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ISSN 1502-819-0 (online)
ISBN 978-82-7553-939-5 (online)

Business Cycles in an Oil Economy: Lessons from Norway*

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October 2016

Abstract

The recent oil price fall has created concern among policy makers regarding the consequences of terms of trade shocks for resource-rich countries. This concern is not a minor one – the world's commodity exporters combined are responsible for 15–20% of global value added. We estimate a two-country New Keynesian model in order to quantify the importance of oil price shocks for Norway – a large, prototype petroleum exporter. Domestic supply chains link mainland (non-oil) Norway to the off-shore oil industry, while fiscal authorities accumulate income in a sovereign wealth fund. Oil prices and the international business cycle are jointly determined abroad. These features allow us to disentangle the structural sources of oil price fluctuations, and how they affect mainland Norway. The estimated model provides three important results: First, pass-through from oil prices to the oil exporter implies up to 20% higher business cycle volatility. Second, the majority of spillover effects stem from non-oil disturbances such as innovations in international investment efficiency. Conventional oil market shocks, in contrast, explain at most 10% of the Norwegian business cycle. Third, the prevailing fiscal regime provides substantial protection against external shocks while domestic supply linkages make the oil exporter more exposed.

*This working paper should not be reported as representing the views of Norges Bank. The views expressed are those of the authors and do not necessarily reflect those of Norges Bank. We would like to thank Martín Uribe, Jordi Galí and Lars E. O. Svensson for helpful comments and discussions. We are also grateful for valuable input by discussants and participants in seminars and workshops hosted by the Bank for International Settlements, Deutsche Bundesbank, Banque de France, and Norges Bank. This work is part of the Norges Bank project Review of Flexible Inflation Targeting (ReFIT).

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1 INTRODUCTION

What drives the business cycle in commodity economies? Declining commodity prices, in particular the massive drop in oil prices, have sparked renewed interest in this question. The concern among market participants and policy makers is not a minor one. Figure 1, taken from the October 2015 Fiscal Monitor Report by the IMF (IMF, 2015), shows that countries relying on non-renewable commodity exports account for a substantial fraction of global economic activity. Thus, understanding interactions between commodity prices and the business cycle of commodity exporters is important for all countries with a stake in international trade. Still, our knowledge about these interactions is limited. Most business cycle research either abstracts from the role of commodities all together, or focuses on commodity users rather than commodity producers. Absence of commodities is particularly evident in the literature using estimated dynamic stochastic general equilibrium (DSGE) models.[1] This is problematic because these models are widely used for projections and policy analysis by most central banks (as well as other policy institutions).

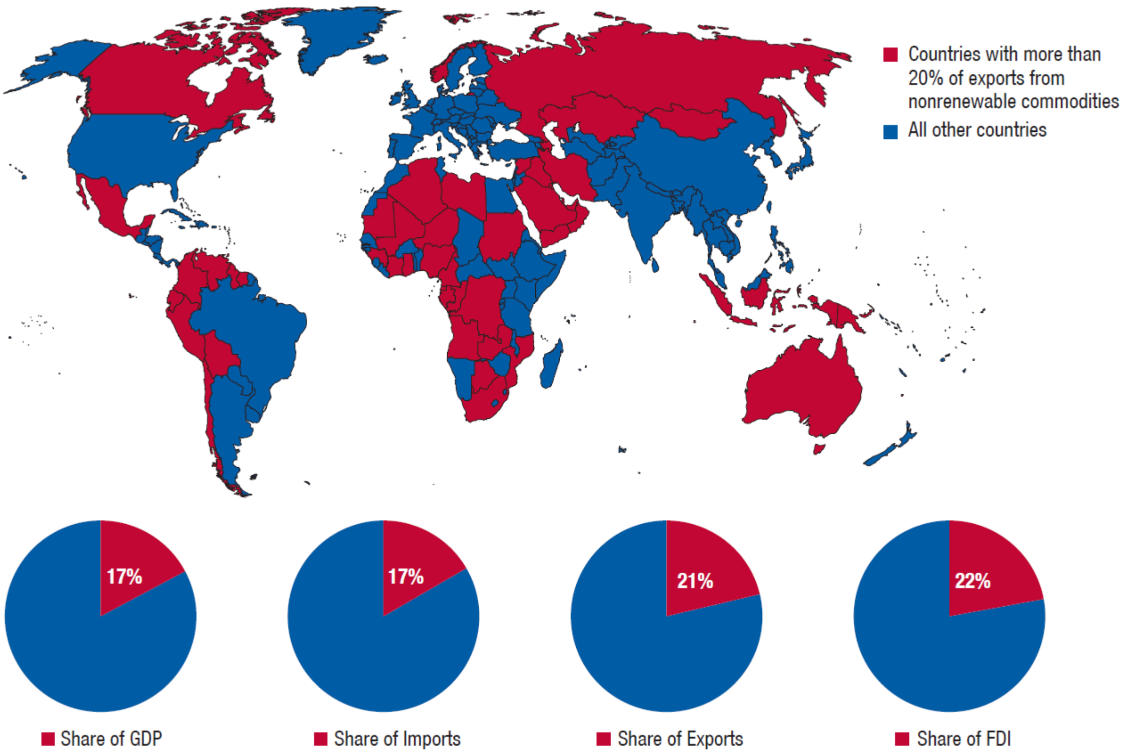
This paper quantifies – through the lenses of an estimated DSGE model – the importance of international oil price shocks for Norway. We believe the Norwegian economy is interesting for two reasons: First, Norway is a highly specialized commodity exporter, with petroleum accounting for 20–25% of GDP and almost 50% of total exports. Second, the economic stabilization policy in Norway has attracted significant international interest, in particular the management and spending of petroleum revenues. Norwegian petroleum revenues are saved in a sovereign wealth fund – the Government Pension Fund Global (GPFG) – which invests solely in international assets.[2] The fund has grown tremendously the last 15 years, both in absolute value and as a share of mainland GDP (see Figure C.1). About 4% of the fund's value is used every year to finance public budget deficits. One contribution of this paper is to evaluate, within the DSGE framework, whether that particular policy has been able to absorb global oil price fluctuations.

Our structural model builds on the one developed by Bergholt and Seneca (2015), and contributes along several dimensions. First, we model the global economy explicitly (assuming optimizing behavior in international markets) rather than its reduced form vector autoregressive (VAR) representation. This allows us to identify domestic responses to a range of international shocks, in addition to the oil shocks considered by e.g. Kilian (2009). Our approach is motivated by Bodenstein, Guerrieri, and Kilian (2012), who argue that "no two structural shocks induce the same monetary policy response [in the US economy], even after controlling for the impact response of the real price of oil". We suppose that the same logic applies to oil-exporting countries. Second, to understand sectoral

[1] Prominent examples without any role for commodities include Adolfson, Laséen, Lindé, and Villani (2007, 2008), Justiniano, Primiceri, and Tambalotti (2010, 2011), and Smets and Wouters (2003, 2007), while Bodenstein and Guerrieri (2012), Kormilitsina (2011) and Nakov and Pescatori (2010) estimate the effects of oil price shocks on the U.S. economy (which, up until recently, was a large net oil importer).

[2] The fund has not, despite its name, any formal pension liabilities. It was established in order to smooth the use of petroleum revenues over time, safeguard Norways' wealth for future generations, and provide room for fiscal policy in periods of economic contraction (http://www.nbim.no/en/the-fund/about-the-fund/).

Figure 1: The role of non-renewable commodity exporters in the global economy



Sources: BP Statistical Review of World Energy 2015, Institutional Investor's Sovereign Wealth Center, Sovereign Wealth Fund Institute, U.S. Geological Survey.

dynamics we distinguish between firms in the petroleum sector, in manufacturing (non-oil traded sector), and in services (non-traded sector). This is important because oil price fluctuations might create sectoral reallocations and trade-offs for policy makers.[3] These trade-offs are at the heart of the current policy debate in many commodity countries. Following Bergholt (2014, 2015), sectoral dynamics in our model are enriched by a supply chain where mainland firms provide productive inputs to the oil industry. This supply chain, we argue, represents a new and economically important transmission channel in the literature. Third, we derive dynamics in oil markets from first principles. In the short run, costly factor adjustments and utilization of existing fields imply relatively inelastic oil supply, in line with empirical evidence (Baumeister and Peersman, 2013a; Hamilton, 2009; Kilian, 2009). Capacity at longer horizons depends on new field investments, and investment decisions are determined by the entire expected path of break-even points – the spreads between oil prices and field costs. Thus, oil companies in the model react to all types of business cycle shocks. Our model also includes a sovereign wealth fund and a fiscal policy regime, accounting for the fact that most oil revenues accrue to the government. Finally, it is important to stress that our focus is on business cycle dynamics. For this reason we abstract from several interesting long-run issues, including the optimal depletion problem studied by Hotelling (1931) and Pindyck (1978), amongst others.

[3]See Charnavoki and Dolado (2014) and Bjørnland and Thorsrud (2016) for recent empirical evidence.

Using Bayesian techniques, we fit the model to data for Norway and EU28. The estimated model is used to address three related questions of relevance for policy: First, how important are oil price fluctuations for business cycles in mainland Norway? That is, to what extent should policy makers in Norway be concerned with oil price volatility? Second, are all oil shocks alike, or does the source of oil price volatility matter? Third, what are the main transmission channels that account for spillover to the domestic economy? This question is key for understanding the effectiveness of different policy targets. Our answer to the first question is that all oil shocks combined, including those in the domestic oil industry, explain only a modest part (10%) of the macroeconomic volatility in mainland Norway. That does not mean that oil is irrelevant. Endogenous oil price responses to non-oil shocks amplify the role of international disturbances, by about 25% according to our model. Regarding the second question we find that conclusions by Bodenstein et al. (2012) carry over to oil exporters: mainland GDP responds 12-15 times stronger when oil prices move due to some demand shocks instead of a supply shock. Highest pass-through in the short run is attributed to investment shocks, while disturbances in foreign labor markets are important at longer horizons. Finally, the model puts forward domestic supply chains as the main channel for spillover to mainland Norway. That is, higher activity in the oil industry transmits mainly because of the associated rise in factor demand. Fiscal policy, in contrast, protects the Norwegian economy against even larger fluctuations. Our model suggests that a spend-as-you-go rule would lead to a three times stronger response of GDP to oil price shocks.

Our work speaks to the literature on connections between oil price fluctuations and macroeconomic activity. Several empirical studies document systematic oil price responses to international shocks, and emphasize the importance of taking the two-way causality into account (Baumeister and Peersman, 2013b; Kilian, 2009; Kilian and Murphy, 2012). While most theoretical work ignores this view,[4] we acknowledge that oil prices are best seen as endogenous. However, our study complements the VAR literature by obtaining identification through the cross-equation restrictions embedded in a fully specified general equilibrium model. This approach facilitates inference based on a relatively large dataset, and allows us to disentangle an array of different business cycle shocks. A few recent studies estimate DSGE models with endogenous demand and supply in global oil markets (Bodenstein and Guerrieri, 2012; Nakov and Pescatori, 2010; Peersman and Stevens, 2013). While they focus on the oil-macro nexus from the point of view of oil importers (in particular the U.S. economy), our contribution is to quantify the role of oil in a representative oil exporting economy.

The rest of the paper is organized as follows. Section 2 reports how the oil exporter is affected by foreign shocks in a simple VAR. The point is to highlight some stylized facts, but also to illustrate the limited scope for structural inference based on VARs. Our benchmark DSGE model is presented in Section 3. Section 4 describes the data, calibration choices and estimation results. The quantitative analysis is presented in Section 5. In Section 6 we analyze a number of counterfactual experiments. Section 7 concludes.

[4] Examples include Kormilitsina (2011), Pieschacon (2012), and Rotemberg and Woodford (1996).

2 SOME STYLIZED FACTS

As a preliminary exercise, we start our analysis with the estimation of a simple VAR for the Norwegian economy. Our goal is to get a first, crude overview of what the data tells us about international shocks and the Norwegian business cycle. To this end we impose only a minimal set of restrictions on the system. The model is summarized below:

$$A_0 \tilde{y}_t = \sum_{j=1}^{\mathcal{J}} A_j \tilde{y}_{t-j} + B\varepsilon_t, \quad \tilde{y}_t = \begin{bmatrix} y_t^* & p_{o,t}^* & q_t & y_{o,t} & y_{m,t} & y_{s,t} \end{bmatrix}',$$
$$\varepsilon_t \text{ iid } N(0,1), \quad B \text{ diagonal}$$

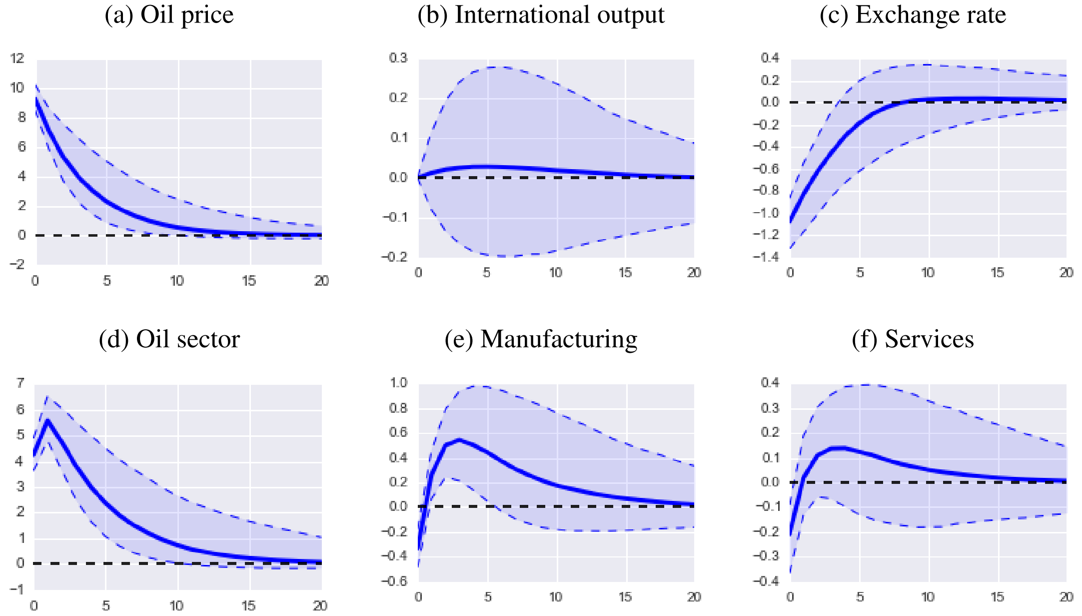
$\tilde{y}_t$ is a (period t) vector of two foreign variables, real activity y_t^* and the real oil price $p_{o,t}^*$, and four domestic variables: The real exchange rate q_t, value added in oil $y_{o,t}$, value added in manufacturing $y_{m,t}$, and value added in services $y_{s,t}$. We make two assumptions in order to obtain structural inference. First, in order to identify the international shocks, we follow Bjørnland and Thorsrud (2016) and impose a Cholesky decomposition of the impact matrix A_0. That is, we assume that only the first element of ε_t affects y_t^* on impact ($A_{0,12} = 0$). The oil price, in contrast, can be contemporaneously affected by both the first and second element of ε_t. The idea is that real activity takes time to adjust while the oil price, like any asset price, is a jump variable. At this point, it is important to emphasize that innovations to the oil price equation might be caused by oil-specific demand disturbances, by oil-specific supply disturbances, or by both. Therefore, we do not interpret oil price innovations as oil supply shocks – they are simply oil price shocks. Second, as in previous literature (Justiniano and Preston, 2010; Zha, 1999) we impose block exogeneity on the system of foreign and domestic variables. In particular, we assume that Norwegian business cycles do not affect y_t^* or $p_{o,t}^*$, either contemporaneously or with a lag (A_0 and A_j are lower block triangular). Block exogeneity is motivated by the fact that Norway is a small open economy with negligible influence on international quantities and prices. As our focus is on the domestic effects of international shocks, we do not make any assumptions regarding the sign and size of domestic responses. For the same reason we do not make any attempt to identify domestic shocks, as this would require further restrictions on the system. Our model is estimated on quarterly data from Norway and EU28, covering the period 2000Q1–2014Q4. EU28 serves as a proxy for the international economy, but should not necessarily be interpreted as a main macro driver of oil prices. Raw data are HP-filtered.[5] The VAR model is estimated with Bayesian techniques. We aim for parsimony and use a non-informative prior (Jeffreys). For the same reason we include only one lag in the VAR.[6] The lag length is also motivated by the limited amount of data available.

