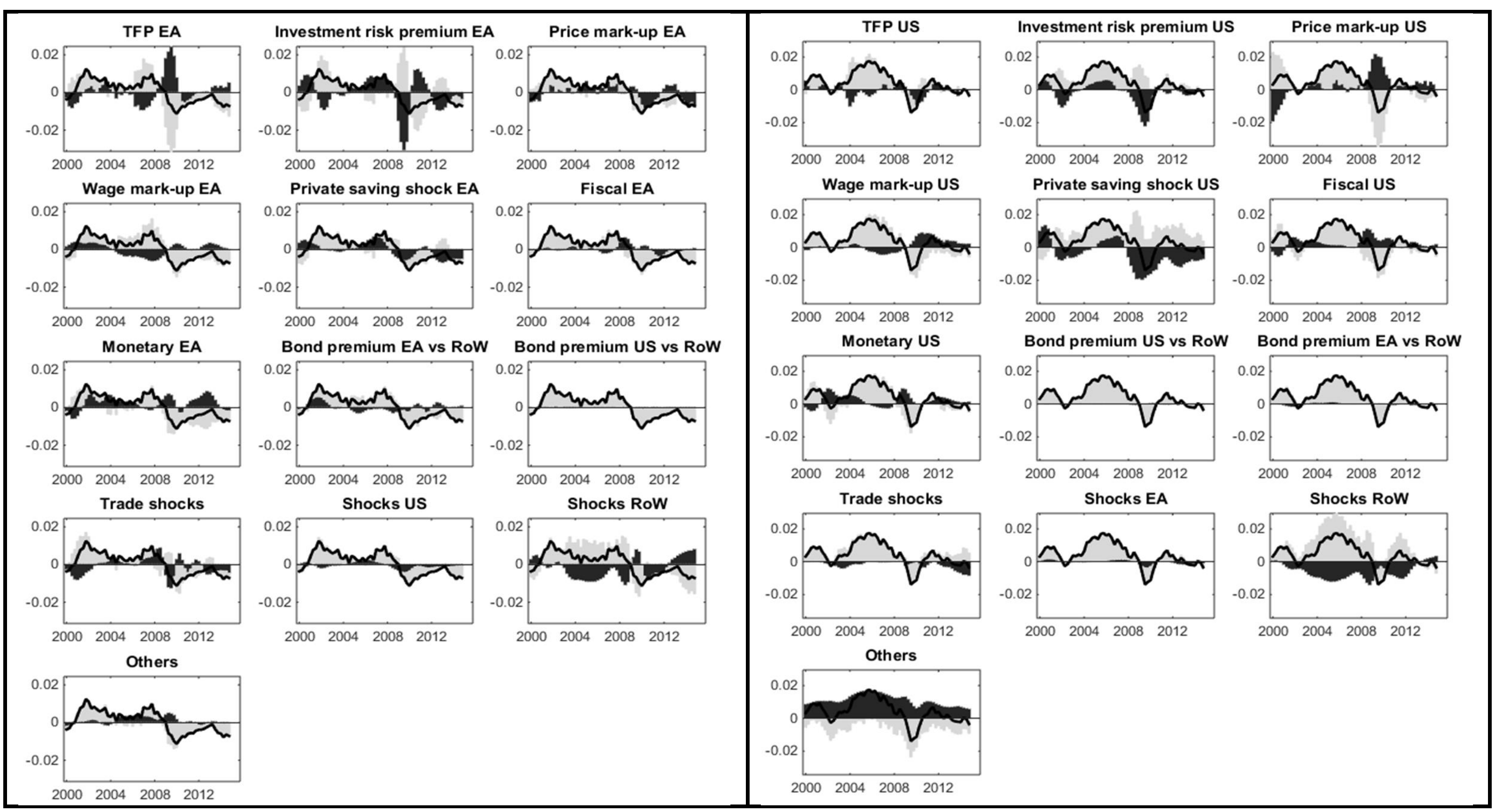


Fig. 4b. Historical decompositions of growth rate (YoY) of GDP deflator in EA [US]: left [right] Panel

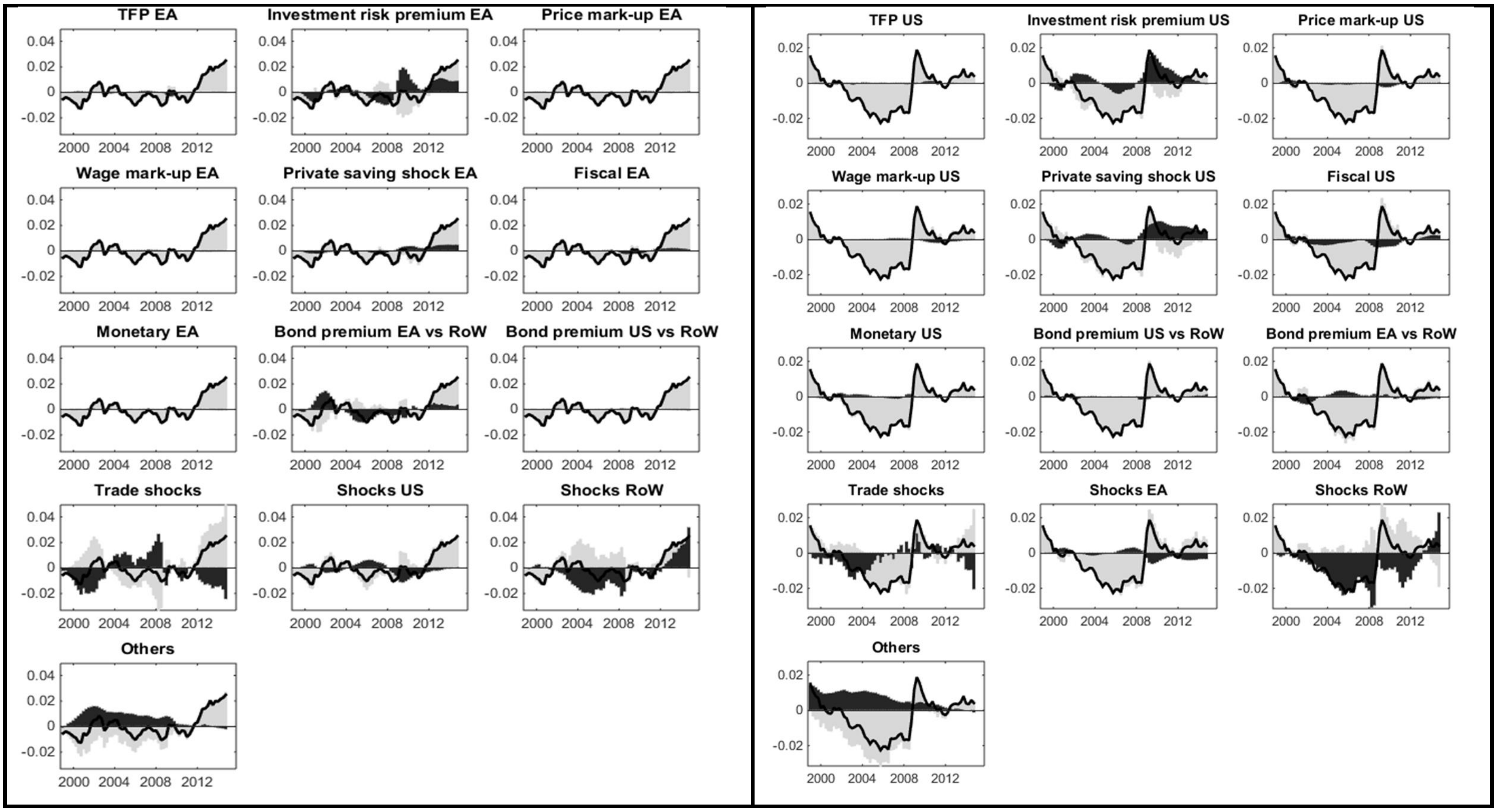


Fig. 4c. Historical decompositions of trade balance/GDP ratio in EA [US]: left [right] Panel

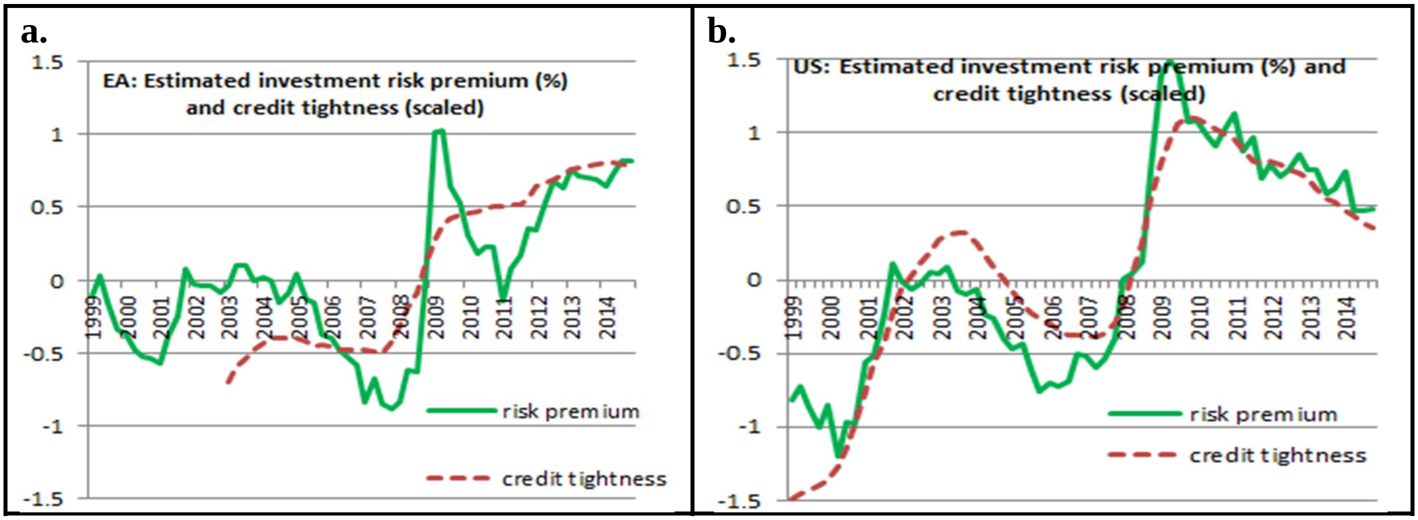


Fig. 5 Estimated investment risk premium and cumulated net credit tightening (scaled) for the EA and the US

Notes: Panels a. and b. pertain to the EA and the US, respectively. Empirical cumulated net credit tightening shown in the Figure are adjusted (using a linear transformation) so that the mean and standard deviation of the adjusted series equals the corresponding moments of the estimated investment risk premium.

APPENDIX: DATA

1. Data sources

Data for the EA (quarterly national accounts, fiscal aggregates, quarterly interest and exchange rates) are taken from Eurostat. Corresponding data for the US come from the Bureau of Economic Analysis (BEA) and the Federal Reserve. Bilateral trade flows are based on trade shares from the GTAP trade matrices for trade in goods and services. ROW series are constructed on the basis of the IMF International Financial Statistics (IFS) and World Economic Outlook (WEO) databases.

2. Constructing of data series for ROW variables

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

For details about the construction of ROW aggregates, see the Not-for-Publication Appendix.

3. List of observables

The estimation uses the following time series for both the EA and the US: GDP, GDP deflator, population, total employment, employment rate, employment in hours, participation rates, relative prices with respect to GDP deflator (VAT-consumption, government consumption, private investment, export, and import), government investment price relative to private investment, nominal policy rate, and nominal shares of GDP (consumption, government consumption, investment, government investment, government interest payment, transfers, public debt, wage bill and exports). The list of observables also includes the oil price and the US exchange rate with respect to EA and ROW. For the ROW we use data on population, GDP, GDP deflator and the nominal policy rate.