Impulse responses to the two identified shocks are reported in Figure 2 and Figure 3, respectively. Consider first the international oil price shock. A one standard deviation shock to the oil price equation raises oil prices by almost 10% on impact, while foreign

[5]More details about the data follow in later sections.

[6]Results are similar if we use a Normal-Wishart prior or include two lags.

Figure 2: International oil price shock



Note: Impulse responses to a one standard deviation shock to the real oil price. Calculations are based on 1000 draws from the posterior distribution. Median and 68 % credible bands.

GDP barely moves at all. These responses are consistent with previous studies (Bjørnland and Thorsrud, 2016; Peersman and Van Robays, 2012) and support the view that oil price shocks play a limited role for international activity.[7] Responses in the Norwegian economy, in contrast, are economically significant. The real exchange rate appreciates by about 1% on impact and value added increases in all three sectors. The peak response in sectoral activity takes place after about 2–4 quarters. Note that oil activity responds stronger than manufacturing while manufacturing responds stronger than services. The latter observation contrasts with the view that windfall shocks crowd out traded industries. Rather, we emphasize the importance of factor demand in the oil sector, which stimulates activity among manufacturing firms producing oil inputs (the supply chain channel).

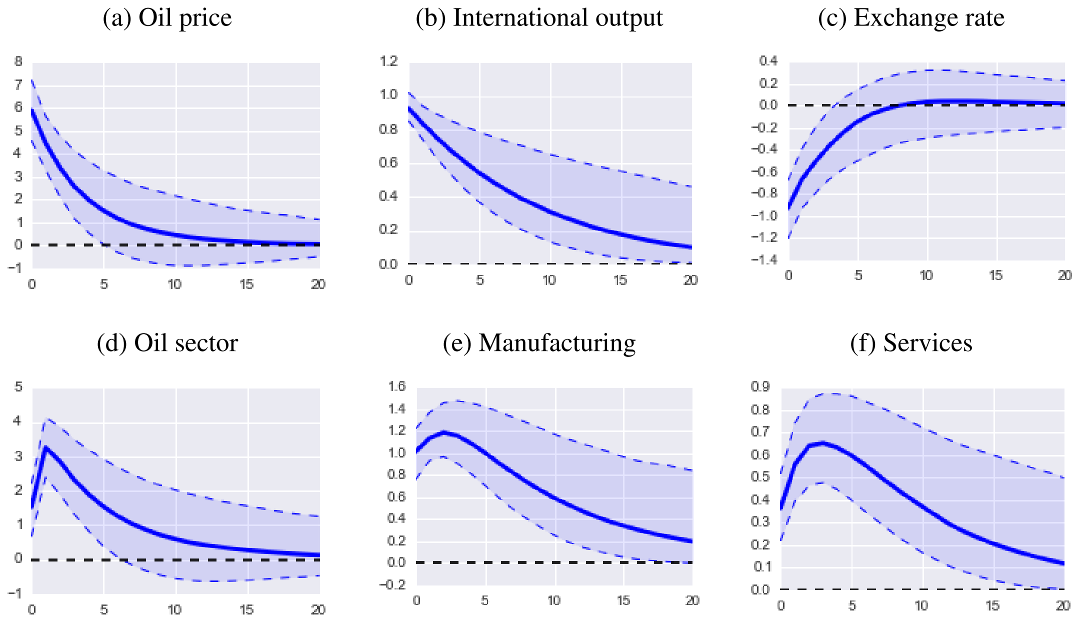
Turning to the shock to international activity, we note that sectoral value added in Norway increases substantially while the exchange rate appreciates.[8] Again, there is a ranking of elasticities: GDP rises more in oil than in manufacturing, and more in manufacturing than in services. Compared with the oil price shock, we see that value added reacts less in oil and more in mainland Norway. Intuitively, while rising oil prices stimulate economic activity in mainland Norway after both shocks, the rise in international activity delivers an additional impulse – higher foreign demand for Norwegian non-oil goods.

In sum, we draw three conclusions based on the preliminary VAR analysis: First,

[7] Another plausible explanation is that oil-specific demand and supply disruptions have offsetting effects on international activity. As stated earlier, our oil price shock is likely a mix of the two.

[8] Bjørnland and Thorsrud (2016) and Peersman and Van Robays (2012) also find that the Norwegian currency appreciates conditional on international activity shocks. The DSGE model presented later attributes this appreciation to higher oil prices.

Figure 3: International activity shock



Note: Impulse responses to a one standard deviation shock to international activity. Calculations are based on 1000 draws from the posterior distribution. Median and 68 % credible bands.

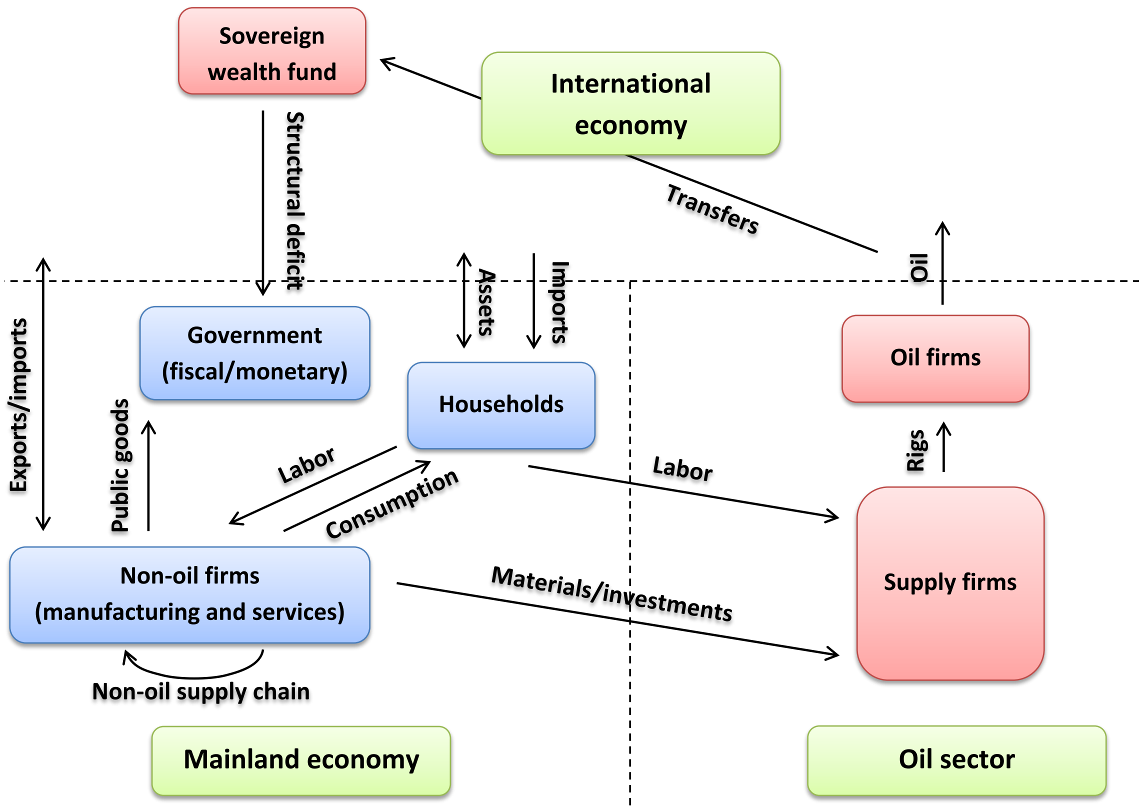
international oil price and activity shocks, in the way they are defined here, cause positive spillover to the Norwegian economy. Second, both shocks are associated with a rather strong exchange rate appreciation. Third, both shocks are associated with higher (positive) pass-through to oil than to non-oil industries. Our preliminary conclusions rest upon a minimal set of identifying restrictions. However, these restrictions do not facilitate much economic inference. Important questions remain unanswered, including: (i) what are the structural disturbances underlying our VAR innovations? (ii) what are the main transmission channels at play? These questions are key for our understanding of the interaction between mainland Norway and international business cycles, and for the way policy should respond to oil price volatility. This is why the rest of the paper is devoted to the role of international shocks from the viewpoint of a medium-scale DSGE model.

3 The DSGE model

In this section we describe our macroeconomic model for a prototype, resource-rich economy. The model is based on that developed in a companion paper by Bergholt and Seneca (2015), which in turn builds on Bergholt (2015). At the core is a two-country version of Smets and Wouters (2007), where one country (home) is small and oil-intensive, while the other (foreign) represents the global economy.[9] Here we only provide a brief summary of the non-oil block, as our focus is on oil and the oil exporter's exposure to global shocks. The full model is described in more detail in the appendix.

[9]Domestic shocks do not influence the rest of the world, which is treated as a closed economy.

Figure 4: A bird's eye view of the home economy



3.1 The oil exporter – an overview

A bird's eye view of the home economy is provided in Figure 4. It consists of a non-oil block – the mainland economy – and an off-shore oil industry. In contrast to Adolfson et al. (2007), the non-oil supply block consists of two sectors: manufacturing (subscript m) and services (subscript s). These differ along several dimensions, but an important one is the relatively high trade intensity in manufacturing. Our two-sector structure facilitates analysis of resource movement effects as emphasized by e.g. Corden and Neary (1982).

Households, living in the mainland economy, finance their consumption and investment expenditures by means of labor income, returns on financial investments, and transfers from the government. Consumption decisions are subject to external habits, and capital accumulation to investment adjustment costs. Aggregate consumption and investment baskets are CES functions of manufactured goods and services. Consumption is relatively service-intensive, implying a lower import share in consumption than investment. Production in the mainland economy requires labor, capital and intermediate inputs produced by other firms. Some intermediate inputs are imported – a direct cost channel for exchange rate fluctuations. Moreover, as with final goods the intermediate input basket is a CES function of manufactured goods and services. This gives rise to cross-sectoral spillover of shocks. Several frictions are included in the model: wage and price setting is subject to monopolistic competition and nominal stickiness à la Calvo (1983). Non-optimized wages and prices are indexed to past inflation. International trade is invoiced in buyer's currency (local currency pricing), implying imperfect exchange rate pass-through at business cycle frequencies. International capital flows are limited by a sovereign risk premium that depends on the net external position. The mainland economy provides productive resources (labor, capital and materials) to oil supply firms (subscript c) – an important demand channel for spillover of oil shocks. Oil investments produced by supply firms are used by a competitive oil extraction company (subscript o) to maintain and develop new oil rigs. Crude oil is extracted by operative rigs and sold in international markets. Finally, we include in the model a government sector that obtains tax revenues from oil activity. These revenues are invested abroad in a sovereign wealth fund. Returns from the fund are used to finance public expenditures. The rest of this section is devoted to details in the oil industry and the public sector.

3.2 The oil industry

3.2.1 Supply firms

Activity in the supply chain is subject to a constant returns to scale production function:

$$Y_{c,t} = Z_{c,t} X_{c,t}^{\phi_c} N_{c,t}^{\psi_c} K_{c,t}^{1-\phi_c-\psi_c}, \tag{1}$$

where $Y_{c,t}$ represents output, $X_{c,t}$ intermediate inputs, $N_{c,t}$ labor hours, $K_{c,t}$ capital, while $Z_{c,t}$ is a productivity shifter. $X_{c,t}$ is a composite of inputs produced in manufacturing and services, respectively: $X_{c,t} = X_{mc,t}^{\zeta_c} X_{sc,t}^{1-\zeta_c}$, where $X_{mc,t}$ ($X_{sc,t}$) denotes supply firms' use of materials produced in the manufacturing (service) sector. In turn, materials from sector $j \in \{m, s\}$ are a composite of domestic and imported goods (subscripts H and F): $X_{jc,t} = \left[\alpha_j^{\frac{1}{\eta}} X_{Hj,t}^{\frac{\eta-1}{\eta}} + (1-\alpha_j)^{\frac{1}{\eta}} X_{Fj,t}^{\frac{\eta-1}{\eta}}\right]^{\frac{\eta}{\eta-1}}$.[10] The representative supply chain firm maximizes profits given by $P_{rc,t}Y_{c,t} - P_{c,t}^{x}X_{c,t} - \Omega_{c,t}N_{c,t} - R_t^k K_{c,t}$, taking prices as given.[11] Optimality conditions in factor markets follow:

$$\begin{aligned} N_{c,t} &= \frac{\psi_c}{\phi_c}\left(\frac{\Omega_{c,t}}{P_{rc,t}^{x}}\right)^{-1} X_{c,t} \qquad & K_{c,t} &= \frac{1-\phi_c-\psi_c}{\phi_c}\left(\frac{R_t^k}{P_{rc,t}^{x}}\right)^{-1} X_{c,t} \\ X_{mc,t} &= \frac{\zeta_{mc}}{\zeta_{sc}}\left(\frac{P_{rm,t}}{P_{rs,t}}\right)^{-1} X_{sc,t} \qquad & X_{Hj,t} &= \frac{\alpha_j}{1-\alpha_j}\left(\frac{P_{rHj,t}}{P_{rFj,t}}\right)^{-\eta} X_{Fj,t}, \quad j \in \{m, s\} \end{aligned} \tag{2}$$

Value added in the supply chain is defined as output net of intermediate inputs:

$$VA_{c,t} = P_{rc,t}Y_{c,t} - P_{rc,t}^{x}X_{c,t} = (1-\phi_c)\,P_{rc,t}Y_{c,t}.$$

[10] The corresponding price indexes for $X_{c,t}$ and $X_{jc,t}$ are, measured in consumption units, $P_{rc,t}^{x} = \frac{1}{\zeta_{mc}^{\zeta_{mc}}\zeta_{sc}^{\zeta_{sc}}} P_{rm,t}^{\zeta_{mc}} P_{rs,t}^{\zeta_{sc}}$ and $P_{rj,t} = \left[\alpha_j P_{rHj,t}^{1-\eta} + (1-\alpha_j)\,P_{rFj,t}^{1-\eta}\right]^{\frac{1}{1-\eta}}$.

[11] Non-oil firms face the same production environment, but also monopolistic competition and sticky prices.

Finally, market clearing between supply chain firms and the oil company is given by

$$I_{o,t}+a\left(U_{o,t}\right)F_{o,t}=Y_{c,t}, \tag{3}$$

where $I_{o,t}$ represents gross oil investments and $a\left(U_{o,t}\right)F_{o,t}$ are the costs associated with maintenance of operative rigs. $a\left(U_{o,t}\right)=\gamma_o^1\left(U_{o,t}-1\right)+\frac{\gamma_o^u\gamma_o^1}{2}\left(U_{o,t}-1\right)^2$ is a function of $U_{o,t}$, the utilization rate of rigs in place $F_{o,t}$ (γ_o^u is defined as $\gamma_o^u=\frac{a''(1)}{a'(1)}$).