March 14, 2016

NOT-FOR-PUBLICATION APPENDIX

The Post-Crisis Slump in the Euro Area and the US: Evidence from an Estimated Three-Region DSGE Model

Robert Kollmann, Beatrice Pataracchia, Rafal Raciborski, Marco Ratto, Werner Roeger, Lukas Vogel

A. Detailed model description and parameter estimates

B. Construction of Rest-of-World (ROW) aggregates

C. Model-predicted and empirical business cycle statistics

D. Effects of fiscal policy under the ZLB constraint

Appendix A: Detailed model description and parameter estimates

We consider a three-country world consisting of the Euro Area (EA), the United States (US), and the rest of the world (RoW). The EA and US blocks of the model are rather detailed, while the RoW block is more stylized.[1] The EA and US blocks assume two (representative) households, a number of layers of firms and a government.

EA and US households provide labor services to firms. One of the two households (savers, or 'Ricardians') in each country has access to financial markets, and she owns her country's firms. The other (liquidity-constrained, or 'non-Ricardian') household has no access to financial markets, does not own financial or physical capital, and in each period only consumes the disposable wage and transfer income. The preferences of both types of household exhibit habit formation in both consumption and leisure, a feature which allows for better capturing persistence of the data.

There is a monopolistically-competitive sector producing differentiated goods in the EA and the US, using domestic labor and capital. The firms in the sector maximize the present value of dividends at a discount factor that is strictly larger than the risk-free rate and varies over time. This is a short-cut for capturing financial frictions facing firms; it can, e.g., be interpreted as a 'principal agent friction' between the owner and the management of the firm (e.g., Hall (2011)). Optimization is subject to investment and labor adjustment costs and a varying capacity utilization rate, which lets the model better capture the dynamics of the current account and other macro variables.

Total output in the EA and the US is produced by combining the domestic differentiated goods bundle with energy input. EA and US wages are set by monopolistic trade unions. Nominal differentiated goods prices are sticky as are the wages paid to the workers. Fiscal authorities in the EA and the US impose distortive taxes and issue debt.

The RoW block is simplified compared to the US and EA blocks. Specifically, the RoW consists of a budget constraint for the representative household, demand functions for domestic and imported goods (derived from CES consumption good aggregators), a production technology that uses labor as the sole factor input, and a New Keynesian Phillips curve. The RoW block abstracts from capital accumulation.

[1] The EA and US blocks build on, but are considerably different than the QUEST model of the EU economy (Ratto et al., 2009).

The behavioral relationships and technology are subject to autocorrelated shocks denoted by ε_t^x , where x stands for the type of shock. ε_t^x will generally follow an AR(1) process with autocorrelation coefficient $\rho^x < 1$ and White Noise innovation u_t^x:

$$\varepsilon_t^x = \rho^x \varepsilon_{t-1}^x + u_t^x$$

There is also a separate category of shocks, denoted A_t^x, whose logs are integrated of order 1.[2] With the exception of the TFP shocks, these shocks are modelled as ARIMA(1,1,0) processes.[3]

We next present a detailed description of EA and US blocks,[4] followed by an overview of the RoW model block. Throughout the derivation the following indexing convention will be preserved. Indices *i* and *j* index firms and households, respectively. These indices will usually be dropped when the equilibrium conditions are derived due to the representative household/firm assumption. Index *l* indicates sovereign states or economic regions. Finally, index *k* will always indicate the 'domestic' economy. This index will be generally dropped for parameters (even if they are country-specific), but will be usually preserved for variables.

A.1. EA and US households

The household sector consists of a continuum of households $j \in [0;1]$. There are two types of households, savers ("Ricardians", superscript s) who own firms and hold government and foreign bonds and liquidity-constrained households (subscript c) whose only income is labor income and who do not save. The share of savers in the population is ω^s.

Both households enjoy utility from consumption C_{jkt}^r and incur disutility from labor N_{jkt}^r $(r = s, c)$. On top of this, Ricardian's utility depends also on the financial assets held.

Date *t* expected life-time utility of household *r*, is defined as:

$$U_{jkt}^r = \sum_{s=t}^{\infty} exp(\varepsilon_{kt}^c)\beta^{s-t}\, u_{jkt}^r(\cdot)$$

where β is the (non-stochastic) discount factor (common for both types of households) and ε_{kt}^c is the saving shock.

A.1.1. Ricardian household

[2] These, in particular, include the TFP shock and the final demand productivity shocks.
[3] TFP is driven by 3 shocks, see below.
[4] The EA and US blocks have the same structure. The parameter values for the equations are country-specific as determined in the estimation.

The Ricardian households work, consume, own firms and receive nominal transfers T_{jkt}^{s} from the government. Ricardians have full access to financial markets and are the only households who own financial assets $\frac{A_{jkt}}{P_{kt}^{c,vat}}$ where $P_{kt}^{c,vat}$ is consumption price, including VAT.[5] Financial wealth of household *j* consists of bonds $\frac{B_{jkt}}{P_{kt}^{c,vat}}$ and shares $\frac{P_{kt}^{S}S_{jkt}}{P_{kt}^{c,vat}}$, where P_{kt}^{S} is the nominal price of shares in *t* and S_{jkt} the number of shares held by the household:

$$\frac{A_{jkt}}{P_{kt}^{c,vat}} = \frac{B_{jkt}}{P_{kt}^{c,vat}} + \frac{P_{kt}^{S}S_{jkt}}{P_{kt}^{c,vat}}$$

In this version of the model it is assumed that households invest only in domestic shares. Bonds consist of government domestic $\frac{B_{jkkt}^{g}}{P_{kt}^{c,vat}}$ and foreign bonds $\frac{e_{lkt}\;\; B_{jlkt}^{g}}{P_{kt}^{c,vat}}$ and private risk-free bonds $\frac{B_{jkt}^{rf}}{P_{kt}^{c,vat}}$ (in zero supply):

$$\frac{B_{jkt}}{P_{kt}^{c,vat}} = \frac{B_{jkt}^{rf}}{P_{kt}^{c,vat}} + \sum\nolimits_{l} e_{lkt}B_{jlkt}^{g}$$

with e_{lkt} the bilateral exchange rate between domestic economy *k* and foreign economy *l* and $e_{kkt} \equiv 1$.[6] The budget constraint of a saver household *j* is:

$$(1-\tau^{N})W_{kt}N_{jkt}^{s} + \sum\nolimits_{l}\left(1+i_{lt-1}^{g}\right)e_{lkt}B_{jlkt-1}^{g} + \left(1+i_{t-1}^{rf}\right)B_{jkt-1}^{rf} + (P_{kt}^{S} + P_{kt}^{Y}d_{kt})S_{jkt-1}$$
$$+ div_{kt} + T_{jkt}^{s} - {tax^{s}}_{jkt} = P_{kt}^{c,vat}C_{jkt}^{s} + A_{jkt}$$

where W_{kt} is the nominal wage rate, P_{kt}^{Y}, is GDP price deflator, i_{lt-1}^{g} are interest rates on government bonds of region *l*, i_{t-1}^{rf} is interest rate on risk-free bond, T_{jkt}^{s} are government transfers to savers and ${tax^{s}}_{jkt}$ are lump-sum taxes paid by savers. Note that savers own all the firms in the economy. div_{kt} represent the profits of all firms other than differentiated goods producers (the latter producers transfer profits to savers by paying dividends d_{kt}).

We define the gross nominal return on domestic shares as:

$$1 + i_{kt}^{s} = \frac{P_{kt}^{S} + P_{kt}^{Y}d_{kt}}{P_{kt-1}^{S}}$$

The instantaneous utility functions of savers, $u^{s}(\cdot)$, is defined as:

---

[5] Note that $P_{kt}^{c,vat}$ is related to P_{kt}^{C}, the private consumption deflator in terms of input factors, by the formula: $P_{kt}^{c,vat} = (1+\tau_{k}^{C})P_{kt}^{C}$ where τ^{c} is the tax on consumption.

[6] For simplicity, at this moment the model assumes only one type of foreign bonds, B_{RoWkt}^{g}, issued by RoW and denominated in RoW currency.

$$u^s\left(C_{jkt}^s, N_{jkt}^s, \frac{U_{jkt-1}^A}{P_{kt}^{c,vat}}\right)$$
$$= \frac{1}{1-\theta}\left(C_{jkt}^s - hC_{kt-1}^s\right)^{1-\theta} - \frac{\omega^N \varepsilon_{kt}^U}{1+\theta^N}\left(C_{kt}^s\right)^{1-\theta}\left(N_{jkt}^s - h_N N_{kt-1}^s\right)^{1+\theta^N}$$
$$- \left(C_{kt}^s - hC_{kt-1}^s\right)^{-\theta} \frac{U_{jkt-1}^A}{P_{kt}^{c,vat}}$$

where $C_{kt}^s = \int C_{jkt}^s,\ C_{kt} = \omega^s C_{kt}^s + (1-\omega^s)C_{kt}^c\ ;\ h, h_N \in (0;1)$ measure the strength of the external habits in consumption and labor and $\varepsilon_{kt}^U$is the labor supply (or wage mark-up) shock. The disutility of holding financial assets, U_{jkt-1}^A, is defined as:

$$U_{jkt-1}^A = \sum_l \left(\left(\alpha_{lk}^{bB0} + \varepsilon_{lkt-1}^B\right) e_{lkt-1} B_{jlkt-1}^g + \frac{\alpha_{lk}^{b1}}{2}\left(\frac{e_{lkt-1}}{P_k^Y Y_k}\right)^2\right) + \left(\alpha_k^{sS0} + \varepsilon_{kt-1}^S\right) P_{st-1}^s\, S_{jkt-1}$$

The Ricardian household problem leads to the following first order conditions (FOC).[7]

The FOC w.r.t. savers' consumption produces:

$$exp(\varepsilon_{kt}^C)(C_{kt}^s - hC_{kt-1}^s)^{-\theta} = \lambda_{kt}^s$$

where λ_{kt}^s is the Lagrange multiplier on the budget constraint.

FOC w.r.t. domestic risk-free bond:

$$\beta E_t\left[\frac{\lambda_{kt+1}^s}{\lambda_{kt}^s}\frac{1+i_{kt}^{rf}}{1+\pi_{kt+1}^{C,vat}}\right] = 1$$

FOC w.r.t. domestic government bonds (α_{kk}^{b1} set to 0):

$$\beta E_t\left[\frac{\lambda_{kt+1}^s}{\lambda_{kt}^s}\frac{1+i_{kt}^g - \varepsilon_{kt}^B - \alpha_{kk}^{b0}}{1+\pi_{kt+1}^{C,vat}}\right] = 1$$

with $\pi_{kt}^{C,vat}$ the consumption deflator inflation rate and ε_{kt}^B the risk-premium on government bonds.

FOC w.r.t. RoW government bonds:

$$\beta E_t\left[\frac{\lambda_{kt+1}^s}{\lambda_{kt}^s}\frac{\left(1+i_{RoWkt}^g\right)\frac{e_{RoWkt+1}}{e_{RoWkt}} - \varepsilon_{RoWkt}^B - \left(\alpha_{RoWk}^{b0} + \alpha_{RoWk}^{b1}\frac{e_{RoWkt}B_{RoWkt}^g}{P_k^Y Y_k}\right)}{1+\pi_{kt+1}^{C,vat}}\right] = 1$$

where ε_{RoWkt}^B the risk-premium on RoW bonds.

FOC w.r.t. domestic stocks:

[7] See subsection A.1.3 for the labor supply condition.

$$\beta E_t \left[\frac{\lambda^s_{kt+1}}{\lambda^s_{kt}} \frac{(1+i^s_{kt+1}) - \varepsilon^S_{kt} - \alpha^{s0}_{kk}}{1+\pi^{C,vat}_{t+1}} \right] = 1$$

where ε^S_{kt} the risk-premium on stocks. The above optimality conditions are similar to a textbook Euler equation, but incorporate asset-specific risk premia, which depend on exogenous shocks ε^B_{kt}, $\varepsilon^B_{RoWkt}, \varepsilon^S_{kt}$, as well as (for ROW bonds) on the size of the asset holdings as a share of GDP (see Vitek (2013, 2014) for a similar formulation). Taking into account the Euler equation for the risk-free bond and approximating, they simplify to the familiar expressions:

$$i^g_{kt} = i^{rf}_{kt} + rprem^g_{kt}$$

$$E_t \left[\frac{e_{RoWkt+1}}{e_{RoWkt}} \right] i^g_{RoWkt} = i^{rf}_{kt} + rprem^g_{RoWkt}$$

$$i^s_{kt} = i^{rf}_{kt} + rprem^s_{kt}$$

In the equations above, $rprem^g_{kt}$ is the risk premium on domestic government bonds. Similarly, $rprem^g_{RoWkt}$ is the risk premium on domestic government bonds sold abroad (to RoW). This feature of the model, hence, helps capture international spillovers that occur via the financial market channel, see Vitek (2013, 2014). Finally, $rprem^s_{kt}$ is a crucial risk premium on domestic shares. It is introduced to capture in a stylized manner financial frictions that are commonly believed to have contributed to the first phase of the financial crisis and may have contributed to its second phase, see also subsection A.2.2, below.[8]

A.1.2. Liquidity-constrained household

The liquidity-constrained household consumes her disposable after-tax wage and transfer income in each period of time ('hand-to-mouth'). The period t budget constraint of the liquidity-constrained household is:

$$(1+\tau^C_k) P^C_{kt} C^c_{jkt} = (1-\tau_k{}^N) W_{kt} N^c_{kt} + T^c_{kt} - tax^c{}_{jkt}.$$

The instantaneous utility functions for liquidity-constrained households. $u^c(\cdot)$, is defined as:

$$u^c\left(C^c_{jkt}, N^c_{jkt}\right) = \frac{1}{1-\theta}\left(C^c_{jkt} - hC^c_{kt-1}\right)^{1-\theta} - (C^c_{kt})^{1-\theta} \frac{\omega^N exp(u^U_{kt})}{1+\theta^N}\left(N^c_{jkt} - h_N N^c_{kt-1}\right)^{1+\theta^N}$$

with $C^c_{kt} = \int C^c_{jkt}$.

A.1.3. Labor supply

Trade unions are maximizing a joint utility function for each type of labor. It is assumed that types of labor are distributed equally over Ricardian and liquidity-constrained households with their respective population weights. The wage rule is obtained by equating a weighted

[8] Observationally, this approach is equivalent to assuming exogenous risk premia as well as endogenous risk premia derived, e.g., in the spirit of Bernanke, Gertler & Gilchrist.

average of the marginal utility of leisure to a weighted average of the marginal utility of consumption times the real wage adjusted for a wage mark-up. Nominal rigidity in wage setting is introduced in the form of adjustment costs for changing wages. The wage adjustment costs are borne by the household. Real wage rigidity is also allowed, producing the following optimality condition:

$$\left((1+\mu_t^W)\frac{\omega^s V_{1-l,jkt}^S+(1-\omega^s)V_{1-l,jkt}^C}{\omega^s U_{c,jkt}^S+(1-\omega^s)U_{c,jkt}^C}(1+\tau_k^C)p_{kt}^C\right)^{1-\gamma^{wr}}\left((1-\tau_k{}^N)\frac{W_{kt-1}}{P_{kt-1}^Y}\right)^{\gamma^{wr}}=(1-\tau_k{}^N)\frac{W_{kt}}{P_{kt}^Y}$$

$$+\gamma^w(\pi_t^W-(1-sf^w)\pi_{t-1}^W)(1+\pi_t^W)\text{-}\gamma^w E_t\left[\frac{L_{t+1}}{L_t}\frac{1+\pi_{t+1}^y}{1+i_{t+1}^{sd}}(\pi_{t+1}^W-(1-sf^w)\pi_t^W)(1+\pi_{t+1}^W)\right]$$

where μ_t^W is the wage mark-up, γ^{wr} is the degree of real wage rigidity, γ^w is the degree of nominal wage rigidity and sf^w is the degree of forward-lookingness in the labor supply equation. $V_{N,jkt}^x$, for x=s,c, is the marginal disutility of labor, defined as:

$$V_{N,jkt}^x=\omega^N exp(u_{kt}^U)C_{kt}{}^{1-\theta}\left(N_{jkt}^x-h_N N_{kt-1}^x\right)^{\theta^N}$$

A.2. EA and US production sector

A.2.1. Total output demand

Total output O_{kt} is produced by perfectly competitive firms by combining value added, Y_{kt}, with energy input, Oil_{kt}, using the following CES production function:

$$O_{kt}=\left[(1-s^{Oil})^{\frac{1}{\sigma^O}}(Y_{kt})^{\frac{\sigma^O-1}{\sigma^O}}+\left(s^{Oil}\right)^{\frac{1}{\sigma^O}}(OIL_{kt})^{\frac{\sigma^O-1}{\sigma^O}}\right]^{\frac{\sigma^O}{\sigma^O-1}}$$

where s^{Oil} is the energy input share in total output and elasticity σ^O controls the substitutability of the two inputs to production. It follows that the demand for Y_{kt} and OIL_{kt} by total output producers is, respectively:

$$Y_{kt}=\left(1-s^{Oil}\right)\left(\frac{P_{kt}^Y}{P_{kt}^O}\right)^{-\sigma^O}O_{kt}$$

$$OIL_{kt}=s^{Oil}\left(\frac{P_{kt}^{Oil}}{P_{kt}^O}\right)^{-\sigma^O}O_{kt}$$

where P_{kt}^Y and P_{kt}^{Oil} are price deflators associated with Y_{kt} and Oil_{kt}, respectively, and the total output deflator P_{kt}^O is such that:

$$P_{kt}^O=\left[(1-s^{Oil})(P_{kt}^Y)^{1-\sigma^O}+s^{Oil}\left(P_{kt}^{Oil}\right)^{1-\sigma^O}\right]^{\frac{1}{1-\sigma^O}}$$

A.2.2. Differentiated goods supply

Each firm $i \in [0;1]$ produces a variety of the domestic good which is an imperfect substitute for varieties produced by other firms. Because of imperfect substitutability, firms are monopolistically competitive in the goods market and face a downward-sloping demand function for goods. Domestic final good producers then combine the different varieties into a homogenous good and sell them to domestic final demand goods producers and exporters.

Differentiated goods are produced using total capital K_{ikt-1}^{tot} and labour N_{ikt} which are combined in a Cobb-Douglas production function:

$$Y_{ikt} = (A_{kt}^{Y} N_{ikt})^{\alpha} (cu_{ikt} K_{ikt-1}^{tot})^{1-\alpha}$$

where A_{kt}^{Y} is labour-augmenting productivity shock common to all firms in the differentiated goods sector and cu_{ikt} is firm-specific level of capital utilization. Total Factor Productivity, TFP_{kt}, can therefore be defined as:

$$TFP_{kt} = (A_{kt}^{Y})^{\alpha}.$$

We allow for three types of shocks related to the technology: a temporary shock ε_{kt}^{AY} which accounts for temporary deviations of A_{kt}^{Y} from its trend, $\bar{A}_{kt}^{Y}$, and two shocks related to the trend components itself:

$$log(A_{kt}^{Y}) - log(\bar{A}_{kt}^{Y}) = \varepsilon_{kt}^{AY}$$

$$log(\bar{A}_{kt}^{Y}) - log(\bar{A}_{kt-1}^{Y}) = g_{kt}^{\overline{AY}} + \varepsilon_{kt}^{L\overline{AY}}$$

$$g_{kt}^{\overline{AY}} = \rho^{\overline{AY}} g_{kt-1}^{\overline{AY}} + \varepsilon_{kt}^{G\overline{AY}} + \left(1 - \rho^{\overline{AY}}\right) g^{\overline{AY}}$$

with $g^{\overline{AY}}$ being the long-run technology growth.

Total capital is a sum of private installed capital, K_{ikt}, and public capital, K_{ikt}^{g}:

$$K_{ikt}^{tot} = K_{ikt} + K_{ikt}^{g}$$

Producers maximize the value of the firm, V_{kt}, equal to a discounted stream of future dividends, $V_{kt} = d_{kt} + E_t[sdf_{kt+1} V_{kt+1}]$, with the stochastic discount factor

$$sdf_{kt} = \left(1 + i_{kt}^{sd}\right) / \left(1 + \pi_{kt}^{C,vat}\right) \approx \left(1 + i_{kt-1}^{rf} + rprem_{kt-1}^{s}\right) / \left(1 + \pi_{kt}^{C,vat}\right)$$

which depends directly on the investment risk premium, $rprem_{kt-1}^{s}$. The dividends are defined as:

$$d_{ikt} = (1 - \tau_k^K) \left(\frac{P_{ikt}^{Y}}{P_{kt}^{Y}} Y_{ikt} - \frac{W_{kt}}{P_{kt}^{Y}} N_{ikt} \right) + \tau_k^K \delta \frac{P_{kt}^{I}}{P_{kt}^{Y}} K_{ikt-1} - \frac{P_{kt}^{I}}{P_{kt}^{Y}} I_{ikt} - adj_{ikt}$$

where I_{ikt} is physical investment, P_{kt}^{I} is investment price, τ_k^K is the profit tax, δ is capital depreciation rate and adj_{ikt} are adjustment costs associated with price P_{ikt}^{Y} and labour input

N_{ikt} adjustment or moving capacity utilization cu_{ikt} and investment I_{ikt} away from their optimal level:

$$adj_{ikt} = adj(P_{ikt}^Y) + adj(N_{ikt}) + adj(cu_{ikt}) + adj(I_{ikt})$$

where

$$adj(P_{ikt}^Y) = \frac{\gamma^p}{2} Y_{kt} \left(\frac{P_{ikt}^Y}{P_{ikt-1}^Y} - 1\right)^2$$

$$adj(N_{ikt}) = \frac{\gamma^n}{2} Y_{kt} \left(\frac{N_{ikt}}{N_{ikt-1}} - 1\right)^2$$

$$adj(cu_{ikt}) = \frac{P_{kt}^I}{P_{kt}^Y} K_{ikt-1} \left(\gamma^{u,1}(cu_{ikt} - 1) + \frac{\gamma^{u,2}}{2}(cu_{ikt} - 1)^2\right)$$

$$adj(I_{ikt}) = \frac{P_{kt}^I}{P_{kt}^Y} \left(\frac{\gamma^{I,1}}{2} K_{kt-1} \left(\frac{I_{ikt}}{K_{kt-1}} - \delta\right)^2 + \frac{\gamma^{I,2}}{2} \frac{(I_{ikt} - I_{ikt-1})^2}{K_{kt-1}}\right)$$

The maximization is subject to the production function, standard capital accumulation equation:

$$K_{ikt} = (1 - \delta)K_{ikt-1} + I_{ikt}$$

and the usual demand condition which inversely links demand for variety *i* goods and the price of the variety:

$$Y_{ikt} = \left(\frac{P_{ikt}^Y}{P_{kt}^Y}\right)^{-\sigma^y} Y_{kt}$$

Let $adj_{X,ikt}$ for $X = P^Y, N, cu, I$ denote additional dynamic terms due to the existence of adjustment costs. Let also define $g_{kt}^X := \frac{X_{kt} - X_{kt-1}}{X_{kt-1}}$ the net growth rate of variable $X = N, Y, I, C, \ldots$ and $\pi_{kt}^X := \frac{\Delta P_{kt}^X}{P_{kt-1}^X}$ the inflation rate of a price deflator associated with variable $X = N, Y, I, C, \ldots$ The main optimality conditions of the differentiated goods producers are as follows.

The usual equality between the marginal product of labor and labor cost holds, with a wedge driven by the labor adjustment costs:

$$\mu_{kt}^y \alpha \frac{Y_{kt}}{N_{kt}} - adj_{N,ikt} = (1 - \tau^k) \frac{W_{kt}}{P_{kt}^Y}$$

with μ_{kt}^y being inversely related to the price mark-up. The capital optimality condition reflects the usual dynamic trade-off faced by the firm:

$$\frac{1 + \pi_{kt+1}^I}{1 + i_{kt+1}^{sd}} \left(\mu_{kt+1}^y (1 - \alpha) \frac{P_{kt+1}^Y Y_{ikt+1}}{P_{kt+1}^I K_{ikt}^{tot}} + \tau^k \delta - adj_{kt}^{cu}/K_{ikt} + (1 - \delta) Q_{kt+1}\right) = Q_{kt}$$

where Q_{kt} has the usual Tobin's interpretation.