3.2.2 Extraction firms

We use standard investment theory, similar to Peersman and Stevens (2013), to characterize how oil extraction takes place. Oil extraction requires both crude oil and rig services:

$$O_t=Z_{o,t}Q_{o,t}^{1-\alpha_o}\bar{F}_{o,t}^{\alpha_o}, \tag{4}$$

where O_t is oil output, $Q_{o,t}$ is available oil in the ground, and $\bar{F}_{o,t}=U_{o,t}F_{o,t}$ represents the effective rigs currently in operation. $Z_{o,t}$ is a conventional productivity shock specific to oil production. As our focus is on business cycle dynamics, we abstract from the issue of depletion as well as the law of motion for new field discoveries. This implies that $Z_{o,t}$ and $Q_{o,t}$ are observationally equivalent and we treat $Q_{o,t}$ as constant. Thus, $\alpha_o\in[0,1)$ implies decreasing returns to scale, capturing that oil in the ground is a fixed factor of production. We also stress that $F_{o,t}$, the number of rigs in place, is given in period t. Therefore, the only way to change output in the very short run is by adjusting $U_{o,t}$. The representative oil company seeks to maximize an expected stream of cash flows:

$$\mathbb{E}_t\sum_{s=t}^{\infty}\mathcal{Z}_{t,s}\Pi_{o,s}=\mathbb{E}_t\sum_{s=t}^{\infty}\mathcal{Z}_{t,s}\left[\mathcal{S}_sP_{ro,s}^*O_s-P_{rc,s}a\left(U_{o,s}\right)F_{o,s}-P_{rc,s}I_{o,s}\right],$$

where $\mathcal{Z}_{t,s}$ is the stochastic discount factor between period t and s, $\mathcal{S}_t$ is the real (consumption) exchange rate, and $P_{ro,t}^*$ is the real oil price. The latter is defined in foreign currency and relative to the international consumer price level. The expression above makes it clear that cash flows are large in circumstances with i) strong foreign currency ($\mathcal{S}_t$), ii) high oil price ($P_{ro,t}^*$), and iii) high oil output (O_t). But also factor costs matter. High activity in the future might call for less positive margins today. Taking the oil price and factor costs as given, the oil company makes decisions along two dimensions. First, it makes an intertemporal decision regarding the accumulation of future production capacity. Second, it makes an intratemporal decision, given current capacity, regarding the level of output. The maximization problem is subject to a law of motion for active rigs:

$$F_{o,t+1}=\left(1-\delta_o\right)F_{o,t}+Z_{F,t}\left[1-\Psi_o\left(\frac{I_{o,t}}{I_{o,t-1}}\right)\right]I_{o,t}. \tag{5}$$

The function $\Psi_o\left(\frac{I_{o,t}}{I_{o,t-1}}\right)=\frac{\epsilon_O}{2}\left(\frac{I_{o,t}}{I_{o,t-1}}-1\right)^2$ captures adjustment costs associated with changes in oil investments. Regarding the efficiency shock $Z_{F,t}$, one might interpret it as an oil field discovery shock. A positive innovation leads to more operative rigs tomorrow for any given level of investment activity today. Finally, the parameter δ_o measures the degree to which oil capital depreciates over time. Optimality conditions for the oil producer with respect to $F_{o,t+1}$ and $I_{o,t}$ are stated below:

$$\mathcal{Q}_{o,t} = \beta \mathbb{E}_t \frac{\Lambda_{t+1}}{\Lambda_t} \left[\alpha_o \frac{\mathcal{S}_{t+1} P^*_{ro,t+1} O_{t+1}}{F_{o,t+1}} - P_{rc,t+1} a \left(U_{o,t+1} \right) + \mathcal{Q}_{o,t+1} \left(1 - \delta_o \right) \right] \tag{6}$$

$$\begin{aligned} P_{rc,t} = \mathcal{Q}_{o,t} Z_{F,t} & \left[1 - \Psi_o \left(\frac{I_{o,t}}{I_{o,t-1}} \right) - \Psi'_o \left(\frac{I_{o,t}}{I_{o,t-1}} \right) \frac{I_{o,t}}{I_{o,t-1}} \right] \\ & + \beta \mathbb{E}_t \frac{\Lambda_{t+1}}{\Lambda_t} \mathcal{Q}_{o,t+1} Z_{F,t+1} \Psi'_o \left(\frac{I_{o,t+1}}{I_{o,t}} \right) \left(\frac{I_{o,t+1}}{I_{o,t}} \right)^2 \end{aligned} \tag{7}$$

Equation (6) determines the properly discounted present marginal value of installed oil rigs $\mathcal{Q}_{o,t}$. Λ_t is the marginal utility of consumption and β is the time discount factor. More rigs tomorrow will, at the margin, add revenues $\alpha_o \frac{\mathcal{S}_{t+1} P^*_{ro,t+1} O_{t+1}}{F_{o,t+1}}$. At the same time the maintenance costs increase by the amount $P_{rc,t+1} a \left(U_{o,t+1} \right)$. $\mathcal{Q}_{o,t+1} \left(1 - \delta_o \right)$ represents the continuation value net of rig depreciation. Equation (7) aligns the marginal cost of new investments, $P_{rc,t}$, with the marginal gain of having more rigs in the next period. The first term represents next period's rig increase net of adjustment costs. The second term reflects that more investments today relaxes the need for investments in the future. Optimal rig utilization is given by a static condition:

$$\alpha_o \mathcal{S}_t P^*_{ro,t} \frac{O_t}{U_{o,t}} = P_{rc,t} a' \left(U_{o,t} \right) F_{o,t}. \tag{8}$$

Equation (8) states that the oil company increases the utilization of rigs up until the point where marginal revenues from higher utilization equals marginal costs. The optimality conditions above summarize how the oil company operates in the model. In the short run, it changes output by adjusting the rate to which active rigs in place operate. In the long run, it undertakes investment projects in order to accumulate future production capacity. This leads to highly forward-looking decision-making. Rather than the current oil price, the oil company cares about the entire expected price path. The forward-looking behavior breaks the contemporaneous link between current oil prices and investment decisions.

3.3 THE PUBLIC SECTOR

Government activity in the model has both fiscal and monetary dimensions. On the fiscal side, the government finances expenditures with tax revenues from the mainland economy, transfers from the sovereign wealth fund, and new public debt. On the monetary side, the central bank chooses an interest rate path based on the monetary policy regime in place. In line with the Norwegian tax system, there is a neutral tax rate τ_o on petroleum income. Public revenues from petroleum activities, $TR^o_t = \tau_o \Pi_{o,t}$, are transferred to a sovereign wealth fund which invests solely in international markets. The law of motion for the sovereign wealth fund is given by

$$SWF_{t+1} = (1-\rho_o)\, R^*_{t-1}\frac{\mathcal{E}_t}{\mathcal{E}_{t-1}}\Pi_t^{-1}SWF_t + TR^o_t, \tag{9}$$

where $\mathcal{E}_t$ is the nominal exchange rate and R^*_{t-1} is the gross return in foreign currency on the previous period's fund allocations. We assume, as is the case in Norway, that fiscal authorities finance public deficits with a fraction ρ_o of the fund's value each period. Thus, the structural public budget deficit is $SBD_t = \rho_o R^*_{t-1}\frac{\mathcal{E}_t}{\mathcal{E}_{t-1}}\Pi_t^{-1}SWF_t$. The intertemporal budget constraint for the government follows as

$$P^g_{r,t}G_t - D_{t+1} = T_t - R_{t-1}D_t\Pi_t^{-1} + SBD_t,$$

where T_t is a lump-sum tax and D_t is public debt.[12] Public spending is a function of the state of the economy. We specify a Taylor-type rule:

$$\frac{G_t}{G} = \left(\frac{G_{t-1}}{G}\right)^{\rho_g}\left[\left(\frac{\Pi_t}{\Pi}\right)^{\rho_{g\pi}}\left(\frac{GDP_t}{GDP_{t-1}}\right)^{\rho_{gy}}\left(\frac{SBD_t}{SBD}\right)^{\rho_{gd}}\right]^{1-\rho_g}. \tag{10}$$

The parameters ρ_{g_π} and ρ_{g_y} can be positive, implying countercyclical forces in the evolution of public demand. As with private consumption, the public consumption basket is a CES function of manufactured goods and services. Cost-minimizing demand schedules are given by $G_{j,t} = \xi^g_j\left(\frac{P_{rj,t}}{P^g_{r,t}}\right)^{-1}G_t$ for $j \in \{m,s\}$, where $P^g_{r,t}$ is the real price of public consumption. Regarding monetary policy, we assume in the baseline model that the central bank follows a flexible inflation targeting regime, approximated by a Taylor-type interest rate rule:

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\rho_r}\left[\left(\frac{\Pi_t}{\Pi}\right)^{\rho_\pi}\left(\frac{GDP_t}{GDP_{t-1}}\right)^{\rho_y}\left(\frac{\mathcal{E}_t}{\mathcal{E}_{t-1}}\right)^{\rho_e}\right]^{1-\rho_r}Z_{R,t}. \tag{11}$$

The inclusion of nominal exchange rates in the policy rule is motivated by e.g. Lubik and Schorfheide (2007), who find that monetary policy in some small open economies responds to exchange rate movements. Finally, $Z_{R,t}$ is a monetary policy shock assumed to follow a white noise process.

3.4 Other domestic relations

We highlight two additional equations in the model of particular relevance for spillover from oil markets. First, aggregate mainland GDP is the sum of value added in manufacturing and services:

$$GDP_t = \sum_{j\in\{m,s\}} VA_{j,t} = \sum_{j\in\{m,s\}}\left(P_{rHj,t}A_{Hj,t} + P^*_{rHj,t}A^*_{Hj,t} - P^x_{rj,t}X_{j,t}\right)$$

[12] Without loss of generality we assume balanced budgets period by period. Moreover, our specification of the fiscal regime, in particular the calibration of ρ_o, ensures a stationary sovereign wealth fund.

$$= C_t + P^i_{r,t} I_t + P^g_{r,t} G_t + TB_t + P^x_{rc,t} X_{c,t}.$$

The first line defines GDP according to the production approach. $P_{rHj,t}$ is the real sector j price on domestically produced goods supplied in domestic markets, $P^*_{rHj,t}$ is the corresponding price on exports, while $A_{Hj,t}$ and $A^*_{Hj,t}$ represent domestic and foreign absorption respectively. $P^x_{rj,t} X_{j,t}$ denotes sectoral expenditures on intermediate inputs. The second line defines GDP according to the expenditure approach – the sum of private and public consumption, investments, and net exports. $P^x_{rc,t} X_{c,t}$ represents the direct supply chain impulse to mainland GDP. There are also indirect effects – higher supply chain activity raises factor prices and investment demand. The second equation of interest is a no-arbitrage condition in international asset markets:

$$\mathbb{E}_t \left\{ \beta \frac{\Lambda_{t+1}}{\Lambda_t} \Pi^{-1}_{t+1} \left[R_t - \frac{\mathcal{E}_{t+1}}{\mathcal{E}_t} R^*_t \Upsilon \left(NFA_{t+1}, Z^*_{B,t} \right) \right] \right\} = 0.$$

This relationship implies that the expected returns on additional savings in domestic and foreign assets are the same. As in Adolfson et al. (2007), we include an endogenous risk premium on foreign returns; $\Upsilon \left(NFA_{t+1}, Z^*_{B,t} \right) = \exp \left(-\epsilon_B \frac{NFA_{t+1} - NFA}{VA} \right) Z^*_{B,t}$. The premium depends on the total net foreign asset position NFA_{t+1} (in deviation from steady state and relative to total value added), which is the sum of private balances and the sovereign wealth fund. This is relevant because oil (and other) shocks influence net foreign assets, and through the premium, the exchange rate.[13]

3.5 Oil in the international economy

While we abstract from domestic oil demand, internationally oil enters both in the aggregate consumption basket and as a factor of production. Optimal demand for oil by foreign households and firms, respectively, is given below:

$$O^*_{c,t} = \frac{\xi^*_o}{1 - \xi^*_o} P^{*-\eta^{od}}_{ro,t} C^*_t \qquad O^*_{yj,t} = \phi^*_o \left(\frac{P^*_{ro,t}}{RMC^*_{j,t}} \right)^{-\eta^{od}} Y^*_{j,t}, \;\; j \in \{m, s\}. \qquad (12)$$

The first equation expresses the trade-off between oil and core consumption C^*_t for foreigners. η^{od} is the substitution elasticity and ξ^*_o is the weight on oil in the aggregate consumption basket. The second equation shows international firms' optimal oil demand as a function of relative prices, sectoral marginal (non-oil) costs, and gross output. ϕ^*_o is the oil share in output (assumed to be the same in both sectors). The two equations above link oil markets to the rest of the global economy, implying that oil price fluctuations have global demand effects. Besides the exceptions just highlighted, we model the foreign block as a closed economy version of the oil exporter (although, in the international economy, oil accounts for a much smaller share of GDP). International oil supply, for instance, is given by the foreign counterpart of equation (8). This completes our model description.

[13]The risk premium also ensures that the steady state is well defined, see Schmitt-Grohé and Uribe (2003).

4 Estimation

Before taking the model to the data, we solve the dynamic system using standard methods. The solution procedure involves several steps:[14] first, derive a recursive solution for the non-stochastic steady state. Second, calculate a log-linear approximation of the model around this steady state. Third, solve the resulting system of rational expectations equations in order to obtain a linear state-space representation. This representation is used for estimation. We estimate the DSGE model using Bayesian techniques. The approach has been popularized by e.g., An and Schorfheide (2007), Geweke (1999), and Smets and Wouters (2003, 2007).

4.1 Data

Our dataset is quarterly and covers the period 2000Q1–2014Q4. The selected sample length is motivated on two grounds. First, several time series, in particular those from the international economy, are available only from 2000Q1. Second, the millennium came with several institutional breaks in the Norwegian economy: the sovereign wealth fund started to accumulate, the oil industry became a significant fraction of total GDP, and an explicit inflation target was introduced as the new monetary policy regime. We use macroeconomic time series from Norway, EU28, and the oil price in order to inform our model. EU28 serves as a proxy for the international economy from a Norwegian point of view. The source for our data is Statistics Norway for Norwegian variables, and Eurostat for European data. Our non-oil observables are (for both Norway and EU28): Sectoral value added, core private consumption, investments, wages, consumer prices, and interest rates. Wages and prices are observed as nominal year-on-year growth rates. Domestic CPI and population are used as deflators.[15] We also include some oil-specific variables, that is the oil price (Brent, from the FRED database), Norwegian oil production, and Norwegian oil investments (both from Statistics Norway). This leaves us with 18 observable variables – 8 domestic, 2 off-shore, and 8 international. The variables display several different trends not accounted for by the model. Thus, in line with common practice in the literature, we filter out trends in all quantity series. We choose to work with a backward-looking HP-filter ($\lambda = 1600$) which, consistent with agents' expectations in the model, does not exploit ex-post information about future data realizations. More details about the construction of observable variables are found in the appendix.

4.2 Calibration

We calibrate a subset of the parameters in the model. Calibrated values are given in Table 1. The time discount factor implies an annual real interest rate of about 4%. A unitary intertemporal elasticity is consistent with balanced growth. The Frisch elasticity φ^{-1}, markup parameters ϵ_w and ϵ_p, and the depreciation rate δ, are all set to standard values.

[14]See the appendix for further details regarding the solution procedure.

[15]The labor force, an alternative and perhaps better deflator, is not available for the EU28 countries.

Table 1: Calibration

		Aggregate			
β	Time discount factor	0.99	ϵ_w, ϵ_p	Monopoly markup	0.2
σ	Inv. intertemporal elasticity	1	δ	Capital depreciation	0.025
φ	Inv. labor supply elasticity	2	ϵ_B	Risk premium elasticity	0.005
τ_o	Tax rate on oil	0.8	ρ_o	Average fiscal transfer	0.04
ρ_g	Fiscal persistence	0.9	ρ_{g_π}	Fiscal response to π	0.1
ρ_{g_y}	Fiscal response to GDP	0.5	ρ_{g_d}	Fiscal response to debt	-0.01
ξ_o^*	Oil intensity, int. cons.	0.012	ϕ_o^*	Oil intensity, int. prod.	0.011
		Sectoral			
		(M), (S)			(M), (S)
ϕ_j	Materials share, gross output	0.50, 0.40	ξ	Consumption shares	0.40, 0.60
ψ_j	Labor share, gross output	0.35, 0.45	ξ_g	Public consumption shares	0.35, 0.65
γ_j^{ex}	Trade share, sector GDP	0.60, 0.21	ϖ	Investment shares	0.70, 0.30
ζ_j	I-O matrix materials	$\begin{bmatrix} 0.7 & 0.3 \\ 0.3 & 0.7 \end{bmatrix}$			
		Oil			
α_o	Crude oil share, gross output	0.32	ϖ_o	Supply investment shares	0.54, 0.46
ϕ_o	Materials share, supply chain	0.48	ζ_o	Supply material shares	0.48, 0.52
ψ_o	Labor share, supply chain	0.22			

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

The risk premium elasticity is low, as in Adolfson et al. (2007). We use national accounts data to match the average share of oil and public expenditures in total GDP. The tax rate on oil is set to 0.8 (the actual tax rate is 0.78) while the average fund transfer is set to 4% (consistent with the fiscal rule in Norway). Fiscal Taylor rule parameters are chosen somewhat ad hoc and in order to get a reasonable persistence and countercyclicality of public expenditures.[16] At the same time, they ensure stationarity of public debt.