FOC w.r.t. investment implies that Tobin's Q varies due to the existence of investment adjustment costs:

$$Q_{kt} = 1 + adj_{I,ikt}$$

Firms adjust their capacity utilization depending on the conditions on the market via the optimality condition:

$$\frac{\mu_{kt}^{y}}{P_{kt}^{I}/P_{kt}^{Y}}(1-\alpha)\frac{Y_{kt}}{cu_{kt}} = adj_{cu,ikt}$$

Finally, the FOC w.r.t. differentiated output price pins down the price mark-up:

$$\frac{\sigma^{y}}{(\sigma^{y}-1)}\mu_{kt}^{y} = (1-\tau^{k}) + \frac{adj_{P^{Y},ikt}}{(\sigma^{y}-1)} + \varepsilon_{kt}^{\mu}$$

with ε_{kt}^{μ} being the markup shock. The latter equation, combined with the FOC w.r.t. labor implies the Phillips curve of the familiar form.

A.3. Trade

A.3.1. Import sector

Aggregate demand components

The final aggregate demand component goods C_{kt} (private consumption good), I_{kt}, (private investment good) G_{kt} (government consumption good) and I_{kt}^{G} (government investment good) are produced by perfectly competitive firms by combining domestic output, O_{kt}^{Z} with imported goods M_{kt}^{Z}, $Z = C, I, G, I^{G}$, using the following CES production function:

$$Z_{kt} = A_{kt}^{p^{z}}\left[(1-exp(\varepsilon_{kt}^{M})s^{M,Z})^{\frac{1}{\sigma^{z}}}(O_{kt}^{Z})^{\frac{\sigma^{z}-1}{\sigma^{z}}} + (exp(\varepsilon_{kt}^{M})s^{M,Z})^{\frac{1}{\sigma^{z}}}(M_{kt}^{Z})^{\frac{\sigma^{z}-1}{\sigma^{z}}}\right]^{\frac{\sigma^{z}}{\sigma^{z}-1}}$$

with $A_{kt}^{p^{z}}$ a shock to productivity in the sector producing goods Z and ε_{kt}^{M} is a shock to the share $s^{M,Z}$ of imports in demand components. We assume that the log difference of the specific productivities, $A_{kt}^{p^{z}}$ follows an AR(1) process, $\varepsilon_{kt}^{p^{z}}$ with mean $g^{p^{z}}$.

It follows that the demand for the domestic and foreign part of demand aggregates is:

$$O_{kt}^{Z} = \left(A_{kt}^{p^{z}}\right)^{\sigma^{z}-1}(1-exp(\varepsilon_{kt}^{M})s^{M,Z})\left(\frac{P_{kt}^{O}}{P_{kt}^{Z}}\right)^{-\sigma^{z}} Z_{kt}$$

$$M_{kt}^{Z} = \left(A_{kt}^{p^{z}}\right)^{\sigma^{z}-1} exp(\varepsilon_{kt}^{M})s^{M,Z}\left(\frac{P_{kt}^{M}}{P_{kt}^{Z}}\right)^{-\sigma^{z}} Z_{kt}$$

where P_{kt}^{Z} are price deflators associated with Z_{kt}, which satisfy:

$$P_{kt}^{Z} = \left(A_{kt}^{p^z}\right)^{-1}\left[(1 - exp(\varepsilon_{kt}^{M})s^{M,Z})(P_{kt}^{O})^{1-\sigma^z} + exp(\varepsilon_{kt}^{M})s^{M,Z}(P_{kt}^{M})^{1-\sigma^z}\right]^{\frac{1}{1-\sigma^Z}}$$

Economy-specific final imports demand

Final imported goods are produced by perfectly competitive firms combining economy-specific homogenous imports goods, M_{lkt}, using CES production function:

$$M_{kt} = \left(\sum_{l}(s_{lkt}^{M})^{\frac{1}{\sigma^{FM}}}(M_{lkt})^{\frac{\sigma^{FM}-1}{\sigma^{FM}}}\right)^{\frac{\sigma^{FM}}{\sigma^{FM}-1}}$$

where σ^{FM} is the price elasticity of demand for country *l*'s goods and $\sum_l s_{lkt}^{M} = 1$ are import shares. The demand for goods from country *l* is then:

$$M_{lkt} = s_{lkt}^{M}\left(\frac{P_{lkt}^{M}}{P_{kt}^{M}}\right)^{-\sigma^{FM}} M_{kt}$$

while the imports price:

$$P_{kt}^{M} = \left(\sum_{l} s_{lkt}^{M}(P_{lkt}^{M})^{1-\sigma^{FM}}\right)^{\frac{1}{1-\sigma^{FM}}}$$

with P_{lkt}^{M} being the country-specific imports good prices.

Supply of economy- and sector-specific imports

The homogenous goods from country *l* are assembled by monopolistically competitive firms from economy- and sector- specific goods using a linear production function and subject to adjustment costs. All products from country *l* are initially purchased at export price P_{lt}^{X} of this country. Firms then maximize a discounted stream of profits, div_{kt}^{IM}, such that :

$$div_{ilkt}^{IM} = \frac{P_{ilkt}^{M}}{P_{kt}^{Y}}M_{ilkt} - e_{lkt}\frac{P_{lt}^{X}}{P_{kt}^{Y}}M_{ilkt} - adj_{ilkt}^{PM}$$

where adj_{ilkt}^{PM} are the adjustment costs that producers face when choosing the bilateral import price.[9] The maximization is subject to the usual inversely-sloping demand equation. These assumptions result in a simple expression for price P_{lkt}^{M} of homogenous goods from country *l*:

$$P_{lkt}^{M} = e_{lkt}P_{lt}^{X} - adj_{M,ilkt}^{PM}$$

where $adj_{M,ilkt}^{PM}$ are additional dynamic terms due to costs of adjustment.

A.3.2. Export sector

[9] $adj_{ilkt}^{PM} = \frac{\gamma^{PM}}{2}\frac{P_{lkt}^{M}}{P_{kt}^{Y}}M_{lkt-1}\left(\frac{P_{ilkt}^{M}}{P_{ilkt-1}^{M}} - 1\right)^2$

The exporting firms are supposed to be competitive and set their prices equal to the output price, up to a shock, ε_{kt}^{X}:

$$P_{kt}^{X} = exp(\varepsilon_{kt}^{X})P_{kt}^{O}$$

A.4. EA and US policy

A.4.1. Monetary policy

Monetary policy is modelled by a Taylor rule where the ECB sets the policy rate i_{kt} in response to area-wide inflation and real GDP growth. The policy rate adjusts sluggishly to deviations of inflation and GDP growth from their respective target levels; it is also subject to random shocks:

$$i_{kt} - \bar{\iota} = \rho^{i}(i_{kt-1} - i) + (1 - \rho^{i})\left(\eta^{i\pi}\left(0.25\left(\sum_{r=0}^{3} \pi_{kt-r}^{c+g}\right) - \bar{\pi}^{C+G}\right) + \eta^{iy}(\tilde{y}_{kt})\right) + u_{kt}^{inom}$$

where $i = r + \pi^{C+G}$ is the steady state nominal interest rate, equal to the sum of the steady state real interest rate and CPI inflation and output gap $\tilde{y}_{kt} = log(Y_{kt}) - \bar{y}_{kt}$

where $\bar{y}_{kt} = log(Y_{kt}^{pot})$ with $Y_{kt}^{pot} = (\bar{A}_{kt}^{Y}\bar{N}_{kt})^{\alpha}(K_{ikt-1}^{tot})^{1-\alpha}$ is (log) potential output. Potential output at date *t* is the output level that would obtain if the labor input equaled steady state per capita hours worked, date *t* capital stock were utilized at full capacity, and TFP at *t* equaled its trend component.

The Taylor rule may be extended to deal with economies with managed exchange rates and other exchange rate regimes, as in Vitek (2013).

It is assumed that the rate on risk-free bonds is equal to the policy rate: $i_{kt}^{rf} \equiv i_{kt}$.

A.4.2. Fiscal policy

Government expenditure and receipts can deviate temporarily from their long-run levels in systematic response to budgetary or business-cycle conditions and in response to idiosyncratic shocks. Concerning government consumption and government investment, we specify the following autoregressive equations:

$$\frac{G_{kt}}{\bar{Y}_{kt}A_{kt}^{PG}} - \bar{G} = \rho^{G}\left(\frac{G_{kt-1}}{\bar{Y}_{kt}A_{kt}^{PG}} - \bar{G}\right) + u_{kt}^{G}$$

$$\frac{I_{kt}^{G}}{\bar{Y}_{kt}A_{kt}^{PI}} - \bar{I}^{G} = \rho^{IG}\left(\frac{I_{kt-1}^{G}}{\bar{Y}_{kt}A_{kt}^{PI}} - \bar{I}^{G}\right) + u_{kt}^{IG}$$

$$\frac{T_{kt}}{\overline{P_{kt}^{Y}Y_{kt}}} - \bar{T} = \rho^{T}\left(\frac{T_{kt-1}}{\overline{P_{kt}^{Y}Y_{kt}}} - \bar{T}\right) + \eta^{DEF,T}\left(\frac{\Delta B_{kt}^{gtot}}{P_{kt}^{Y}Y_{kt}} - def^{T}\right) + \eta^{B,T}\left(\frac{B_{kt}^{gtot}}{P_{kt}^{Y}Y_{kt}} - \bar{B}_{k}^{G}\right) + u_{kt}^{T}$$

with B_{kt}^{gtot} total nominal government debt. Government transfers react to the level of government debt and government deficit relative to the associated debt and deficit targets $\bar{B}_k^G$ and def^T.

The government budget constraint is

$$B_{kt}^g = \left(1 + i_{kt-1}^g\right) B_{kt-1}^g - R_{kt}^G + P_{kt}^G G_{kt} + P_{kt}^{IG} I_{kt}^G + T_{kt}$$

where government (nominal) revenue:

$$R_{kt}^G = \tau_k^K (P_{kt}^Y Y_{kt} - W_{kt} N_{kt} - P_{kt}^I \delta_k K_{kt-1}) + \tau^N W_{kt} N_{kt} + \tau^C P_{kt}^C C_{kt} + tax_{kt}$$

consists of taxes on consumption, labor and corporate income as well as lump-sum tax.

Finally, the accumulation equation for government capital is:

$$K_{kt}^G = \left(1 - \delta^G\right) K_{kt-1}^G + I_{kt}^G$$

A.5. The RoW block

The model of the RoW economy (subscript k=RoW) is a simplified structure with fewer shocks. Specifically, the RoW consists of a budget constraint for the representative household, demand functions for domestic and imported goods (derived from CES consumption good aggregators), a production technology that uses labor as the sole factor input, and a New Keynesian Phillips curve. The RoW block abstracts from capital accumulation. There are shocks to labor productivity, price mark-ups, the subjective discount rate, the relative preference for domestic vs. imported goods, as well as monetary policy shocks in the RoW.

More specifically the budget constraint for the RoW representative household is:

$$P_{RoWt}^Y Y_{RoWt} + P_{RoWt}^{Oil} OIL_{RoWt} = P_{RoWt}^C C_{RoWt} + P_{RoWt}^X X_{RoWt} - \sum_l \frac{size_l}{size_{RoW}} e_{lRoWt} P_{lt}^X M_{lRoWt}$$

where X_{RoWt} are non-oil exports by the RoW, and the intertemporal equation for aggregate demand derived from the FOC for consumption:

$$\beta_t \frac{\lambda_{RoWt+1}}{\lambda_{RoWt}} \frac{1 + i_{RoWt}}{1 + \pi_{RoWt+1}^C} = 1$$

with $\beta_t = \beta \exp(\varepsilon_{RoWt}^C)$, $\left(C_{RoWt} - hC_{RoWt-1}\right)^{-\theta} = \lambda_{RoWt}$ and ε_{RoWt}^C is the RoW demand shock.

FOC w.r.t. RoW government bonds:

$$\beta E_t \left[\frac{\lambda_{RoWt+1}}{\lambda_{RoWt}} \frac{\left(1 + i_{RoWt}^g\right) - \left(\alpha_{RoW}^{b0} + \alpha_{RoW}^{b1} \frac{B_{RoWt}^g}{P_{RoW}^Y Y_{RoW}}\right)}{1 + \pi_{RoWt+1}^Y} \right] = 1$$

As for the EA and the US, final aggregate demand C_{RoWt} (in the absence of investment and government spending in the RoW block) is a combination of domestic output, Y_{RoWt} and imported goods, M_{RoWt}, using the following CES function:

$$C_{RoWt} = A_{RoWt}^{p}\left[(1 - exp(\varepsilon_{RoWt}^{M})s^{M})^{\frac{1}{\sigma}}(Y_{RoWt}^{C})^{\frac{\sigma-1}{\sigma}} + (exp(\varepsilon_{RoWt}^{M})s^{M})^{\frac{1}{\sigma}}(M_{RoWt}^{C})^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}$$

which gives the demand for the domestic and foreign goods in RoW demand:

$$Y_{RoWt}^{C} = \left(A_{RoWt}^{p}\right)^{\sigma-1}(1 - exp(\varepsilon_{RoWt}^{M})s^{M})\left(\frac{P_{RoWt}^{Y}}{P_{RoWt}^{C}}\right)^{-\sigma} C_{RoWt}$$

$$M_{RoWt}^{C} = \left(A_{RoWt}^{p}\right)^{\sigma-1} exp(\varepsilon_{RoWt}^{M})s^{M}\left(\frac{P_{RoWt}^{M}}{P_{RoWt}^{C}}\right)^{-\sigma} C_{RoWt}$$

where the consumer price deflator P_{RoWt}^{C} satisfies:

$$P_{RoWt}^{C} = \left(A_{RoWt}^{p}\right)^{-1}[(1 - exp(\varepsilon_{RoWt}^{M})s^{M})(P_{RoWt}^{Y})^{1-\sigma} + exp(\varepsilon_{RoWt}^{M})s^{M}(P_{RoWt}^{M})^{1-\sigma}]^{\frac{1}{1-\sigma}}$$

The RoW non-oil output is produced with the technology:

$$Y_{RoWt} = A_{RoWt}^{Y} N_{RoWt}$$

Price setting for RoW non-oil output follows a New Keynesian Phillips curve:

$$\pi_{RoWt}^{Y} - \bar{\pi}_{RoW}^{Y} = \beta \frac{\lambda_{RoWt+1}}{\lambda_{RoWt}}(sfp(E_t \pi_{RoWt+1}^{Y} - \bar{\pi}_{RoW}^{Y}) + (1 - sfp)(\pi_{RoWt-1}^{Y} - \bar{\pi}_{RoW}^{Y})) + \varphi_{RoW}^{Y} \ln(Y_{RoWt} - \bar{Y}_{RoW}) + \varepsilon_{RoWt}^{Y}$$

Monetary policy in the RoW follows a Taylor rule:

$$i_{RoWt} - \bar{\imath} = \rho^{i}(i_{RoWt-1} - \bar{\imath}) + \left(1 - \rho^{i}\right)\left(\eta^{i\pi}(\pi_{RoWt}^{Y} - \bar{\pi}_{RoW}^{Y}) + \eta^{iy}\tilde{y}_{RoWt}\right) + \varepsilon_{RoWt}^{inom}$$

where $\tilde{y}_{RoWt}$ is the deviation of actual output from trend output.

The RoW net foreign asset (NFA) position equals minus the sum of the EA and US NFA positions.

Finally, oil is assumed to be fully imported from the RoW and the oil price is assumed as follows:

$$P_{RoWt}^{Oil} = \frac{\bar{P}^{Y}}{A_{ROWt}^{p^{oil}} e_{RoW,US}}$$

where $A_{ROWt}^{p^{oil}}$ is oil-specific productivity and oil is priced in USD.

Total nominal exports are defined as:

$$P^X_{RoWt}X_{RoWt} = \sum_l P^X_{lRoWt}M_{RoWlt}$$

with the bilateral export price being defined as the domestic price subject to a bilateral price shock:

$$P^X_{lRoWt} = \exp(\varepsilon^{PX}_{lRoWt})\, P^Y_{RoWt}$$

A.6 Closing the economy

Market clearing requires that:

$$Y_{kt}P^Y_{kt} + div^M_{kt}P^Y_{kt} = P^C_{kt}C_{kt} + \ P^I_{kt}I_{kt} + P^{IG}_{kt}IG_{kt} + TB_{kt}$$

Exports is a sum of imports from the domestic economy by other countries:

$$X_{kt} = \sum_l M_{klt}$$

where M_{klt} stands for imports from the domestic economy to economy *l*. Total imports are defined as:

$$P^{Mtot}_{kt}M^{tot}_{kt} = P^M_{kt}M_{kt} + P^{oil}_{kt}OIL_{kt}$$

where non-oil imports

$$P^M_{kt}M_{kt} = P^M_{kt}(M^C_{kt} + M^I_{kt} + M^G_{kt} + M^{IG}_{kt})$$

Net foreign assets, NFA_{kt}, evolve according to

$$e_{RoWk,t}B^w_{k,t} = +(1 + i^{bw}_{t-1})e_{RoWk,t}B^w_{k,t-1} + P^X_{kt}X_{kt} - \sum_l \frac{size_l}{size_k} e_{lkt}P^X_{lt}M_{lkt} - P^{Oil}_{kt}OIL_{kt} + ITR_k\overline{P^Y_{kt}Y_{kt}}$$

where $P^X_{kt}X_{kt} - \sum_l \frac{size_l}{size_k} e_{lkt}P^X_{lt}M_{lkt} - P^{Oil}_{kt}OIL_{kt} = TB_{kt}$ defines the trade balance, with domestic importers buying the imported good at the price $\mathrm{P}^{\mathrm{X}}_{\mathrm{lt}}$ .We allow non-zero trade balance and include an international transfer, ITR_k, calibrated in order to satisfy zero NFA in equilibrium.

Finally, net foreign assets of each country sum to zero:

$$\sum_l NFA_{lt}size_l = 0.$$

$size_l$ is the relative size of economy *l*.

Table A.1. Prior and posterior distributions of key estimated model parameters: EA and US

	Posterior distributions				Prior distributions		
	EA		US				
	Mode	Std	Mode	Std	Distrib.	Mean	Std
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Preferences							
h	0.88	0.07	0.86	0.06	B	0.5	0.2
h_N	0.38	3.13	0.85	0.10	B	0.5	0.2
θ	1.47	0.87	1.37	0.61	G	1.5	0.2
θ^N	2.32	4.91	2.10	3.74	G	2.5	0.5
α_{RoW}^{b1}	0.007	0.005	0.002	0.004	B	0.005	0.005
Steady state share of Ricardian households							
ω^s	0.70	0.03	0.74	0.04	B	0.65	0.05
Production functions							
σ^o	0.33	0.19	0.33	0.13	B	0.5	0.08
σ^z	4.30	0.71	4.05	0.76	G	2	1
σ^{FM}	1.06	0.94	0.28	0.61	G	2	1
Nominal and real frictions							
γ^p	23.2	10.1	57.4	36.8	G	60	40
SFP	0.60	0.09	0.75	0.11	B	0.5	0.2
γ^w	4.69	8.22	2.93	4.71	G	5	2
γ^{wr}	0.97	0.06	0.96	0.05	B	0.5	0.2
SFW	0.53	0.31	0.51	0.62	B	0.5	0.2
$\gamma^{I,1}$	8.79	7.16	16.2	8.11	G	60	40
$\gamma^{I,2}$	26.6	13.8	12.2	7.79	G	60	40
γ^n	4.90	1.80	12.8	8.06	G	60	40
$\gamma^{u,2}$	0.06	0.03	0.07	0.05	B	0.1	0.04
γ^{pM}	0.13	0.09	0.40	0.21	B	2	0.8
Monetary policy							
ρ^i	0.85	0.03	0.83	0.03	B	0.7	0.12
$\eta^{i\pi}$	2.23	0.56	1.76	0.24	B	2	0.4
η^{iy}	0.08	0.05	0.07	0.02	B	0.5	0.2
Fiscal policy							
ρ^T	0.97	0.05	0.96	0.07	B	0.7	0.1
$\eta^{DEF,T}$	-0.01	0.00	-0.01	0.01	B	-0.03	0.01
$\eta^{B,T}$	-0.001	0.00	-0.001	0.00	B	-0.001	0.001
ρ^G	0.95	0.01	0.95	0.02	B	0.7	0.1
ρ^{IG}	0.81	0.07	0.92	0.04	B	0.7	0.1
Autocorrelations of forcing variables							
ρ^{AY}	0.78	0.12	0.50	0.16	B	0.5	0.2
$\rho^{\overline{GAY}}$	0.95	0.12	0.96	0.04	B	0.85	0.075
$\rho^{Ap,C}$	0.08	0.15	0.34	0.12	B	0.5	0.2
$\rho^{Ap,G}$	0.20	0.09	0.27	0.14	B	0.5	0.2
$\rho^{Ap,I}$	0.15	0.17	0.39	0.13	B	0.5	0.2
$\rho^{Ap,IG}$	0.88	0.04	0.97	0.01	B	0.5	0.2
ρ^c	0.80	0.10	0.79	0.08	B	0.5	0.2
ρ^b	0.91	0.05	0.93	0.05	B	0.5	0.2
$\rho^{b,RoW}$	0.85	0.09	0.57	0.46	B	0.5	0.2

ρ^{s}	0.94	0.05	0.96	0.03	B	0.85	0.05
ρ^{μ}	0.24	0.15	0.76	0.12	B	0.5	0.2
ρ^{M}	0.93	0.02	0.85	0.05	B	0.5	0.2
ρ^{X}	0.94	0.02	0.85	0.04	B	0.5	0.2
ρ^{PX}_{lRoW}	0.99	0.01	0.98	0.01	B	0.5	0.2
Standard deviations (%) of innovations to forcing variables							
u^{AY}	0.92	0.17	1.45	0.35	G	0.50	0.20
$u^{L\overline{AY}}$	0.09	1.41	0.09	0.98	G	0.10	0.04
$u^{G\overline{AY}}$	0.02	0.05	0.03	0.03	G	0.02	0.008
$u^{Ap,C}$	0.19	0.02	0.20	0.03	G	1.00	0.40
$u^{Ap,G}$	0.45	0.04	0.39	0.04	G	1.00	0.40
$u^{Ap,I}$	0.32	0.05	0.59	0.05	G	1.00	0.40
$u^{Ap,IG}$	0.76	0.05	0.38	0.05	G	1.00	0.40
u^{c}	0.96	0.92	1.19	0.91	G	1.00	0.40
u^{b}	0.11	0.01	0.13	0.01	G	1.00	0.40
$u^{b,RoW}$	0.24	0.01	0.31	0.27	G	1.00	0.40
u^{s}	0.18	0.09	0.16	0.08	G	0.10	0.02
u^{μ}	3.65	1.55	3.80	2.93	G	2.00	0.80
u^{n}	1.16	1.87	1.84	2.35	G	1.00	0.40
u^{M}	5.83	0.91	6.51	1.07	G	2.00	0.80
u^{X}	0.61	0.07	0.81	0.04	G	1.00	0.40
u^{PX}_{lRoW}	4.24	0.47	2.45	0.18	G	1.00	0.40
u^{inom}	0.09	0.01	0.12	0.01	G	1.00	0.40
u^{G}	0.06	0.01	0.13	0.01	G	1.00	0.40
u^{IG}	0.12	0.01	0.07	0.01	G	1.00	0.40
u^{T}	0.10	0.01	0.23	0.02	G	1.00	0.40

Notes: Cols. (1) lists model parameters. Cols. (2)-(3) and Cols. (4)-(5) show the mode and the standard deviation (Std) of the posterior distributions of EA parameters and of US parameters, respectively. Cols. (6) (labelled 'Distrib.') indicates the prior distribution function (B: Beta distribution; G: Gamma distribution). Identical priors are assumed for EA and US parameters.