Remaining parameters are sectoral and deserve further attention. We use a rich set of sectoral data obtained from Statistics Norway and EuroStat in order to calibrate the model. We set ϕ_j, ψ_j and ζ_j in order to match the sectoral expenditure shares in input-output table 1750 for the year 2013, publicly available from Statistics Norway. Based on the same source we choose ϖ to match sectoral investment shares. Sectoral consumption shares ξ and ξ_g, as well as sectoral trade shares γ_j^{ex} and γ_j^{im}, are calibrated based on average numbers in the national accounts for our data sample. We assume same depreciation rate (δ_o) in oil as in the non-oil economy. Given this number, we choose α_o in order to match the average cost share in petroleum. ϕ_o and ψ_o are obtained directly from Statistics Norway while ζ_o and ϖ_o are taken from Eika, Prestmo, and Tveter (2010).[17] Regarding foreign sector shares, we assume the same values as in Norway due to lack of available data. However, based on data from Eurostat for EU27, we choose ξ_o^* and ϕ_o^* in order to match an oil share in GDP of 3%, and a consumption share in total oil demand of 33%.

[16] The estimation results are robust to this calibration.

[17] See their tables 4.1 and 4.2.

Table 2: Steady state ratios in the benchmark model

	Description	*Data*	*Model*
C/VA	Consumption share in aggregate GDP	0.38	0.39
I/VA	Investment share in aggregate GDP	0.21	0.21
G/VA	Public spending share in aggregate GDP	0.21	0.20
$(A_H^* + O)/\text{VA}$	Export share in aggregate GDP	0.48	0.48
A_F/VA	Import share in aggregate GDP	0.28	0.28
GDP_o/VA	Oil share in aggregate GDP	0.22	0.21
GDP_m/VA	Manufacturing share in aggregate GDP	0.29	0.33
GDP_s/VA	Service sector share in aggregate GDP	0.49	0.46
I_o/I	Oil share in aggregate investments	0.25	0.24
$O/(A_H^* + O)$	Oil share in aggregate exports	0.47	0.45
μ_m	Share of labor force in manufacturing	–	0.41
μ_s	Share of labor force in services	–	0.57
μ_o	Share of labor force in oil sector	–	0.02

Note: This table presents ratios in the non-stochastic steady state as implied by the calibration in Table 1. Data refers to corresponding sample averages in the data.

Table 2 offers a comparison of selected steady state ratios in the model with corresponding sample averages in the data. Compared with many other developed economies, Norway has a relatively low consumption share and relatively high public sector share in aggregate GDP. Note that we do not have data on labor shares across sectors. Still, the minor labor share in oil is consistent with surveys conducted by Statistics Norway.[18]

4.3 Priors and posterior estimates

Remaining parameters are estimated based on Bayesian inference. Selected prior distributions are reported in Table 3. We choose the priors based on existing open economy DSGE literature, e.g. Adolfson et al. (2007), Christiano, Trabandt, and Walentin (2011), and Justiniano and Preston (2010). Most distributions are standard but some remarks are appropriate. First, although our prior imposes symmetry across countries, the posterior does not. Second, microeconomic evidence suggests cross-sectoral variation in the degree of price stickiness (Bils and Klenow, 2004; Nakamura and Steinsson, 2008). Consistent with this view we assume a beta distribution for Calvo parameters in manufacturing that is skewed more to the left. Regarding oil-related parameters, we center the prior for oil supply and demand elasticities around 0.3. This number is in the ballpark of suggestive VAR evidence (Baumeister and Peersman, 2013a; Kilian and Murphy, 2012), although quite high compared with assumptions used in some DSGE studies (e.g. Nakov and Pescatori (2010)). Note that we estimate η^{os} directly, and use the steady state identity $\gamma_o^u \equiv \frac{a''(1)}{a'(1)} = \frac{\alpha_o}{\eta^{os}} + \alpha_o - 1$ to back out γ_o^u. Finally, wage and price markup shocks are nor-

[18]The indirect labor share, which includes labor used in the production of oil-related products, is higher both in the model and in the data.

Table 3: Prior and posterior distributions

		Prior	Posterior domestic and oil			Posterior foreign		
		Prior(P1,P2)	Mode	Mean	5%-95%	Mode	Mean	5%-95%
χ_C	Habit	B(0.70,0.10)	0.80	0.76	0.67-0.86	0.51	0.65	0.52-0.78
ϵ_I	Inv. adj. cost	G(5.00,1.00)	4.72	4.85	3.47-6.12	4.50	4.92	3.38-6.44
θ_w	Calvo wages	B(0.65,0.07)	0.77	0.77	0.71-0.85	0.76	0.71	0.64-0.79
ι_w	Indexation, π_w	B(0.30,0.15)	0.27	0.30	0.06-0.51	0.27	0.26	0.04-0.47
θ_{pm}	Calvo manu.	B(0.45,0.07)	0.65	0.66	0.58-0.73	0.41	0.44	0.36-0.53
θ_{ps}	Calvo serv.	B(0.75,0.07)	0.84	0.89	0.84-0.94	0.84	0.87	0.80-0.94
ι_p	Indexation, π_p	B(0.30,0.15)	0.17	0.29	0.07-0.50	0.12	0.19	0.02-0.35
ρ_r	Smoothing, r	B(0.50,0.10)	0.94	0.93	0.91-0.95	0.86	0.85	0.82-0.89
ρ_π	Taylor, π	N(2.00,0.20)	1.74	1.70	1.32-2.06	1.90	1.90	1.61-2.19
ρ_{de}	Taylor, Δe	N(0.10,0.05)	0.02	0.01	-0.04-0.07	–	–	–
ρ_y	Taylor, gdp	N(0.13,0.05)	0.17	0.16	0.08-0.23	0.15	0.14	0.07-0.20
η	H-F elasticity	G(1.00,0.15)	0.58	0.60	0.49-0.70	–	–	–
ϵ_O	Inv. adj. cost oil	G(5.00,1.00)	4.69	4.47	2.99-5.97	–	–	–
η^{od}	Oil demand elast.	G(0.30,0.15)	0.28	0.20	0.09-0.31	–	–	–
η^{os}	Oil supply elast.	G(0.30,0.15)	0.03	0.03	0.01-0.04	–	–	–
ρ_A	Technology	B(0.35,0.15)	0.53	0.52	0.40-0.65	0.74	0.69	0.56-0.83
ρ_I	Investment	B(0.35,0.15)	0.19	0.21	0.07-0.35	0.50	0.39	0.21-0.57
ρ_U	Preferences	B(0.35,0.15)	0.13	0.23	0.06-0.39	0.54	0.40	0.18-0.61
ρ_W	Wage markup	B(0.35,0.15)	0.28	0.29	0.11-0.45	0.05	0.10	0.02-0.17
ρ_M	Price markup	B(0.35,0.15)	0.72	0.64	0.48-0.80	0.66	0.50	0.17-0.79
ρ_B	UIP	B(0.50,0.15)	0.86	0.83	0.77-0.89	–	–	–
ρ_F	Oil investment	B(0.50,0.15)	0.38	0.41	0.25-0.58	–	–	–
ρ_{Ao}	Oil supply	B(0.50,0.15)	0.37	0.47	0.29-0.64	0.82	0.82	0.77-0.87
σ_{Am}	Sd tech. manu.	IG(0.50,2.00)	2.77	2.81	2.23-3.37	0.37	0.40	0.28-0.52
σ_{As}	Sd tech. serv.	IG(0.50,2.00)	4.03	4.36	3.60-5.12	0.79	0.82	0.63-1.01
σ_I	Sd investment	IG(0.50,2.00)	12.49	14.19	9.56-18.71	6.58	8.40	4.77-12.00
σ_U	Sd preferences	IG(0.50,2.00)	5.19	4.86	2.93-6.92	1.56	2.32	1.32-3.25
σ_W	Sd labor supply	IG(0.10,2.00)	0.80	0.75	0.56-0.93	1.11	1.11	0.92-1.31
σ_{Mm}	Sd markup manu.	IG(0.10,2.00)	0.97	1.06	0.62-1.50	0.14	0.31	0.08-0.54
σ_{Ms}	Sd markup serv.	IG(0.10,2.00)	0.15	0.19	0.09-0.28	0.15	0.17	0.09-0.26
σ_R	Sd mon. pol.	IG(0.02,2.00)	0.06	0.06	0.05-0.07	0.08	0.07	0.06-0.08
σ_B	Sd UIP	IG(0.50,2.00)	0.34	0.44	0.30-0.57	–	–	–
σ_F	Sd oil inv.	IG(0.50,2.00)	24.95	23.05	15.08-30.29	–	–	–
σ_{Ao}	Sd oil supply	IG(0.50,2.00)	4.56	4.18	3.52-4.87	3.54	2.59	1.11-4.04

Note: Posterior moments are computed from 5,000,000 draws generated by the Random Walk Metropolis-Hastings algorithm, where the first 4,000,000 are used as burn-in. B denotes the beta distribution, N normal, G gamma, and IG inverse gamma. P1 and P2 denote the prior mean and standard deviation. For IG, P1 and P2 denote the prior mode and degrees of freedom, respectively. Shock volatilities are multiplied by 100 relative to the text.

malized so that they enter the New Keynesian Phillips curves with coefficients of unity. We use inverse gamma distributions with two degrees of freedom as priors for standard deviations of all shocks'. This implies infinite prior variances for the shocks' volatilities.

The joint posterior distribution is built using the random walk Metropolis-Hastings algorithm. We generate 5,000,000 draws and discard the first 4,000,000 as burn-in. The large number of draws is needed in order to obtain convergence.[19] The jumping distri-

[19]Convergence tests are provided in the computational appendix.

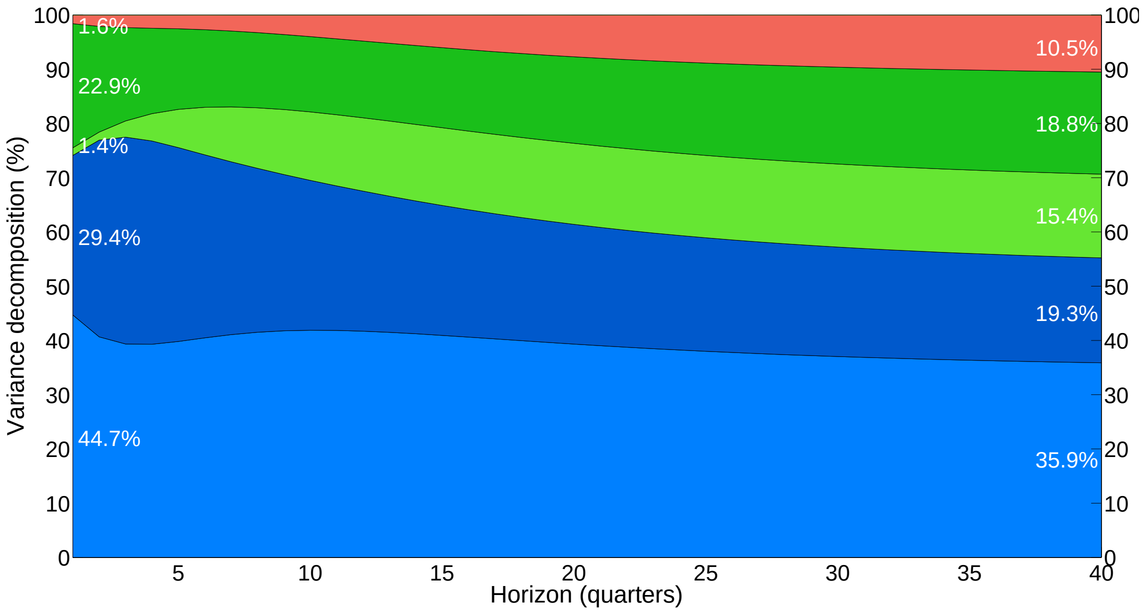
Table 4: Data and model moments

		Standard deviation		Autocorrelation	
		Data	Model M(5%-95%)	Data	Model M(5%-95%)
			Domestic variables		
gdp	GDP	2.87	3.00(1.76-4.42)	0.91	0.85(0.69-0.95)
gdp_m	GDP manufacturing	4.06	4.41(2.95-6.17)	0.89	0.73(0.50-0.89)
gdp_s	GDP services	2.25	3.53(2.34-4.99)	0.87	0.75(0.55-0.90)
c	Consumption	1.34	3.54(1.89-5.45)	0.73	0.91(0.80-0.97)
i	Investment	7.08	11.33(5.98-16.96)	0.90	0.93(0.84-0.97)
π_w	Wage inflation	1.27	1.00(0.78-1.28)	0.77	0.80(0.69-0.88)
π	Price inflation	0.78	0.62(0.45-0.81)	0.85	0.86(0.79-0.92)
r	Interest rate	0.17	0.22(0.13-0.33)	0.96	0.89(0.80-0.96)
Δe	Exchange rate	2.69	2.62(2.10-3.17)	0.21	$-0.07(-0.28$-$0.15)$
o	Output oil	4.20	5.11(3.81-6.62)	0.32	0.47(0.22-0.71)
i_o	Investment oil	7.20	17.46(10.75-25.20)	0.56	0.86(0.75-0.94)
			International variables		
gdp^*	GDP	2.50	2.54(1.42-3.80)	0.90	0.91(0.82-0.97)
gdp^*_m	GDP manufacturing	3.16	3.06(1.73-4.63)	0.90	0.91(0.84-0.97)
gdp^*_s	GDP services	2.04	2.26(1.31-3.44)	0.90	0.89(0.79-0.96)
c^*	Consumption	1.83	2.00(1.22-2.94)	0.89	0.88(0.77-0.96)
i^*	Investment	5.62	7.66(4.14-11.81)	0.90	0.92(0.85-0.97)
π_w	Wage inflation	0.96	1.11(0.86-1.38)	0.59	0.73(0.60-0.83)
π^*	Price inflation	0.58	0.35(0.26-0.45)	0.90	0.84(0.77-0.91)
r^*	Interest rate	0.27	0.22(0.14-0.31)	0.98	0.85(0.74-0.93)
p^*_{ro}	Oil price	37.50	21.24(13.84-29.89)	0.93	0.76(0.58-0.89)

Note: Standard deviations and first order autocorrelations in data versus simulations from the estimated model. Standard deviations are expressed in percent. We report the posterior mean and the 90% highest probability intervals from the simulations. Posterior moments are computed based on every 1000th draw from the posterior MCMC chain.

bution used is tuned in order to get an acceptance rate of 30%. Table 3 summarizes the joint posterior distribution. Most parameters are found to be in line with those from previous studies. Most parameter estimates are also fairly similar when comparing economies, although habit persistence and price stickiness in manufacturing are higher in Norway. Consistent with microeconomic evidence the posterior points to large differences in the degree of price stickiness across sectors. The estimates suggest that prices in services change on average only about every 10th quarter. Also, the estimated interest rate inertia is quite high in both countries, a result of the substantial interest rate persistence in our sample. Regarding elasticities in the oil sector, we find that the supply elasticity is close to zero, in line with arguments put forward by Kilian and Murphy (2012). The estimated demand elasticity is somewhat lower than that found in the DSGE model by Bodenstein, Erceg, and Guerrieri (2011) for the US economy, but higher than in recent empirical studies (Baumeister and Peersman, 2013a,b). Turning to the shock processes we get highly persistent UIP and oil supply shocks, suggesting that they can be important at longer horizons. Investment efficiency shocks are the most volatile, but one should have in mind that their impact elasticity – the capital depreciation rate – is low. In total, there is a tendency

Figure 5: Forecast error variance decomposition of mainland GDP



Note: Forecast error variance decomposition of GDP in mainland Norway. Calculated at the posterior mean. Shocks are decomposed as follows: Domestic supply shocks (light blue), domestic demand shocks (dark blue), international supply shocks (light green), international demand shocks (dark green), and shocks in oil markets (light red). Numbers in white at the left and right hand side are decompositions at the 1- and 40-quarter horizons, respectively.

of more volatile domestic innovations, while at the same time more persistence in the foreign business cycle shocks. Smoothed shock series are reported in the appendix.