Table A.2. Prior and posterior distributions of key estimated model parameters: ROW

	Posterior distributions		Prior distributions		
	Mode	Std	Distribution	Mean	Std
(1)	(2)	(3)	(4)	(5)	(6)
Preferences					
h	0.95	0.03	B	0.7	0.1
θ	1.48	1.53	G	1.5	0.2
α_{RoW}^{b1}	0.001	0.005	B	0.002	0.0008
Firms					
σ	0.06	0.21	G	2	1
SFP	0.96	0.13	B	0.5	0.2
φ_{RoW}^{Y}	0.11	0.04	G	0.5	0.2
Monetary policy					
ρ^{i}	0.93	0.01	B	0.7	0.1
$\eta^{i\pi}$	1.03	0.16	B	2	0.4
η^{iy}	1.06	0.43	B	0.5	0.2
Autocorrelations of forcing variables					
$\rho^{\overline{AY}}$	0.90	0.07	B	0.85	0.075
ρ^{c}	0.81	0.09	B	0.5	0.2
ρ^{M}	0.85	0.09	B	0.5	0.2
ρ^{Y}	0.80	0.08	B	0.5	0.2
Standard deviations (%) of innovations to forcing variables					
$u^{G\overline{AY}}$	0.39	0.08	G	0.1	0.04
u^{c}	1.21	1.12	G	1.00	0.40
u^{M}	3.12	1.01	G	2.00	0.80
u^{Y}	0.08	0.03	G	1.00	0.40
u^{inom}	0.07	0.01	G	1.00	0.40

Notes: Cols. (1) lists model parameters. Cols. (2)-(3) show the mode and the standard deviation (Std) of the posterior distributions of EA parameters and of US parameters, respectively. Cols. (4) indicates the prior distribution function (B: Beta distribution; G: Gamma distribution).

Table A.3. Calibrated model parameters and ratios

		EA	US	RoW
(1)	(2)	(3)	(4)	(5)
Preferences				
Intertemporal discount factor	β	0.9990	0.9986	0.9992
Import share in final demand	s^{M}	0.16	0.12	0.05
Preference for imports from RoW	$s^{M,ROW}$	0.86	0.79	
Preference for imports from US	$s^{M,US}$	0.14		0.50
Preference for imports from EA	$s^{M,EA}$		0.21	0.50
Substitutability btw domestic varieties	σ^{y}	5.1	18.9	
Preference for gov bonds	α^{b0}	-0.002	-0.002	
Preference for stocks	α^{s0}	-0.002	0.002	
Preference for RoW bonds	α^{bw0}	0.012	0.012	0.012
Weight of disutility of labour	ω^{N}	26.0	436.6	
Production				
Cobb-Douglas labour share	α	0.65	0.65	
Depreciation of private capital stock	δ	0.014	0.017	
Depreciation of public capital stock	δ^{G}	0.014	0.017	
Share of oil in total output	s^{Oil}	0.03	0.03	
Linear capacity utilisation adj costs	$\gamma^{u,1}$	0.02	0.02	
Monetary policy				
Nominal interest rate in SS	i	0.008	0.008	0.008
CPI inflation in SS	π^{C}	0.004	0.005	
GDP inflation in SS (p.a.)	π^{Y}	0.02	0.02	0.02
Fiscal policy				
Gov consumption share in SS	G/Y	0.22	0.17	
Gov investment share in SS	IG/Y	0.03	0.04	
Transfers share in SS	T/Y	0.18	0.10	
Consumption tax	τ^{C}	0.20	0.20	
Corporate profit tax	τ^{K}	0.30	0.30	
Labour tax	τ^{N}	0.45	0.21	
Deficit target	def^{T}	0.024	0.025	
Debt target	B^{G}	3.2	3.4	
Size of the region (% of world)	size	17	25	58
Trend of total factor productivity	g^{AY}	0.0022	0.0023	0.0025
Trend of private consumption specific productivity	g^{PC}	-0.0002	-0.0006	
Trend of gov consumption specific productivity	g^{PG}	-0.0005	-0.0038	
Trend of private investment specific productivity	g^{PI}	0.0006	0.0005	
Trend of gov investment specific productivity	g^{PIG}	0.0006	0.0005	

Notes: Col. (1) lists model parameters, Col. (2) the corresponding symbols in the model description, and Cols. (3)-(5) the respective parameter values in the EA, US (and if applicable) RoW blocks.

B. Construction of Rest-of-World (ROW) aggregates

The series for ROW real GDP (GDPR) is constructed as follows. First, we normalise the series for GDP in national currency (NAC) at constant prices for each country (i) at the common base year t=0:

$$\frac{GDPR_t^i}{GDPR_0^i} = \prod_{k=1}^{t} \left(\frac{GDPR_k^i}{GDPR_{k-1}^i}\right)$$

Then we calculate the time-varying share of each country in the block based on nominal GDP (GDPN) in USD. Finally, we compute ROW GDPR as the GDPN-weighted average of the 58 countries, which gives the ROW GDPR index with base year t=0:

$$GDPR_t^{ROW} = \sum_{i=1}^{58} \frac{GDPN_t^{USD,i}}{GDPN_t^{USD,ROW}} GDPR_t^i$$

The aggregation applies time-varying weights in order to account for changes in the relative economic weight of individual ROW countries over the sample period. ROW GDPR is normalised to 1 in year 2005.

The series for the ROW GDP deflator (PGDP) is constructed analogously to the ROW GDPR series. First, we normalise the series for the PGDP for each country (i) to base year t=0:

$$\frac{PGDP_t^i}{PGDP_0^i} = \prod_{k=1}^{t} \left(\frac{PGDP_k^i}{PGDP_{k-1}^i}\right)$$

Then we calculate the time-varying share of each country in the block based on GDP in USD and compute the ROW PGDP as the GDP-weighted average of the 58 country series, which gives the ROW GDPR index with base year t=0:

$$PGDP_t^{ROW} = \sum_{i=1}^{58} \frac{GDPN_t^{USD,i}}{GDPN_t^{USD,ROW}} PGDP_t^i$$

ROW GDPR is normalised to 1 in year 2005. An index of ROW nominal GDP (GDPN) with base year 2005 can be calculated by multiplying ROW GDPR with ROW PGDP.

The ROW block in the model has a flexible nominal exchange rate. The ROW nominal exchange rate to the USD (e) is calculated as GDP-weighted average of bilateral exchange rates against the USD for the 58 countries. As for GDPR and PGDP above, we normalise bilateral USD exchange rates in each country to the base year t=0:

$$\frac{e_t^{i,\$}}{e_0^{i,\$}} = \prod_{k=1}^{t} \left(\frac{e_k^{i,\$}}{e_{k-1}^{i,\$}}\right)$$

The ROW nominal exchange rate to the USD with base year t=0 is then calculated as GDP-weighted average of the 58 country series:

$$e_t^{ROW,\$} = \sum_{i=1}^{58} \frac{GDPN_t^{i,\$}}{GDPN_t^{ROW,\$}} e_t^{i,\$}$$

The ROW exchange rate to the USD is normalised to 1 in 2005. The exchange rate series includes exchange rate movements between members of the ROW group instead of attributing them to the ROW price index.

The short-term interest rate for the ROW is the GDP-weighted average of interest rate series for countries (i) in the ROW. The sample is reduced to 47 countries due to limited data availability and the GDP weights are adjusted accordingly.

The ROW trade balance (TB) balances international trade flows:

$$TB_t^{ROW} = -(TB_t^{EA} + TB_t^{US})$$

ROW exports equal the sum of EA and US imports from the ROW. The bilateral imports from the ROW are obtained by subtracting imports from the US (EA) from total EA (US) imports based on trade matrices for international good and service trade. Analogously, imports of the ROW equal EA plus US exports to the ROW.

C. Model-predicted and empirical business cycle statistics (first-differenced variables)

	Model				Data			
variable	std (%)	Corr. with domestic GDP	Cross-country corr. with EA	Cross-country corr. with US	std (%)	Corr. with domestic GDP	Cross-country corr. with EA	Cross-country corr. with US
	(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*
GDP EA	0.62	1.00		0.27	0.64	1.00		0.52
Consumption EA	0.53	0.27			0.39	0.69		
Investment EA	3.20	0.60			2.77	0.80		
Government cons. EA	0.35	0.03			0.34	0.00		
Hours worked EA	0.56	0.62			0.49	0.74		
Interest rate EA	0.52	0.08			0.40	0.14		
GDP deflator EA	0.38	-0.11		0.19	0.20	0.06		0.36
Consumption price EA	0.37	0.21			0.31	0.57		
Exchange rate EA/US	4.06	0.15			4.19	0.10		
Trade balance/GDP EA	1.92	-0.05			0.92	-0.12		
GDP US	0.73	1.00	0.27		0.67	1.00	0.52	
Consumption US	0.70	0.40			0.59	0.67		
Investment US	3.36	0.59			3.30	0.79		
Government cons. US	0.86	0.13			0.83	0.11		
Hours worked US	0.56	0.53			0.58	0.48		
Interest rate US	0.60	0.02			0.55	-0.01		
GDP deflator US	0.47	-0.12	0.19		0.25	0.22	0.36	
Consumption price US	0.56	0.10			0.38	0.35		
Trade balance/GDP US	2.48	-0.03			1.120	-0.07		
GDP ROW	0.96	1.00	-0.05	0.06	0.85	1.00	0.19	0.43
GDP deflator ROW	0.90	-0.43	0.12	0.14	0.85	0.84	-0.09	0.36
Exchange rate ROW_US	1.91	0.05			1.41	-0.18		

Note: the Table reports model predicted standard deviations (Col.,1), correlations with domestic GDP (Col. 2) and cross country correlations for GDP and GDP deflators (Cols. 3-4), as well as the corresponding empirical statistics based on quarterly data for the period 1999q1-2014q4 (Cols. (5)-(8)). All statistics pertain to growth rates (first differences for interest rates and the trade balance/GDP ratio). The model-predicted moments are generated by a version of the linearized model in which the covariance matrix of all exogenous variables is set at the covariance matrix of the smoothed estimates of the innovations.

D. Fiscal policy under the ZLB constraint

We perform smoothed estimates of latent variables and shocks in the DSGE model by enforcing the ZLB constraints in both EA and US, using the estimated parameters in the baseline estimation without ZLB. We use the Occbin solution method developed by Guerrieri and Iacoviello (2015) to treat the occasionally binding constraint via a piecewise linear solution[10]. Moreover, we implement an algorithm similar to Anzoategui, et al. (mimeo, 2015, Appendix A2) to obtain smoothed estimates of latent variables as well the sequence of regimes along the historical periods. Finally, we use these smoothed estimates to measure the *non-additive* impact of individual shocks onto GDP, namely a non-linear extension of linear/additive historical shock decompositions (M. Ratto, 2016).

D.1 Estimation of latent variables and shocks under the ZLB

Let i_{kt}^{NC} be the unconstrained nominal interest rate that follows the Taylor rule without monetary shock:

$$i_{kt} - \bar{\iota} = \rho^{i}(i_{kt-1} - i) + \left(1 - \rho^{i}\right)\left(\eta^{i\pi}\left(0.25\left(\sum_{r=0}^{3} \pi_{kt-r}^{c+g}\right) - \bar{\pi}^{C+G}\right) + \eta^{iy}(\tilde{y}_{kt})\right) + u_{kt}^{inom}$$

The actual realized nominal policy interest rate i_{kt} set by the central bank will follow the usual Taylor rule if $i_{kt}^{NC} > i^{LB}$:

$$i_{kt} = i_{kt}^{NC} + \upsilon_{kt}^{inom}$$

while it will be constrained if $i_{kt}^{NC} \leq i^{LB}$

$$i_{kt} = i^{LB} + \upsilon_{kt}^{inom}$$

We set the lower bound for quarterly short-term nominal interest rates at 0.001 (i.e. 0.4% yearly). Under the constrained ZLB regime, the variable i_{kt}^{NC} acts as a ‘shadow’ interest rate that, within the Occbin algorithm, allows determining endogenously when the constraint is no longer binding. Moreover, we still use an exogenous monetary shock under the constrained regime, in order to keep observing the actual policy rates in the data. This shock does not alter the behavior of the piecewise linear solution in terms of transmission mechanisms under the ZLB constraint.