4.4 MODEL FIT

Given the large number of observables and the tight restrictions embedded in the model, it is a massive challenge to fit all the second moments in data. To gauge the model's fit, we compare empirical second moments with moments based on model simulations. This is done as follows: for every 1000 draw from the posterior MCMC chain, we perform 100 stochastic simulations, each of 500 periods. For every simulation we save a subsample of the same size as the data sample and calculate moments of interest.

Selected results are summarized in Table 4.[20] The model provides a reasonable fit to data. Qualitatively, it matches the empirical observation that Norwegian variables tend to be more volatile while foreign variables tend to be more persistent. Quantitatively, most data moments are covered by the model's credible bands, but it misses out on some moments of interest. For instance, domestic consumption and oil investments are significantly less volatile and persistent in the data than in the model. The difficulty of matching consumption data is a well known problem in the literature, although we note a fairly good fit of foreign consumption. The estimated model also predicts too little volatility and persistence in the oil price. We attribute these discrepancies to large observed oil

[20]See Figure C.3 and Figure C.4 in the appendix for empirical and simulated cross-correlation functions.

price fluctuations – large compared with that called for by economic mechanisms in the model.[21] Some oil price volatility is soaked up by oil price shocks, some volatility comes about due to low estimated demand and supply elasticities, and some is attributed by the model to unusually large shocks in the selected data sample. Still, in total the model gives a reasonable description of the data, and the fit is comparable with that of other estimated DSGE models for small open economies.[22]

5 Business cycle analysis

This section documents the importance of international oil and non-oil shocks for the Norwegian business cycle, as implied by the estimated model. We decompose macroeconomic fluctuations into the parts attributed to specific shocks, and analyze how selected international disturbances transmit into mainland Norway.

5.1 Variance decompositions

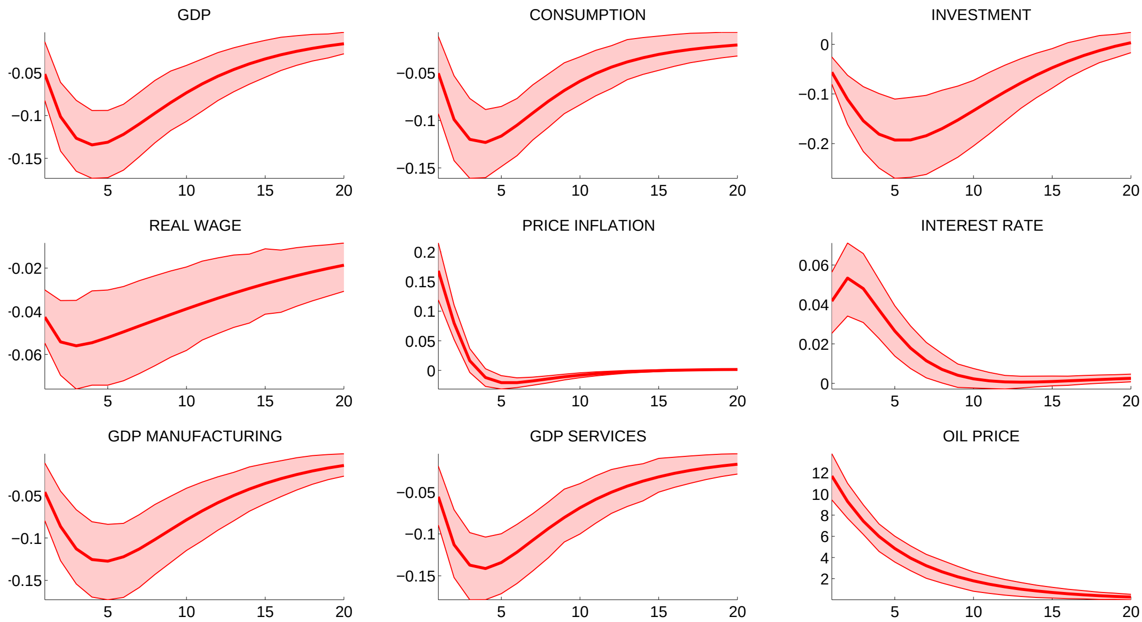
Figure 5 shows the forecast error variance decomposition of mainland GDP at different business cycle horizons. We label as domestic (foreign) supply shocks innovations to domestic (foreign) sectoral TFP, price markups, and wage markups. The remaining non-oil shocks are defined as demand driven (note that all non-oil innovations are demand shocks from oil producers' point of view). Blue areas summarize the total contribution from shocks originating in mainland Norway. In addition we report the role of shocks that originate internationally and in offshore Norway. In the very short run (1 quarter), about 75% of the unexpected volatility in mainland Norway can be traced back to domestic shocks. Of these, both supply and demand factors are important, in particular innovations to sectoral TFP and investment efficiency. Oil shocks, in contrast, account for only a minor share of the volatility. The importance of shocks outside mainland Norway rises as the forecasting horizon expands. At the 5-year horizon they account for about 40% of the fluctuations in GDP, substantially more than found in e.g. estimated small open economy models for the Swedish economy (Adolfson et al., 2007; Christiano et al., 2011). At least some of this difference is likely due to the importance of petroleum exports for Norway, a point we will get back to later.[23] The total contribution by oil shocks is not large, about 10% in the long run (less than a quarter of the international spillover). That is, our model does not support the view that oil shocks are crucial for macroeconomic fluctuations in mainland Norway. Later we argue that the foreign non-oil block in our model is able to soak up some of the oil price fluctuations in the data – fluctuations that would otherwise be interpreted as oil shocks. Regarding the role of individual shocks, Table C.3 in the appendix reports the unconditional decomposition for mainland variables, as well as a set of

[21] Note that we abstract from several features that are likely to be important for the oil price, including frictions in the futures market, speculation, and other strategic interactions.

[22] Further model validation, including 1-step ahead forecasts, is provided in the appendix.

[23] It is well known that estimated DSGE models for small open economies have a hard time accounting for foreign shocks, see Bergholt (2015) and Justiniano and Preston (2010) for in-depth analysis.

Figure 6: International responses to an international oil price shock



Note: Bayesian impulse responses of international variables to an international oil price shock (one standard deviation). Mean (solid line) and 90% highest probability intervals (shaded area) based on every 1000th draw from the posterior MCMC chain. Inflation and the interest rate are expressed in annual terms.

oil variables. Among domestic shocks, the most important are innovations to investment efficiency, markup in services, and wage markup shocks. International transmission, in contrast, comes about from shocks to foreign investment, foreign wages, and oil prices. The prominent role of supply type disturbances reflects low correlation between prices and quantities in Norwegian and European data (compared with U.S. data).

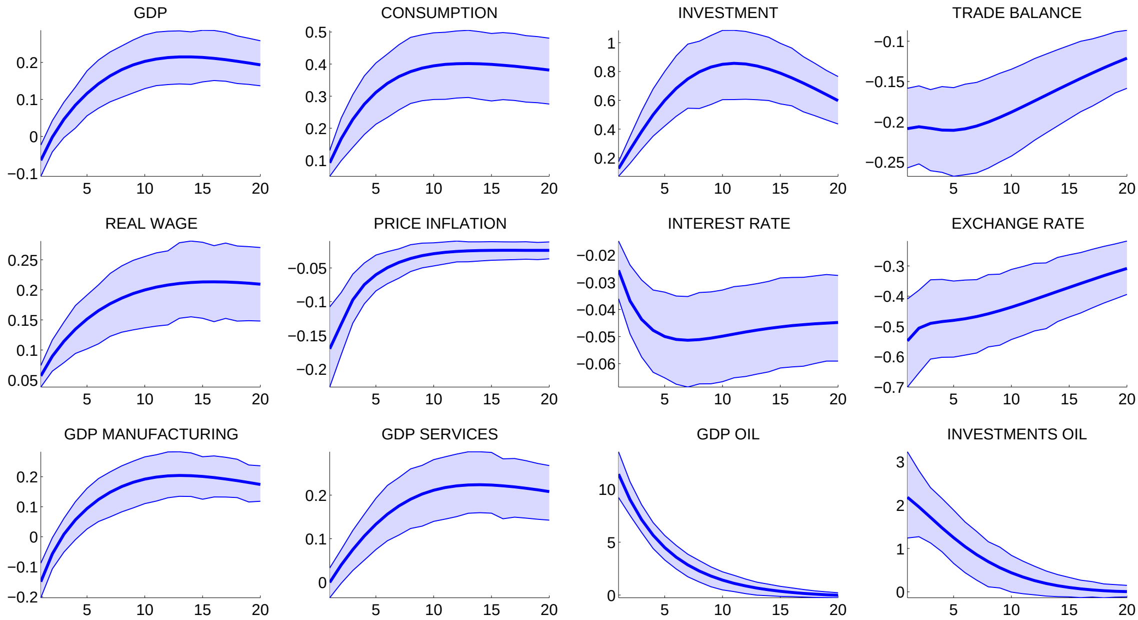
At this point, we emphasize that the limited importance of oil shocks for mainland Norway might understate the role of oil price fluctuations for domestic volatility. This is because significant oil price volatility – about 40% – is attributed by the model to conventional business cycle events. Oil price fluctuations caused by non-oil disturbances create volatility in mainland Norway. But those fluctuations are not understood by the model as oil shocks per se. Rather, they are interpreted as demand shocks from the point of view of oil producers.[24]

5.2 On the transmission to mainland Norway

This section sheds light on the transmission of international shocks to mainland Norway. First, we analyze the propagation of an oil price shock. Other disturbances are more important for the Norwegian business cycle, but this shock provides a better understanding of how oil price movements transmit through the economy. Second, we study an international investment shock – a significant source of volatility in the domestic economy.

[24] In other words, the model predicts that 40% of oil price volatility is demand-driven. This is less than in some VAR studies, but more than in most estimated DSGE models (e.g. Nakov and Pescatori (2010)).

Figure 7: Domestic responses to an international oil price shock



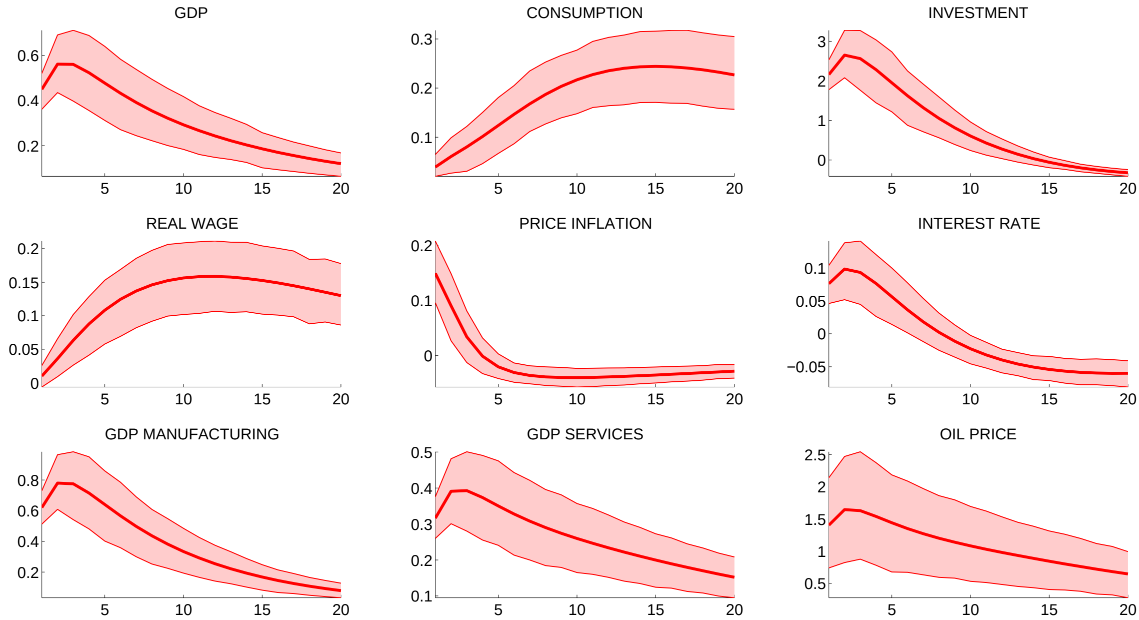
Note: Bayesian impulse responses of domestic variables to an international oil price shock (one standard deviation). Mean (solid line) and 90% highest probability intervals (shaded area) based on every 1000th draw from the posterior MCMC chain. All variables except value added and investments in oil are from the mainland economy. Inflation and the interest rate are expressed in annual terms.

5.2.1 International oil price shocks

As a starting point we describe how oil price shocks (productivity innovations among foreign oil producers) affect the international economy. Figure 6 shows the estimated responses of all foreign observables to a drop in international oil productivity. Several contractionary effects are at play: On the firm side, the cost effect of higher oil prices implies rising inflation as firms want to stabilize their markup. Monetary authorities increase the policy rate and the entire real interest rate path shifts up. On the household side, aggregate demand declines as a result of higher real interest rates. Although non-oil consumption becomes cheaper relative to oil, the substitution effect is quantitatively small (due to low estimated substitution elasticity) and also non-oil consumption drops. Thus, the oil price shock causes a contraction in demand as well as supply in the international economy. We stress that the entire array of international responses might matter for transmission to the oil exporter. Thus, from the oil exporter's point of view, an oil price shock involves a system of international impulses – rather than just the oil price innovation itself.

Figure 7 shows the implications for observables in mainland Norway. The oil price shock is associated with a small decline in mainland GDP on impact, followed by a prolonged period of higher economic activity. Mainland GDP peaks after three years at 0.2%. This domestic boom is a result of rising demand, in part due to a stronger need for productive inputs in the oil sector. Higher activity leads to more demand for productive resources, rising mainland investments, and higher factor prices. The non-oil trade balance drops because of the strong exchange rate appreciation, which in turn comes about

Figure 8: International responses to an international investment efficiency shock



Note: Bayesian impulse responses to an international investment efficiency shock (one standard deviation). See Figure 6 for details.

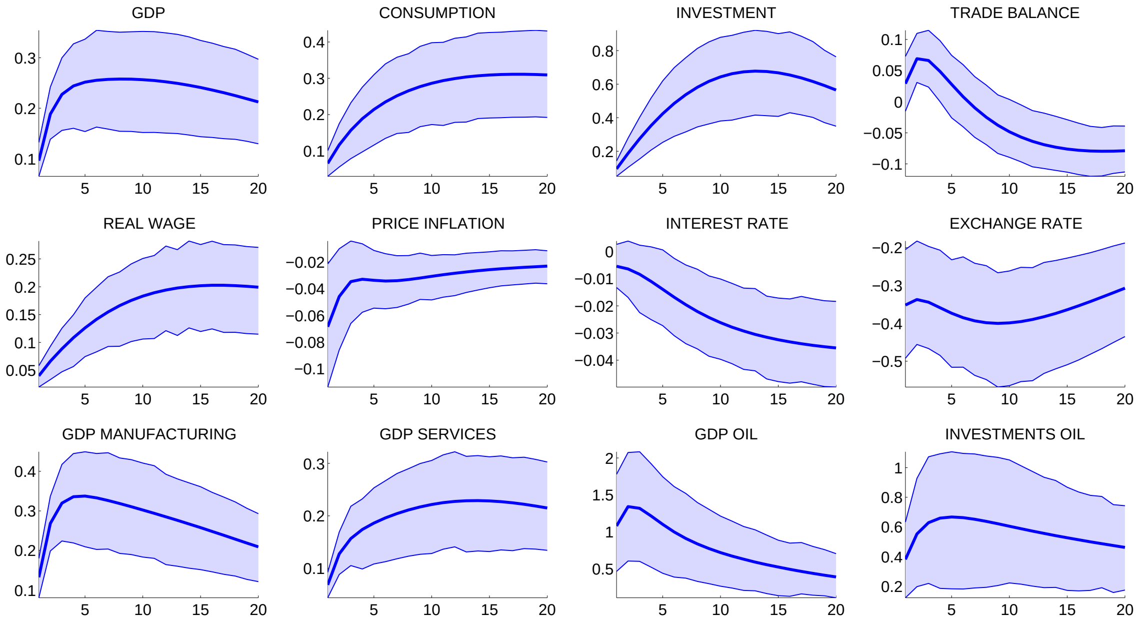
as a result of expected future improvements in external balances. Imports also increase because some demand, in particular from oil firms, is targeted towards foreign markets. Despite all these demand-side effects, domestic inflation actually falls. This effect is attributed to the exchange rate appreciation. Monetary authorities, trying to bring inflation back to target, respond by lowering policy rates. These developments are associated with a downward shift in the real interest rate path, implying rising consumption in mainland Norway. Regarding sectoral responses, we see that value added in manufacturing and services displays fairly similar dynamics, at least after some periods. The reason is that both sectors provide inputs to the supply chain. Value added in the oil sector closely tracks the oil price, while oil output hardly moves on impact (not shown). The latter observation is attributed to large short-run costs associated with changes in oil production. However, in order to accumulate production capacity down the road, oil firms raise investments by about 2% – an important source of increased activity in the mainland economy.

5.2.2 International investment shocks

Next we analyze the effects of an international investment shock.[25] International responses are shown in Figure 8. The shock causes an international boom, in particular among manufacturing firms who produce most investment goods. Consumption is in part crowded out by investments, and in part stimulated by expected future capital abundance. The latter effect dominates throughout, according to our model. Higher aggregate demand

[25] This shock implies higher investment efficiency abroad, and thus, higher investment demand than implied by capital returns and investment prices.

Figure 9: Domestic responses to an international investment efficiency shock



Note: Bayesian impulse responses to an international investment efficiency shock (one standard deviation). See Figure 7 for details.

implies inflation and rising interest rates. The oil price increases because oil is used both in production and consumption. In total we get responses that, in contrast to the oil price shock, resemble a demand-driven business cycle in the international economy.

Dynamics in the oil-exporting economy are plotted in Figure 9. Domestic activity is stimulated in part because of international demand, and in part because of a higher oil price. Mainland GDP peaks at 0.24% after two years. In a two-country model without oil, one would typically expect depreciation at home after foreign demand shocks. However, in our setup rising oil prices abroad cause a substantial improvement in the overall external position, explaining why the exchange rate appreciates. Appreciation, in turn, has a series of interesting implications: domestic inflation declines, as do nominal and real interest rates. This stimulates consumption and investment demand. The non-oil trade balance turns negative after some periods, a result of appreciation coupled with higher demand among oil firms for imported factors of production. In total, we conclude that oil price responses associated with foreign demand can cause both higher domestic activity and appreciation of the oil exporter's currency – in line with estimated effects from VARs.

5.2.3 Conditional pass-through to mainland GDP

One question of particular relevance for policy is whether propagation of oil price fluctuations depends on the underlying structural disturbances. Suppose the oil price increases by 10%. Are the effects in mainland Norway different if this is due to, say, policy rather than technology? Or are all shocks alike? Table 5 provides some information about this issue. If oil prices jump 10% because of reduced international oil supply, then mainland

Table 5: Peak response of mainland GDP to 10% oil price increase

	Response of mainland GDP		
Underlying international shock	*Mean*	*HPD interval*	*# lags*
Oil supply	0.18	(0.12-0.24)	13
Manufacturing productivity	2.68	(1.03-4.43)	4
Service productivity	1.50	(−0.05-3.04)	7
Investment demand	1.57	(0.94-2.13)	8
Consumption demand	0.54	(0.42-0.65)	2
Labor market	2.04	(1.09-2.94)	7
Manufacturing markup	1.36	(0.17-2.88)	3
Service markup	1.17	(0.26-2.02)	6
Monetary policy	0.88	(0.50-1.25)	6

Note: Pass-through from oil price to mainland GDP. Defined as the peak response of GDP when the oil price increases 10%, conditional on a given shock. Based on every 1000th draw from the posterior MCMC chain. HPD interval represents the 90% highest probability interval. # lags denotes the number of periods from the shock to the peak response.

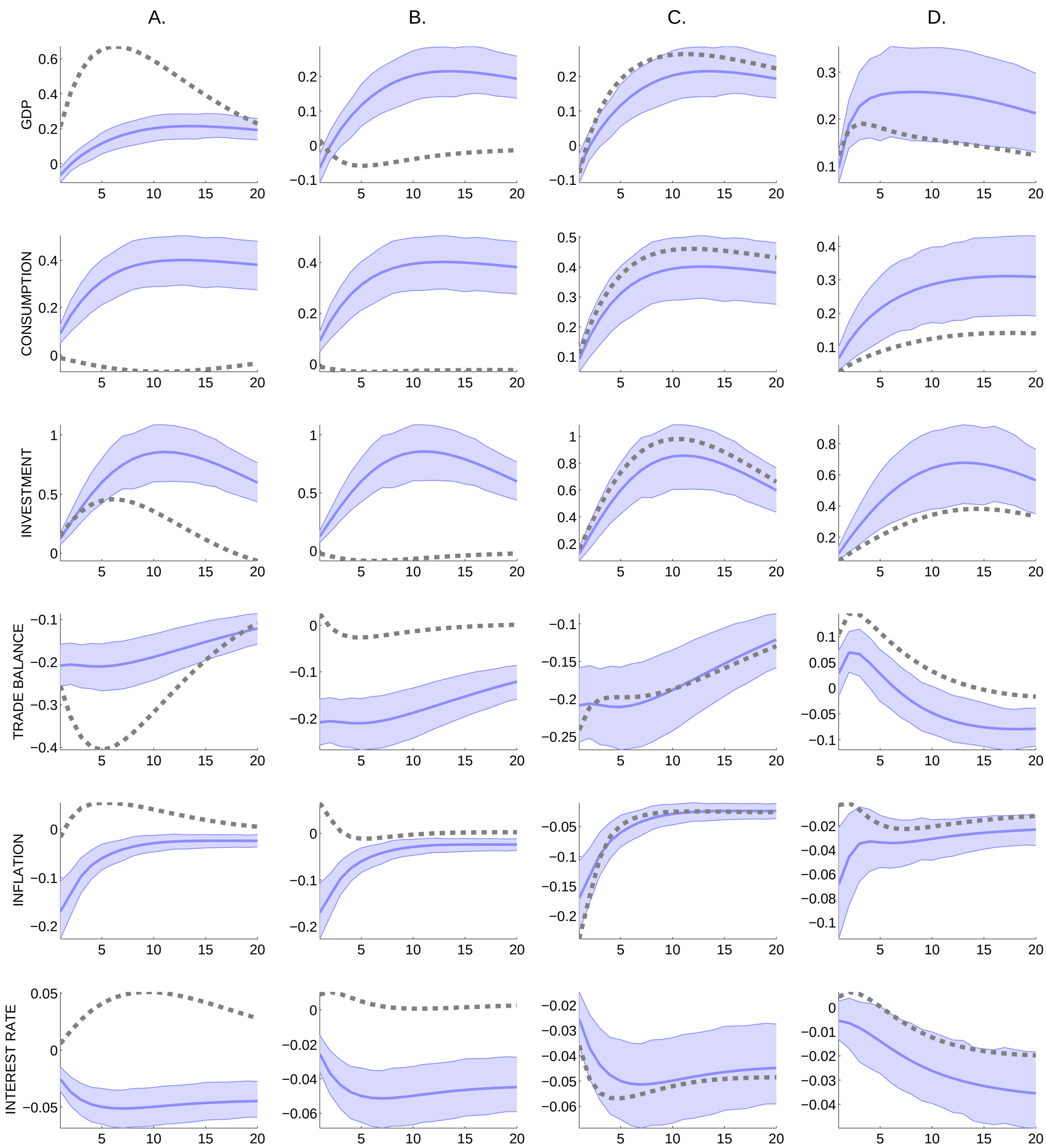
GDP increases only by 0.12–0.24%. An oil price rise of the same magnitude, but driven by productivity in international manufacturing, increases mainland GDP by 1.03-4.43%. That is, for the same observed oil price change, the peak response of GDP is 12-15 times stronger in the latter case. Our model predicts this difference because contractionary oil supply shocks disrupt international non-oil activity. The consequence is a minor boom for the oil exporter. More generally, the extent to which mainland GDP responds to oil price fluctuations depends on the source of volatility, and no two structural shocks are alike. Also the time from where a shock occurs to the peak in GDP differs across shocks, from two quarters for consumption driven innovations to three years for oil supply disruptions. However, one should have in mind that many of the shocks considered here play only a minor role for oil price fluctuations. The extent of productivity shocks required in international manufacturing for a 10% oil price change is never seen in our data.

6 Inspecting the mechanisms

Transmission of international business cycle shocks to the oil exporter happens through several channels. The final effect on domestic GDP and other variables depends on factors such as fiscal and monetary policy, income effects in labor and goods markets, and sectoral reallocations in the supply industry. This section inspects selected mechanisms at play. To this end we conduct a series of counterfactual experiments. The approach is simple: we simulate the posterior model, but with alternative assumptions regarding some potentially important parameters. Impulse responses are reported in Figure 10.[26]

[26]The full set of impulse responses is provided in the appendix. We refer to these throughout the discussion in this section.

Figure 10: Counterfactual dynamics



Note: Bayesian impulse responses to international shocks (one standard deviation). Baseline model (blue) and counterfactual simulations (gray). Column A: An international oil price shock without the sovereign wealth fund. Column B: An international oil price shock without the supply chain. Column C: An international oil price shock without feedback to macro. Column D: An international investment shock without feedback to oil. See Figure 7 for details.

6.1 Fiscal policy

First we ask to what extent the fiscal regime in Norway is able to shield the domestic economy from volatility in international commodity markets. Key features of the current regime are (i) a sovereign wealth fund and (ii) the public spending rule for oil wealth. In the baseline model (and in reality) all public oil revenues are transferred to the fund.

Moreover, the fund is invested solely in international markets. Only about 4% of the fund's value is used every year to finance public expenditures. Next we simulate the model conditional on a vastly different fiscal regime: instead of saving for the future, we assume that all oil revenues are spent on a continuous basis by fiscal authorities. The rest of the model is left unchanged. Column A in Figure 10 contrasts the impulse responses to an oil price shock under this counterfactual with those from the baseline estimation. mainland GDP increases by more than 0.6%, driven by high public demand. Private consumption is crowded out by the public sector and actually falls. Also non-oil investments display a more muted response. Monetary policy increases the interest rate in order to stabilize output and bring inflation back to target. In total, we get quite dramatic dynamics in the mainland economy. Note that the symmetry of the model implies an equally dramatic recession in the case of an oil price fall. Finally, taking into account the whole array of shocks, we find that this specification increases the role of foreign shocks by 30% compared with the baseline.

6.2 The supply chain

Next we study the importance of supply chain flows. Column B in Figure 10 reports the impulse responses to an oil price shock when we assume that no mainland inputs are needed in order to extract oil. In the model, this is the same as setting $\alpha_o = 0$. Now, oil revenues increase one-to-one with the oil price. But because all oil revenues are transferred to the fund, the effect on mainland Norway has to take place via expected future government spending. The differences compared with the baseline model are striking: Mainland GDP, consumption and investment fall, CPI inflation and the interest rate increase, and the real exchange rate depreciates on impact. The latter effect comes about because inflation and interest rates rise in the international economy – a result of higher producer costs abroad. The intuition behind the drop in domestic GDP is as follows: in our baseline model, higher oil prices lead to lower activity in the international economy, but also to rising factor demand in the oil industry. Rising factor demand is, from the point of view of mainland firms, a positive demand shock. In the baseline model, such factor demand dominates the international recession. But in absence of positive demand effects among supply firms, the contractionary effects in the international economy become the major driver. We note that the total role of international shocks for domestic GDP drops by 35% without the supply chain channel. This channel, therefore, seems important not only for the transmission of oil price shocks, but also for international non-oil shocks.

6.3 On the two-way causality between oil and macro

Finally we turn to the implications of ignoring the endogenous interactions between oil and macro in the international economy. This is done in two steps. First, we shut down all feedback from oil prices to the macroeconomy abroad. Second, we shut down all feedback from macro shocks to international oil markets.

6.3.1 An oil price shock without macro effects

In order to remove macro effects from oil price volatility we simulate a version of the model where oil intensities in consumption and production abroad are set to zero ($\xi_o^* = \phi_o^* = 0$). This calibration implies that international variables do not react at all to oil price fluctuations. Column C in Figure 10 reports the impulse responses. Mainland GDP and other real variables respond more strongly than in the baseline model, although the differences are quantitatively small. A stronger effect under this counterfactual is attributed to our abstraction from the effects at home of lower activity abroad. Relatively low oil intensity in consumption and production explains why differences are minor.[27] We note that also the empirical literature tends to find rather small macro effects from oil supply shocks (Kilian, 2009; Kilian and Murphy, 2012).

6.3.2 A macro shock without oil price effects

Finally, we impose that the oil price only reacts to productivity in the foreign oil sector. This effectively leaves us with an AR(1) process for the real oil price, as commonly assumed in the theoretical literature (Blanchard and Galí, 2007; Kormilitsina, 2011; Pieschacon, 2012). Oil price exogeneity has implications for all shocks in the model – we limit our attention to a rise in international investment efficiency. Column D in Figure 10 reports the impulse responses. Increased investment efficiency is associated with more demand and higher prices abroad, resulting in positive spillover to the domestic economy. Rising oil prices represent an important part of this spillover, as evidenced by comparing the baseline with the counterfactual in the figure. In fact, our model suggests that oil price endogeneity increases the role of foreign shocks for mainland GDP by about 25%. We conclude that international oil-macro interactions make an economically significant difference for the transmission to the oil-exporting economy.

6.4 Robustness

We have conducted a battery of robustness tests in order to inspect the stability of our results. As alternatives, we estimated model versions assuming (i) nominal wage flexibility, (ii) nominal price flexibility, (iii) no habits in consumption, (iv) no investment adjustment costs, and (v) no real or nominal frictions in the model (an RBC version). Regarding the high volatility of oil prices, we have estimated model versions where (vi) the oil price is detrended with an HP filter and (vii) the observation equation for oil prices includes a measurement error. The idea is to let the measurement error soak up some of the oil price volatility not explained by the model's economic mechanisms. Finally, we have simulated the model under different assumptions about policy regimes, including various parameterizations of the fiscal Taylor rule, as well as alternative monetary policy regimes (including strict inflation targeting). The main results, in particular the description of international propagation of business cycle shocks, hold across these specifications.

[27] Oil price shocks account for only 1-2% of the fluctuations in international GDP in our baseline model.

7 Concluding remarks

Declining commodity prices, in particular the massive drop in oil prices, have sparked renewed interest in the macroeconomic implications of external shocks for resource-rich economies. In this paper we study how the business cycle of an oil-exporting, small open economy is affected by international shocks. The contribution is two-fold: first, while most previous literature has focused on the role of oil for net importers, we analyze how oil price fluctuations influence a prototype oil exporter. Second, we do so through the lenses of an estimated DSGE model rather than reduced form regressions. The model comes with a fully specified international block, including endogenous determination of supply and demand in oil markets. In this way our approach allows us to identify and interpret a rich set of dynamics at play, complementing previous VAR-based literature.