The algorithm for estimating latent variables is as follows:

1) Guess an initial sequence of regimes for each historical period $R_t^{(0)}$ for $t = 1, \dots T$
2) Given the sequence of regimes, compute the piecewise linear state space matrices $\boldsymbol{\Upsilon}_{\boldsymbol{t}}^{(0)}$ following the Occbin methodology
3) For each iteration $j = 1, \dots, n$

[10] This solution may also be viewed as an iterative application of the solution of Cagliarini and Kulish (2013) where the iterations are used to find the expected duration, which is consistent with the binding constraint.

a. feed the state space matrices $\mathbf{\Upsilon}_t^{(j-1)}$ to a Kalman Filter[11]/ Fixed interval smoothing algorithm to determine initial conditions, smoothed variables $\boldsymbol{y}_t^{(j)}$ and shocks $\boldsymbol{\epsilon}_t^{(j)}$.
b. given initial conditions and shocks perform Occbin simulations that endogenously determine a new sequence of regimes $R_t^{(j)}$, from which a new sequence of states space matrices is derived $\mathbf{\Upsilon}_t^{(j)}$

4) The algorithm stops when $R_t^{(j)} = R_t^{(j-1)}$ for all $t = 1, \dots, T$.

The algorithm used for estimating latent variables yields initial conditions and a sequence of smoothed variables and shocks, consistent with the observables, and taking into account the occasionally binding constraint, i.e. it also estimates a sequence of regimes along the historical periods.

Table 1 Estimation of the historical sequence of occasionally binding regimes

	EA		*US*	
time	regime sequence[12]	starting period of regime[13]	regime sequence	starting period of regime
2008	0	1	0	1
2008.25	0	1	0	1
2008.5	0	1	0	1
2008.75	0	1	0	1
2009	0 1 0	1 3 8	0 1 0	1 3 7
2009.25	0 1 0	1 2 7	0 1 0	1 2 7
2009.5	0 1 0	1 2 4	1 0	1 3
2009.75	1 0	1 2	1 0	1 2
2010	0	1	0	1
2010.25	0	1	0	1
2010.5	0	1	0	1
2010.75	0	1	0	1
2011	0	1	0	1
2011.25	0	1	0	1
2011.5	0	1	0	1
2011.75	0	1	0	1
2012	0	1	0	1
2012.25	0	1	0	1
2012.5	0	1	0	1
2012.75	0	1	0	1

[11] Kulish et al. (2014) also apply the piecewise linear solution in the Kalman filter to estimate DSGE models with forward guidance.
[12] 0 = unconstrained; 1 = constrained.
[1 0] indicates a constrained regime. [0 1 0] indicates a regime that anticipates FUTURE constraints.
[13] Periods for which the regime starts.
[1 7] indicates a constrained regime for 6 periods. [1 2 7] indicates a regime that anticipates FUTURE constraints starting in period 2 until period 6.

2013	1 0	1 3	1 0	1 2
2013.25	1 0	1 3	1 0	1 3
2013.5	1 0	1 3	1 0	1 3
2013.75	1 0	1 3	1 0	1 3
2014	1 0	1 3	1 0	1 3
2014.25	1 0	1 3	0	1
2014.5	1 0	1 3	0	1
2014.75	1 0	1 3	1 0	1 3

The sequence of regimes is reported in the next Table 1. It is worth noting that agents in both EA and US anticipated ZLB starting in 2009q1. EA in particular anticipates quite prolonged ZLB, which influences significantly shock contributions in EA in 2009. Moreover, *both* EA and US faced a constrained monetary policy in the second half of 2009. Monetary policy is again constrained for both US and EA since 2013q1.

In Figure 1 we show the historical pattern of the 'shadow' unconstrained nominal interest rate (i_{kt}^{NC}, black dots) versus the actual data of policy rates (i_{kt}, red)[14]. When i_{kt}^{NC} is below the threshold the constraint is binding, otherwise the regime will be either 'normal' or anticipating future binding regimes. This is provided in Table 1 as well.

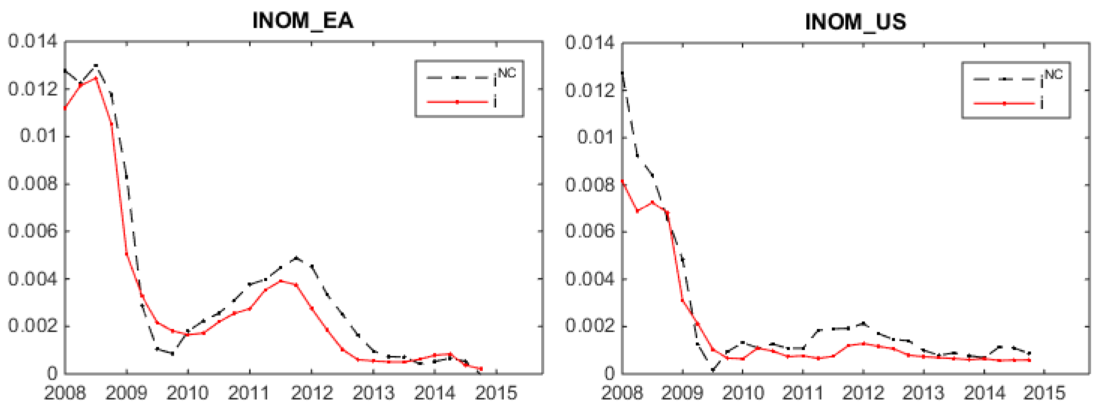


Figure 1. Observed interest rate vs. 'shadow' interest rate

D.2 Estimating contributions of shocks for the piecewise linear solution

One interesting issue is the estimation of the shock contributions to the observed data consistent with the piecewise linear solution, namely the extension of the standard historical shock decompositions to the case of occasionally binding regimes. The contribution of individual smoothed shocks, however, is not the mere additive superposition of each shock propagated by the sequence of state space matrices $\mathbf{\Upsilon}^{(j)}$ estimated with the smoother. The sequence of regimes associated to the state matrices, in fact, is a *non-linear function* of the whole set of shocks *simultaneously* affecting the economy, i.e. it is *conditional* on the sequence and combination of shocks simultaneously hitting the economy:

$$\mathbf{\Upsilon}_{\boldsymbol{t}}^{(\epsilon)} = f(\epsilon_{1t}, \dots, \epsilon_{kt}), t = 1, \dots, T$$

[14] Note that, in the estimation, we used the money market rate for US. The latter fell less abruptly in 2008/09 than the Fed Funds rate.

It is easy to verify that, taking subsets of shocks or individual shocks, the sequence of regimes will change. One way of measuring the effect of shocks in this non-linear context is to consider simulations conditional to given shock patterns.

In particular, we consider a definition that generalize the concept of shock contributions to the non-linear case, which degenerates to the standard shock decompositions for the linear case (M. Ratto, 2016). We define ϵ_{lt} the shock or group of shocks of interest, while $\epsilon_{\sim lt}$ denotes the complementary set of shocks. We compute the contribution of ϵ_{lt} by setting to zero the shocks ϵ_{lt} and performing simulations using the initial condition *and* the sequence of smoothed shocks for the *complementary* set of shocks $\epsilon_{\sim lt}$. We define this simulation as $y_t(\epsilon_{\sim lt}|\epsilon_{\sim lt}, y_0)$. The contribution of the shocks of interest will be the *complement* of this simulation to the smoothed variable y_t : $y_t(\epsilon_{lt}|\epsilon_{\sim lt}, y_0) = y_t - y_t(\epsilon_{\sim lt}|\epsilon_{\sim lt}, y_0)$. We call this the *residual contribution* of ϵ_{lt}.

Note that each of these simulations provides a different sequence of regimes, which in general will be different from the historical one. We use the *residual contribution* to measure the impact of the ZLB on the contribution of shocks to observed variables. In particular, we focus in Figure 2 on the impact of fiscal shocks on yoy GDP in EA and US.

The two major outcomes of this non-linear analysis are:

a) the effect of fiscal shocks in 2009 changes *both in sign and size*, implying a significant *positive contribution* of fiscal measures at the onset of the great recession;
b) the negative contribution of fiscal shocks in the subsequent slump is magnified by the ZLB. This makes the impact of fiscal policy more visible, although this is still not the main driver of the slump. In EA, in particular, the contribution of fiscal shocks in 2013 is about -0.35% out of a maximum decline of about -2.6% in 2013q1 (i.e. about 15% the decline). In 2014, the fiscal shocks under ZLB still have a negative impact in the first three quarters, by about -0.15% out of an overall GDP decline of -0.55%. The linear shock decomposition, in turn, implies no or slightly positive contribution of the fiscal shocks in 2014 for the EA.

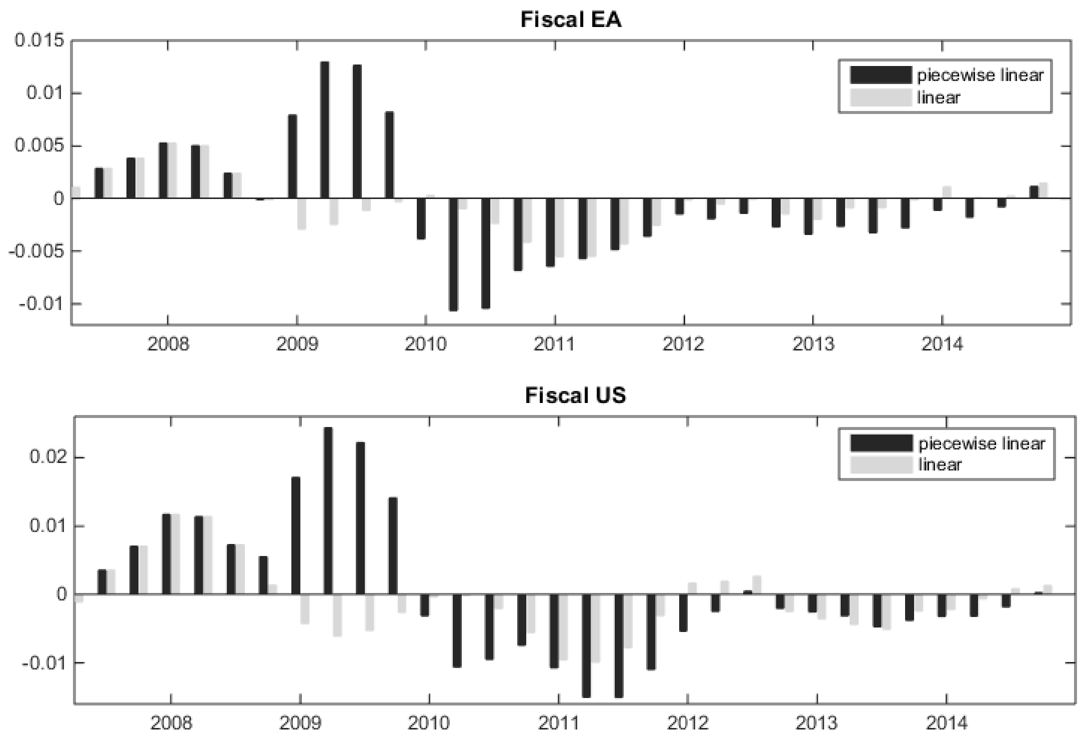


Figure 2. Contribution of fiscal shocks to yoy GDP growth in EA and US. Comparison of linear and piecewise linear solutions

To better understand the interaction between shocks and regime sequences, we report in Table 2 the regimes obtained shutting off the fiscal shocks. This shows that, for both EA and US, without fiscal shocks there would have been more severely binding constrained regimes in 2009. Moreover, in EA, constrained regimes would be less binding in 2013 without fiscal shocks. In US, the absence of fiscal shocks would have implied more prolonged constrained regimes in 2010, 2012 and 2014.