We estimate the model using data for Norway and its main trading partner, EU28. The Norwegian economy is of particular interest: it is a highly specialized commodity exporter, with a fiscal regime (the sovereign wealth fund and the spending rule) that has gained significant international attention in recent years. The estimated model provides several important insights: first, pass-through from oil prices to the oil exporter implies significantly higher business cycle volatility. Second, the majority of the spillover effects are attributed to non-oil disturbances such as foreign investment efficiency shocks. Conventional oil price shocks, in contrast, explain at most 10% of the Norwegian business cycle. Third, in line with Bodenstein et al. (2012), we find that no two shocks are alike: a given oil price increase propagates far more if it is caused by some non-oil shocks instead of oil-specific disturbances. Regarding the effects of an oil price shock, we find that it typically creates a boom in all sectors of mainland Norway, coupled with a strong exchange rate appreciation and lower inflation. This result is consistent with those from an estimated VAR model with only a few identifying restrictions. The positive spillover to mainland Norway is significantly weakened by the fact that all oil revenues are saved in a sovereign wealth fund. Domestic supply chains, in contrast, amplify spillover. We quantify each of these transmission channels: with a spend-as-you-go fiscal rule, the peak response of mainland GDP is more than three times higher. Without the supply chain, the oil price shock actually leads to lower GDP and higher inflation.

Finally, we want to point out some possibilities for future research. First, while our focus is on business cycles in commodity economies, we do not account for the fact that oil is a non-renewable resource. Analyzing this issue requires other solution approaches and makes estimation significantly more challenging. Second, a natural next step is to address policy implications. Existing literature on optimal fiscal and monetary policy (in commodity economies) is based on highly stylized and calibrated models (Bergholt, 2014; Catão and Chang, 2013; Hevia and Nicolini, 2013). Our work might serve as a starting point for more quantitative investigation of policy and welfare, along the lines of Schmitt-Grohé and Uribe (2006). Third, we stress that our analysis abstracts from several frictions that are likely to play a role in practice. Financial frictions, in particular those originating in commodity markets, represent an interesting avenue for future work.

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Online appendix (not for publication)

A The full model

Here we describe in detail the non-linear DSGE model. It is based on Bergholt and Seneca (2015), which in turn builds on Bergholt (2015). The model consists of two blocks, referred to as home and foreign. The home block is a small scale version of its foreign counterpart, which represents the rest of the world. Our focus is on the limiting case where home's relative size goes to zero, implying that foreign approximates a closed economy. We focus on the non-oil economy that is abstracted from in the main text.

A.1 Households

Consider household member $h \in [0,1]$ working in sector $j \in \{m, s, c\}$ (manufacturing, services or supply chain). He maximizes expected lifetime utility, given in period t by

$$\mathcal{W}_{j,t}(h) = \mathbb{E}_t \sum_{s=t}^{\infty} \beta^{s-t} Z_{U,s} \left[\frac{(1-\chi_C)^{\sigma} (C_t(h) - \chi_C C_{t-1})^{1-\sigma}}{1-\sigma} - \chi_N \frac{L_{j,t}(h)^{1+\varphi}}{1+\varphi} \right].$$

$C_t(h)$ denotes period t consumption while $L_{j,t}(h)$ denotes hours worked for household member h. β is the subjective time discount factor. $Z_{U,t}$ is an intertemporal preference shock. We assume the existence of a complete set of tradable Arrow securities within each economy. This makes consumption independent of the wage history, and household member h's consumption equals aggregate consumption. We drop the h-subscript whenever possible from now on. Maximization of lifetime utility is subject to a sequence of budget constraints. The period t constraint takes the following form when measured in consumption units:

$$\begin{aligned} &C_t + P^i_{r,t} I_t + B_{rH,t+1} + \mathcal{S}_t B^*_{rF,t+1} \\ &\quad \leq \Omega_t L_t + R^k_t K_t + \mathcal{D}_t - T_t + R_{t-1} B_{rH,t} \Pi_t^{-1} + R^*_{t-1} \Upsilon_{t-1} \mathcal{S}_t B^*_{rF,t} \Pi_t^{*-1} \end{aligned} \tag{A.1}$$

Aggregate consumption, investment, and domestic and foreign bond savings are denoted by C_t, I_t, and $B_{rH,t+1} + \mathcal{S}_t B^*_{rF,t+1}$ respectively. $P^i_{r,t}$ and $\mathcal{S}_t$ represent the real investment price and the real exchange rate. The income side consists of aggregate labor income $\Omega_t L_t$, capital income $R^k_t K_t$, dividends from firms $\mathcal{D}_t$, lump-sum taxes, and bond returns. The aggregate real wage rate, capital rental rate, and nominal rates on domestic and foreign savings are denoted by Ω_t, R^k_t, R_t and R^*_t respectively. Π_t and Π^*_t represent domestic and foreign (gross) consumer price inflation. Households face a premium in foreign bond markets given by $\Upsilon_{t-1} = \exp\left(-\epsilon_B \frac{NFA_t - NFA}{VA}\right) Z^*_{B,t}$, where $\frac{NFA_t}{VA} = \mathcal{S}_t \frac{NFA^*_t}{VA}$ is the net foreign asset position (the sum of privately held foreign bonds and the sovereign wealth fund) in real terms and as a share of steady state value added. $Z^*_{B,t}$ captures deviations from uncovered interest rate parity, referred to as risk premium shocks. Investments are subject to a law of motion for aggregate capital. It involves investment adjustment costs and an investment efficiency shock $Z_{I,t}$:

$$K_{t+1} = (1 - \delta) K_t + Z_{I,t} \left[1 - \Psi \left(\frac{I_t}{I_{t-1}} \right) \right] I_t \tag{A.2}$$

The adjustment cost is specified as $\Psi \left(\frac{I_t}{I_{t-1}} \right) = \frac{\epsilon_I}{2} \left(\frac{I_t}{I_{t-1}} - 1 \right)^2$. Optimality conditions with respect to C_t, $B_{rH,t+1}$, $B^*_{rF,t+1}$, K_{t+1}, and I_t, follow below:

$$\Lambda_t = Z_{U,t} (1 - \chi_C)^{\sigma} (C_t - \chi_C C_{t-1})^{-\sigma} \tag{A.3}$$

$$\mathbb{E}_t \left(R_t^{-1} \right) = \beta \mathbb{E}_t \left(\frac{\Lambda_{t+1}}{\Lambda_t} \Pi_{t+1}^{-1} \right) \tag{A.4}$$

$$\mathbb{E}_t \left(R_t^{*-1} \right) = \beta \mathbb{E}_t \left(\frac{\Lambda_{t+1}}{\Lambda_t} \Pi_{t+1}^{*-1} \frac{\mathcal{S}_{t+1}}{\mathcal{S}_t} \Upsilon_t \right) \tag{A.5}$$

$$\mathcal{Q}_t = \beta \mathbb{E}_t \left(\frac{\Lambda_{t+1}}{\Lambda_t} \left[R^k_{t+1} + (1 - \delta) \mathcal{Q}_{t+1} \right] \right) \tag{A.6}$$

$$\begin{aligned} P^i_{r,t} &= \mathcal{Q}_t Z_{I,t} \left[1 - \Psi \left(\frac{I_t}{I_{t-1}} \right) - \Psi' \left(\frac{I_t}{I_{t-1}} \right) \frac{I_t}{I_{t-1}} \right] \\ &\quad + \beta \mathbb{E}_t \left[\frac{\Lambda_{t+1}}{\Lambda_t} \mathcal{Q}_{t+1} Z_{I,t+1} \Psi' \left(\frac{I_{t+1}}{I_t} \right) \left(\frac{I_{t+1}}{I_t} \right)^2 \right] \end{aligned} \tag{A.7}$$

Equation (A.3) equates the marginal utility of consumption with the shadow value of the budget constraint. Equation (A.4) defines the optimal intertemporal consumption path while foreign bond savings are defined by (A.5). Equation (A.6) determines $\mathcal{Q}_t$, the present marginal value of capital. Finally, (A.7) equates the relative price of investments with the gain of more capital tomorrow. The optimality conditions above are intertemporal and aggregate. Sectoral (intratemporal) consumption and investment demand follow from the Cobb-Douglas aggregators $C_t = C^{\xi}_{m,t} C^{1-\xi}_{s,t}$ and $I_t = I^{\varpi}_{m,t} I^{1-\varpi}_{s,t}$, respectively:

$$\frac{C_{m,t}}{C_{s,t}} = \frac{\xi}{1 - \xi} \frac{P_{s,t}}{P_{m,t}}, \qquad \frac{I_{m,t}}{I_{s,t}} = \frac{\varpi}{1 - \varpi} \frac{P_{s,t}}{P_{m,t}} \tag{A.8}$$

Thus, relative sector demand depends on the sector prices $P_{m,t}$ and $P_{s,t}$. We exploit input-output data from Statistics Norway to parameterize the expenditure weights on manufactured goods; ξ and ϖ.

Sectoral labor markets are similar to the labor market in Erceg, Henderson, and Levin (2000), but we assume that workers cannot move freely across sectors within the business cycle. Denote by $\mu_j \in (0, 1)$ the measure of household members working in sector j ($\sum_{j=\{m,s,c\}} \mu_j = 1$). A competitive labor bundler buys hours from all the household members employed in the sector in order to construct an aggregate labor service $N_{j,t}$.

$$N_{j,t} = \left[\left(\frac{1}{\mu_j} \right)^{\frac{\epsilon_{w,t}}{1+\epsilon_{w,t}}} \int_{\mu_j} L_{j,t} (h)^{\frac{1}{1+\epsilon_{w,t}}} dh \right]^{1+\epsilon_{w,t}},$$

where $\epsilon_{w,t}$ is referred to as a wage markup shock. Optimal demand for worker h-hours is

$$L_{j,t}(h) = \frac{1}{\mu_j}\left(\frac{W_{j,t}(h)}{W_{j,t}}\right)^{-\frac{1+\epsilon_{w,t}}{\epsilon_{w,t}}} N_{j,t} = \left(\frac{W_{j,t}(h)}{W_{j,t}}\right)^{-\frac{1+\epsilon_{w,t}}{\epsilon_{w,t}}} L_{j,t},$$

where $W_{j,t}(h)$ ($W_{j,t}$) is the nominal worker-specific (sectoral) wage rate. $L_{j,t} = \frac{N_{j,t}}{\mu_j}$ is defined as average effective labor hours per worker in the sector. Each period, only a fraction $1-\theta_w$ of the workers can re-optimize wages. The remaining $1-\theta_w$ workers index wages according to the indexation rule $W_{j,t}(h) = W_{j,t-1}(h)\ddot{\Pi}_{w,t}$ ($\ddot{\Pi}_{w,t} = \Pi_{t-1}^{\iota_w}\Pi^{1-\iota_w}$). Let $\bar{W}_{j,t}$ denote the optimal wage for those that re-optimize. It is common across workers and satisfies

$$0 = \mathbb{E}_t \sum_{s=t}^{\infty} (\beta\theta_w)^{s-t} \Lambda_s \frac{L_{j,s}(h)}{P_s}\left[\bar{W}_{j,t}\prod_{i=1}^{s-t}\ddot{\Pi}_{w,s-i} - (1+\epsilon_{w,t}) MRS_{j,s|t}(h) P_s\right]. \quad \text{(A.9)}$$

$MRS_{j,s|t}(h)$ is the marginal rate of substitution (between consumption and labor) in period s, given a wage last set in period t. Finally, sectoral wages follow the law of motion

$$W_{j,t} = \left[\theta_w \left(W_{j,t-1}\ddot{\Pi}_{w,t}\right)^{-\frac{1}{\epsilon_{w,t}}} + (1-\theta_w)\bar{W}_{j,t}^{-\frac{1}{\epsilon_{w,t}}}\right]^{-\epsilon_{w,t}},$$

from which one can derive a sectoral New Keynesian wage Phillips curve.

A.2 Firms

Output by domestic firm f in sector j is given by

$$Y_{j,t}(f) = Z_{Aj,t} X_{j,t}(f)^{\phi_j} N_{j,t}(f)^{\psi_j} K_{j,t}(f)^{1-\phi_j-\psi_j} - \Phi_j. \quad \text{(A.10)}$$

$X_{j,t}(f)$, $N_{j,t}(f)$ and $K_{j,t}(f)$ are firm f's use of materials, labor and capital respectively. Φ_j is a fixed production cost that will be calibrated to ensure zero profit in steady state. $Z_{Aj,t}$ represents sector-specific productivity shocks. Intermediate trade is modeled as in Bouakez, Cardia, and Ruge-Murcia (2009) and Bergholt (2015), where $X_{j,t}$ is a composite of inputs produced in manufacturing and services: $X_{j,t}(f) = X_{mj,t}(f)^{\zeta_j} X_{sj,t}(f)^{1-\zeta_j}$. Firm f maximizes an expected stream of dividends given by $\mathbb{E}_t \sum_{s=t}^{\infty} \mathcal{Z}_{t,s} P_s \mathcal{D}_{j,s}(f)$, where $\mathcal{Z}_{t,s} = \beta^{s-t}\frac{\Lambda_s}{\Lambda_t}\frac{P_t}{P_s}$ is the stochastic discount factor. Dividends and total costs are specified below:

$$\mathcal{D}_{j,s}(f) = P_{rHj,s}(f) A_{Hj,s}(f) + P^*_{rHj,s}(f) A^*_{Hj,s}(f) - TC_{rj,s}(f)$$
$$TC_{rj,s}(f) = P^x_{rj,s} X_{j,s}(f) + \Omega_{j,s} N_{j,s}(f) + R^k_s K_{j,s}(f),$$

$A_{Hj,s}(f)$ is total domestic absorption of the firm's output while $A^*_{Hj,s}(f)$ is the exported counterpart. $P_{rHj,s}(f) = \frac{P_{Hj,s}(f)}{P_s}$ and $P^*_{rHj,s}(f) = \frac{\mathcal{E}_s P^*_{Hj,s}(f)}{P_s}$ are the associated real prices in domestic currency, $\mathcal{E}_s$ is the nominal exchange rate. Optimality conditions in sectoral factor markets follow below:

$$\begin{aligned} \frac{N_{j,t}(f)}{X_{j,t}(f)} &= \frac{\psi_j}{\phi_j}\frac{P^x_{rj,t}}{\Omega_{j,t}}, \\ \frac{K_{j,t}(f)}{X_{j,t}(f)} &= \frac{1-\phi_j-\psi_j}{\phi_j}\frac{P^x_{rj,t}}{R^k_t}, \\ \frac{X_{mj,t}(f)}{X_{sj,t}(f)} &= \frac{\zeta_j}{1-\zeta_j}\frac{P_{s,t}}{P_{m,t}} \end{aligned} \tag{A.11}$$

Price setting is subject to monopolistic competition and sticky prices in a way analogous to the labor market. Firms set prices à la Calvo (1983), but exported goods are priced in local currency (LCP). We denote by $1-\theta_{pj}$ the probability of an optimal price change. Non-optimizing firms index prices according to rules $P_{Hj,t}(f) = P_{Hj,t-1}(f)\ddot{\Pi}_{Hj,t}$ ($\ddot{\Pi}_{Hj,t} = \Pi^{\iota_p}_{Hj,t-1}\Pi^{1-\iota_p}_{Hj}$) and $P^*_{Hj,t}(f) = P^*_{Hj,t-1}(f)\ddot{\Pi}^*_{Hj,t}$ ($\ddot{\Pi}^*_{Hj,t} = \Pi^{*\iota_p}_{Hj,t-1}\Pi^{*1-\iota_p}_{Hj}$). Let $\bar{P}_{jH,t}$ and $\bar{P}^*_{Hj,t}$ be the optimal new prices. They are common across firms, and satisfy the following equations:

$$\begin{aligned} 0 &= \mathbb{E}_t \sum_{s=t}^{\infty} \theta^{s-t}_{pj} \mathcal{Z}_{t,s} X_{Hj,s}(f) \left[\bar{P}_{Hj,t} \prod_{i=1}^{s-t} \ddot{\Pi}_{Hj,s-i} - (1+\epsilon_{p,s}) P_s RMC_{j,s}(f)\right] \\ 0 &= \mathbb{E}_t \sum_{s=t}^{\infty} \theta^{s-t}_{pj} \mathcal{Z}_{t,s} X^*_{Hj,s}(f)\, \mathcal{E}_s \left[\bar{P}^*_{Hj,t} \prod_{i=1}^{s-t} \ddot{\Pi}^*_{Hj,s-i} - (1+\epsilon_{p,s}) P_s RMC_{j,s}(f)\right] \end{aligned} \tag{A.12}$$

Our production technology implies that all firms face the same real marginal cost $RMC_{j,t}$:

$$RMC_{j,t} = \frac{1}{Z_{Aj,t}} \left(\frac{P^x_{rj,t}}{\phi_j}\right)^{\phi_j} \left(\frac{\Omega_{j,t}}{\psi_j}\right)^{\psi_j} \left(\frac{R^k_t}{1-\phi_j-\psi_j}\right)^{1-\phi_j-\psi_j}, \tag{A.13}$$

The staggered price setting structure combined with partial indexation implies the following price dynamics:

$$\begin{aligned} P_{Hj,t} &= \left[\theta_{pj}\left(P_{Hj,t-1}\ddot{\Pi}_{Hj,t}\right)^{-\frac{1}{\epsilon_{p,t}}} + (1-\theta_{pj})\,\bar{P}_{Hj,t}^{-\frac{1}{\epsilon_{p,t}}}\right]^{-\epsilon_{p,t}} \\ P^*_{Hj,t} &= \left[\theta_{pj}\left(P^*_{Hj,t-1}\ddot{\Pi}^*_{Hj,t}\right)^{-\frac{1}{\epsilon_{p,t}}} + (1-\theta_{pj})\,\bar{P}_{Hj,t}^{*\,-\frac{1}{\epsilon_{p,t}}}\right]^{-\epsilon_{p,t}} \end{aligned}$$

One can combine these with the optimal pricing equations in order to derive New Keynesian price Phillips curves for domestic goods and exports. Import prices ($P_{Fj,t}$) are set similarly, except that they are chosen by foreign firms with costs in foreign currency.