Table 2 Sequence of regimes obtained removing fiscal shocks in EA and US respectively

	EA		*US*	
time	regime sequence[15]	starting period of regime[16]	regime sequence	starting period of regime
2008	0	1	0	1
2008.25	0	1	0	1
2008.5	0	1	0	1
2008.75	0	1	0 1 0	1 3 6
2009	0 1 0	1 2 8	1 0	1 9
2009.25	1 0	1 7	1 0	1 8
2009.5	1 0	1 5	1 0	1 6

[15] 0 = unconstrained; 1 = constrained.
[1 0] indicates a constrained regime. [0 1 0] indicates a regime that anticipates FUTURE constraints.
[16] Periods for which the regime starts.
[1 7] indicates a constrained regime for 6 periods. [1 2 7] indicates a regime that anticipates FUTURE constraints starting in period 2 until period 6.

2009.75	1 0	1 3	1 0	1 4
2010	1 0	1 3	1 0	1 3
2010.25	0	1	1 0	1 5
2010.5	0	1	1 0	1 4
2010.75	0	1	1 0	1 3
2011	0	1	1 0	1 3
2011.25	0	1	0	1
2011.5	0	1	0	1
2011.75	0	1	0	1
2012	0	1	0 1 0	1 2 3
2012.25	0	1	1 0	1 3
2012.5	0	1	1 0	1 4
2012.75	0	1	1 0	1 5
2013	0	1	1 0	1 3
2013.25	0	1	1 0	1 4
2013.5	0 1 0	1 2 3	1 0	1 3
2013.75	1 0	1 3	1 0	1 3
2014	1 0	1 2	1 0	1 5
2014.25	1 0	1 3	1 0	1 3
2014.5	1 0	1 3	1 0	1 3
2014.75	1 0	1 4	1 0	1 4

We repeat the same exercise for the investment risk premia shocks. As shown in Figure 3, the effect of these shocks is (slightly) amplified considering the ZLB constraint. Moreover, looking at Figure 4, we can also note that this amplified effect is obtained with *smaller values* of the smoothed shock estimated with the piecewise linear solution during the ZLB regimes. Therefore, the transmission mechanism itself triggers this amplification.

Finally, it is worth mentioning that we obtained *unconstrained* monetary policy for the entire historical period for EA (US), when the investment risk premium shock in EA (US) is set to zero.

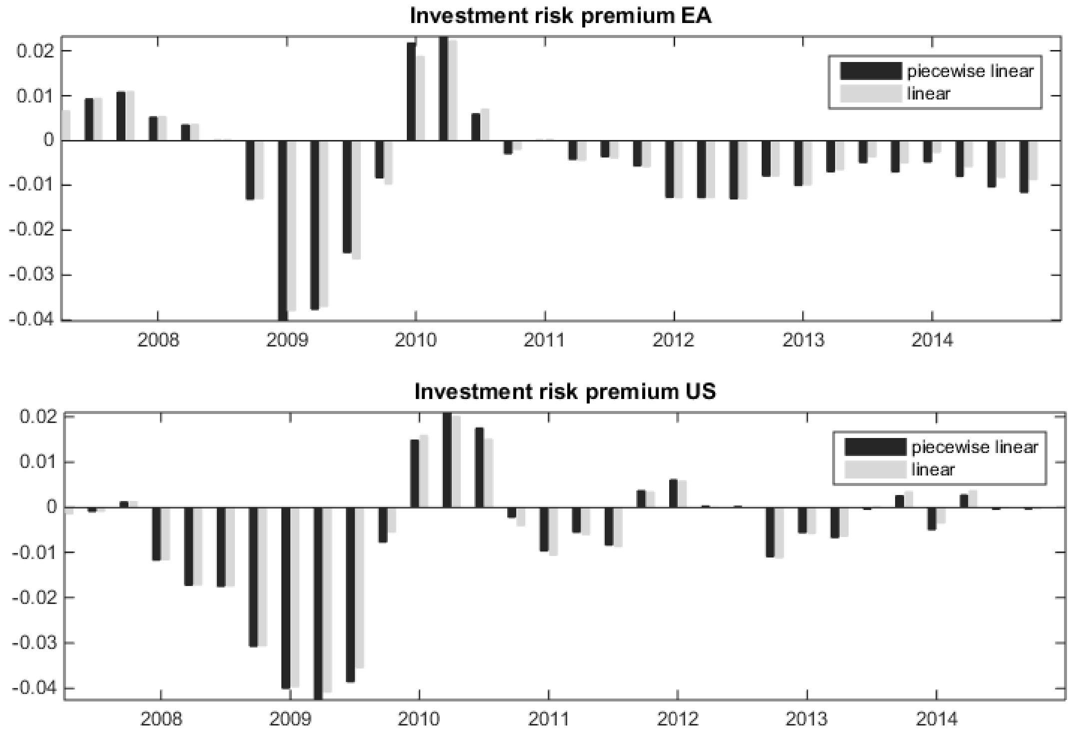


Figure 3. Contribution of investment risk premia shocks to yoy GDP growth in EA and US. Comparison of linear and piecewise linear solution

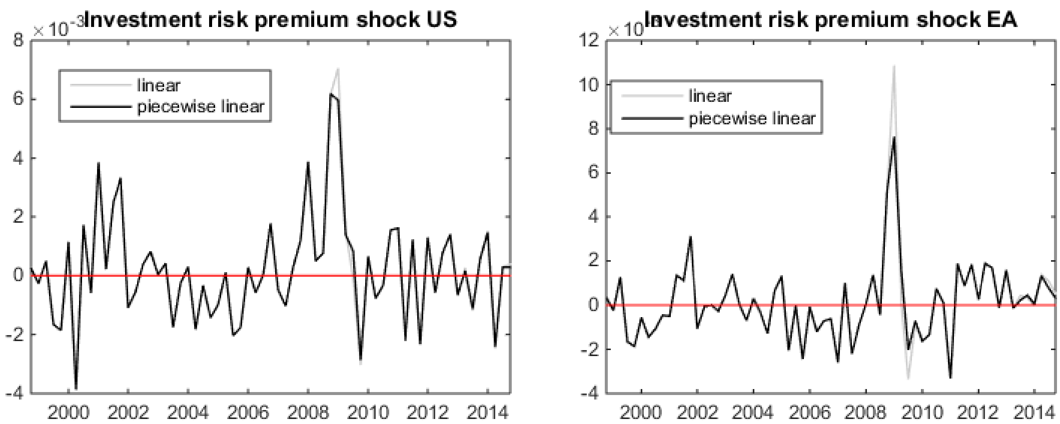


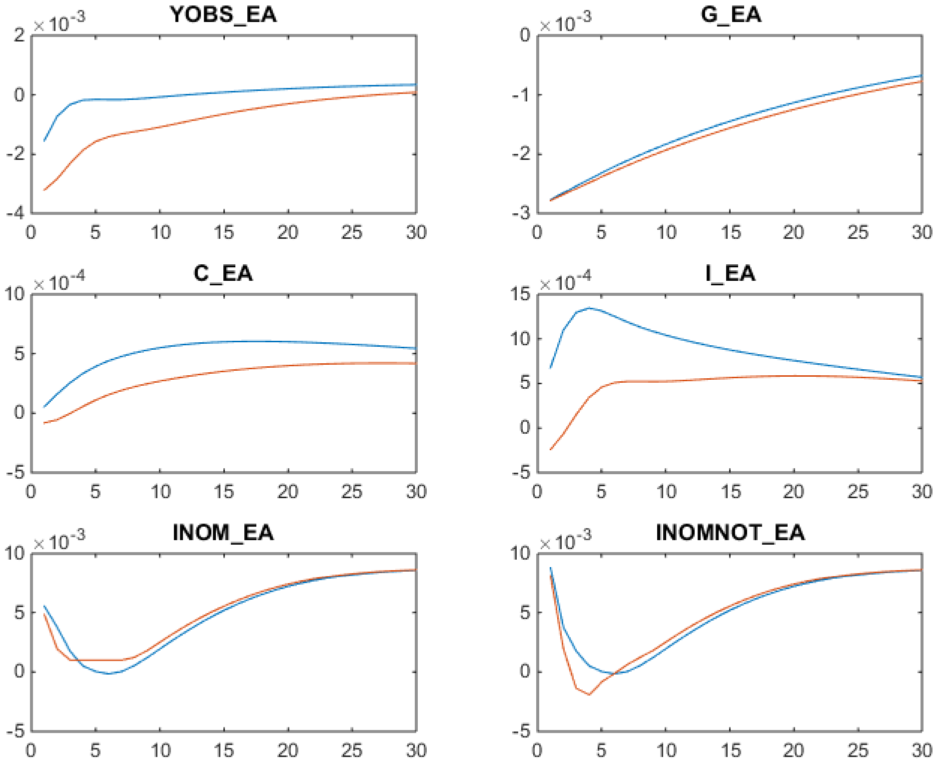
Figure 4. Smoothed estimate of innovations to the investment risk premia AR(1) processes.

D.3 Fiscal multipliers/IRFs under constrained regimes

We perform IRFs with ZLB consistent with the estimated timing and duration of the constrained regimes.

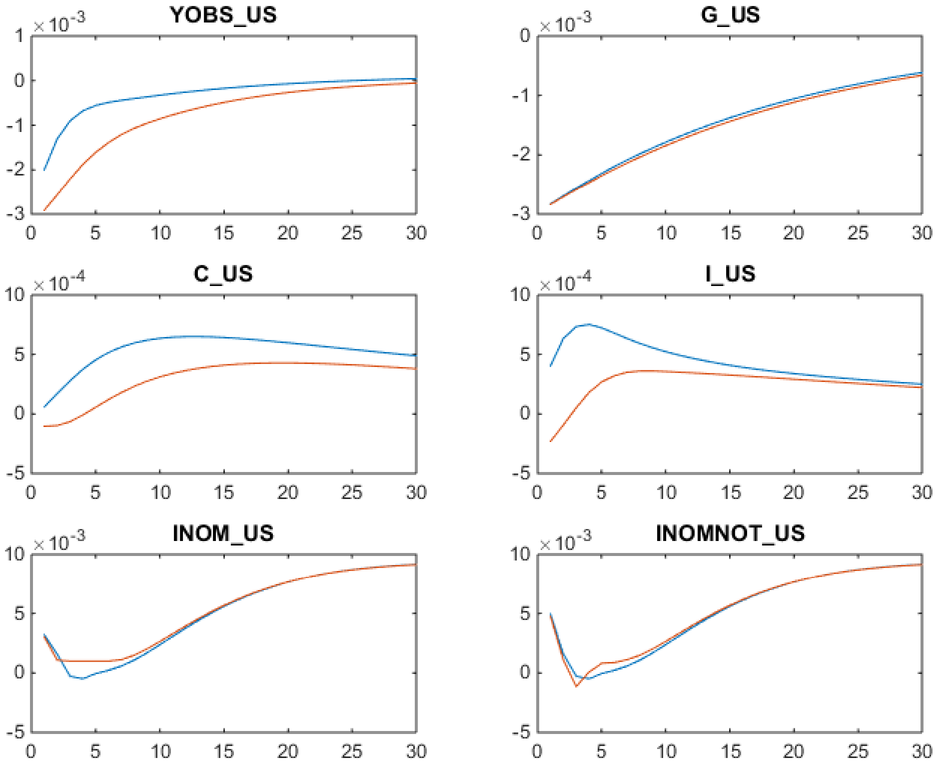
As an example, we perform counterfactual exercises as follows. Using as starting point the smoothed variables in 2008q4, we shut off all fiscal shocks and simulate the model with all other shocks.

We perform another simulation adding a negative government spending shock of -0.25% of quarterly GDP. The difference between the two simulations provides the IRF of a government spending shock under a constrained regime. For both EA and US the multiplier becomes bigger than one and fiscal consolidation generates a *comovement* of consumption and investment with government spending for some periods at the beginning of the simulations.



Negative fiscal shock of 0.25% of GDP in EA in 2009q1, on top of all the other historical shocks. Blue is the linear model, red is the piecewise linear one.

INOM = nominal int. rate; INOMNOT = shadow int. rate



Negative fiscal shock of 0.25% of GDP in US in 2009q1, on top of all the other historical shocks. Blue is the linear model, red is the piecewise linear one.

INOM = nominal int. rate; INOMNOT = shadow int. rate

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