A.3 AGGREGATION

Each non-oil sector $j \in \{m, s, c\}$ consists of a competitive bundler who combines individual goods into a final aggregate good $A_{j,t}$. Aggregation is subject to a nested CES structure (exports are aggregated in the same way abroad):

$$
\begin{aligned}
A_{Hj,t} &= \left(\int_0^1 A_{Hj,t}\left(f\right)^{\frac{1}{1+\epsilon_{p,t}}} df \right)^{1+\epsilon_{p,t}} \\
A_{Fj,t} &= \left(\int_0^1 A_{Fj,t}\left(f\right)^{\frac{1}{1+\epsilon^*_{p,t}}} df \right)^{1+\epsilon^*_{p,t}} \\
A_{j,t} &= \left[\bar{\alpha}_j^{\frac{1}{\eta}} A_{Hj,t}{}^{\frac{\eta-1}{\eta}} + (1-\bar{\alpha}_j)^{\frac{1}{\eta}} A_{Fj,t}{}^{\frac{\eta-1}{\eta}} \right]^{\frac{\eta}{\eta-1}}
\end{aligned}
\tag{A.14}
$$

Domestically produced goods and imports at the sector level are denoted by $A_{Hj,t}$ and $A_{Fj,t}$, respectively. The expenditure weight $\bar{\alpha}_j$ is defined as $\bar{\alpha}_j = 1 - (1-\varsigma)(1-\alpha_j)$, where $\varsigma \in [0,1]$ represents the relative population size of home and $\alpha_j \in [0,1]$ is the degree of home bias. Cost minimization gives rise to a set of optimal demand schedules, expressed below in the limit as $\varsigma \to 0$:

$$
\begin{aligned}
A_{Hj,t}\left(f\right) &= \left(\frac{P_{Hj,t}(f)}{P_{Hj,t}} \right)^{-\frac{1+\epsilon_{p,t}}{\epsilon_{p,t}}} A_{Hj,t}, \quad & A_{Fj,t}\left(f\right) &= \left(\frac{P_{Fj,t}(f)}{P_{Fj,t}} \right)^{-\frac{1+\epsilon^*_{p,t}}{\epsilon^*_{p,t}}} A_{Fj,t}, \\
A_{Hj,t} &= \alpha_j \left(\frac{P_{H,t}}{P_{j,t}} \right)^{-\eta} A_{j,t}, & A_{Fj,t} &= (1-\alpha_j) \left(\frac{P_{Fj,t}}{P_{j,t}} \right)^{-\eta} A_{j,t}
\end{aligned}
\tag{A.15}
$$

The final good $A_{j,t}$ is used to cover private and public sectoral demand:

$$
A_{j,t} = C_{j,t} + I_{j,t} + G_{j,t} + X_{jm,t} + X_{js,t} + X_{jc,t}
$$

Our setup implies equal import shares across goods within sectors (e.g. $C_{j,t}$ and $I_{j,t}$), but different import shares across aggregate goods (such as C_t and I_t).

Market clearing at the firm level dictates that $Y_{j,t}\left(f\right) = A_{Hj,t}\left(f\right) + A^*_{Hj,t}\left(f\right)$. Sectoral market clearing follows:[28]

$$
Y_{j,t} = \int_0^1 \left(A_{Hj,t}\left(f\right) + A^*_{Hj,t}\left(f\right) \right) df = A_{Hj,t}\Delta_{Hj,t} + A^*_{Hj,t}\Delta^*_{Hj,t},
$$

where sectoral output is defined as

$$
Y_{j,t} = \int_0^1 Y_{j,t}(f)\, df = Z_{Aj,t} X_{j,t}^{\phi_j} N_{j,t}^{\psi_j} K_{j,t}^{1-\phi_j-\psi_j} - \Phi_j.
$$

$X_{j,t} = \int_0^1 X_{j,t}(f)\, df$, $N_{j,t} = \int_0^1 N_{j,t}(f)\, df$, and $K_{j,t} = \int_0^1 K_{j,t}(f)\, df$ represent total factor use. Total hours worked, in contrast, is $\int_{\mu_j} L_{j,t}(h)\, dh = \frac{1}{\mu_j} N_{j,t}\Delta_{wj,t} = L_{j,t}\Delta_{wj,t}$.[29] Hours worked per person in the entire economy is $L_t = \sum_{j=1}^{\mathcal{J}} \mu_j L_{j,t}$.

We note, for completeness, that all variables are measured per home capita. Firm

[28] $\Delta_{Hj,t} = \int_0^1 \left(\frac{P_{Hj,t}(f)}{P_{Hj,t}} \right)^{-\frac{1+\epsilon_{p,t}}{\epsilon_{p,t}}} df = 1$ and $\Delta^*_{Hj,t} = \int_0^1 \left(\frac{P^*_{Hj,t}(f)}{P^*_{Hj,t}} \right)^{-\frac{1+\epsilon_{p,t}}{\epsilon_{p,t}}} df = 1$ hold up to first order.

[29] $\Delta_{wj,t} = \int_{\bar{\mu}_{j-1}}^{\bar{\mu}_j} \left(\frac{W_{j,t}(h)}{W_{j,t}} \right)^{-\frac{1+\epsilon_{w,t}}{\epsilon_{w,t}}} dh = \mu_j$ holds up to first order.

f's exports per foreign capita, denoted by $\tilde{A}^*_{Hj,t}(f)$, is linked to $A^*_{Hj,t}(f)$ by the identity $A^*_{Hj,t}(f) = \frac{1-\varsigma}{\varsigma}\tilde{A}^*_{Hj,t}(f)$. It follows that per capita absorption abroad is given by $\tilde{A}^*_{Hj,t} = 0$, $\tilde{A}^*_{Fj,t} = 0$, and $A^*_{Fj,t} = A^*_{j,t}$ when $\varsigma \to 0$. This is the sense in which the foreign block approximates a closed economy.

Finally we define real value added at the sector level in consumption units. It can be written in three different, but model consistent ways:

$$\begin{aligned} VA_{j,t} &= P_{rHj,t}A_{Hj,t} + P^*_{rHj,t}A^*_{Hj,t} - P^x_{rj,t}X_{j,t} \\ &= \Omega_{j,t}N_{j,t} + R^k_t K_{j,t} + \mathcal{D}_{j,t} \\ &= P_{rj,t}\left(C_{j,t} + I_{j,t} + G_{j,t}\right) + TB_{j,t} + P_{rj,t}\sum_{l=\{m,s,c\}} X_{jl,t} - P^x_{rj,t}X_{j,t} \end{aligned} \tag{A.16}$$

The first line defines sectoral value added according to the output approach, i.e. as the value of gross output minus the value of intermediate inputs. The second line measures value added according to the income approach, where $\mathcal{D}_{j,t} = \int_0^1 \mathcal{D}_{j,t}(f)\,df$ is the sum of sectoral dividends. The last line uses the expenditure approach, where $TB_{j,t} = P^*_{rHj,t}A^*_{Hj,t} - P_{rFj,t}A_{Fj,t}$ is the trade balance. The cross-sectoral balance for intermediate inputs cancels out in the aggregate, non-oil economy. Thus, aggregate non-oil GDP is

$$GDP_t = \sum_{j\in\{m,s\}} VA_{j,t} = C_t + P^i_{r,t}I_t + P^g_{r,t}G_t + TB_t + P^x_{rc,t}X_{c,t},$$

as in the main text. The private economy's aggregate trade balance, $TB_t = TB_{m,t} + TB_{s,t}$, contributes to the accumulation of privately held foreign bonds:

$$\mathcal{S}_t B^*_{rF,t+1} = R^*_{t-1}\Upsilon_{t-1}\mathcal{S}_t B^*_{rF,t}\Pi^{*-1}_t + TB_t$$

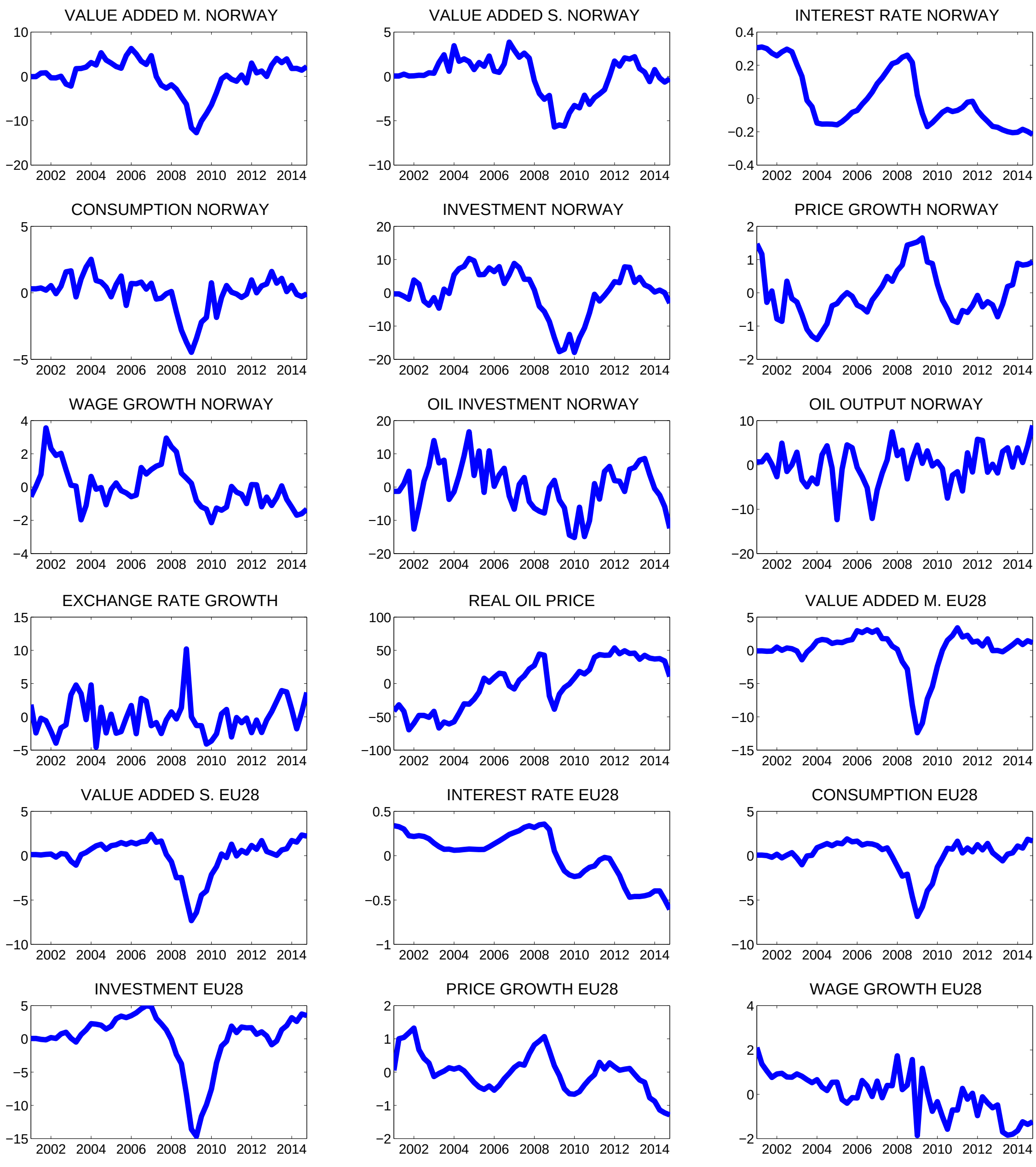
The total net foreign asset position of home follows as the sum of private and public savings in international assets:

$$NFA_{t+1} = \mathcal{S}_t B^*_{rF,t+1} + \mathcal{S}_t SWF^*_{t+1}$$

This completes our model description.

B DATA

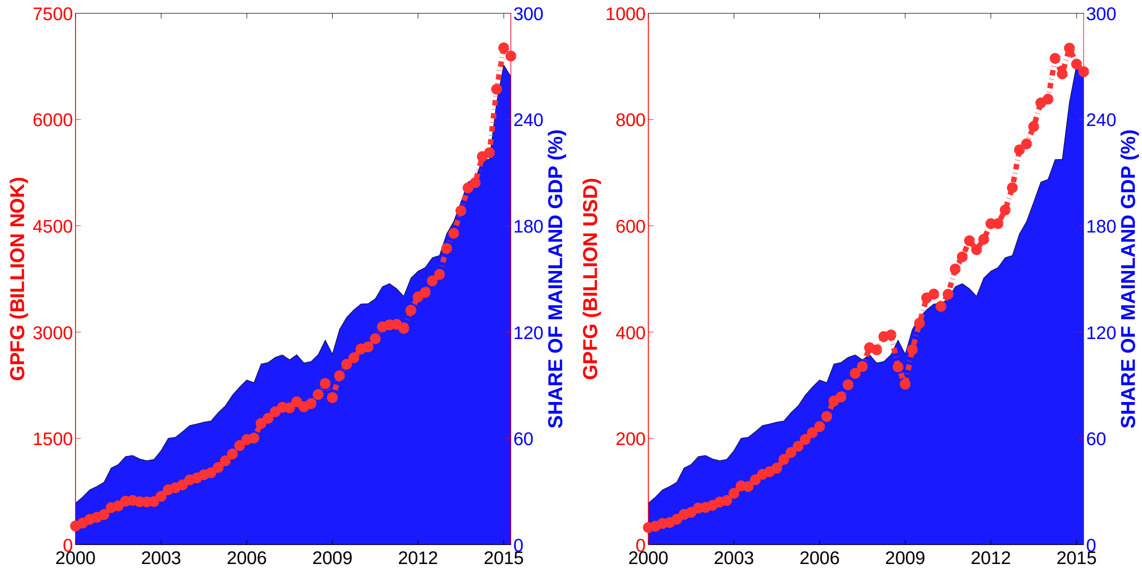
Figure B.1: Data series 2000Q1–2014Q4



Note: Full dataset. Real variables are HP-filtered with $\lambda = 1600$. Model correspondence: sectoral value added is gdp_j, interest rate r, consumption c, investment i, price growth π, wage growth π_w, oil investment i_o, oil output o, exchange rate growth Δe, and real oil price p_{ro}. Wages and prices are measured as year-on-year growth.

C Additional figures and tables

Figure C.1: Norway's Government Pension Fund Global



Note: The Government Pension Fund Global (GPFG) in Norwegian kroner (left) and in US dollars (right).

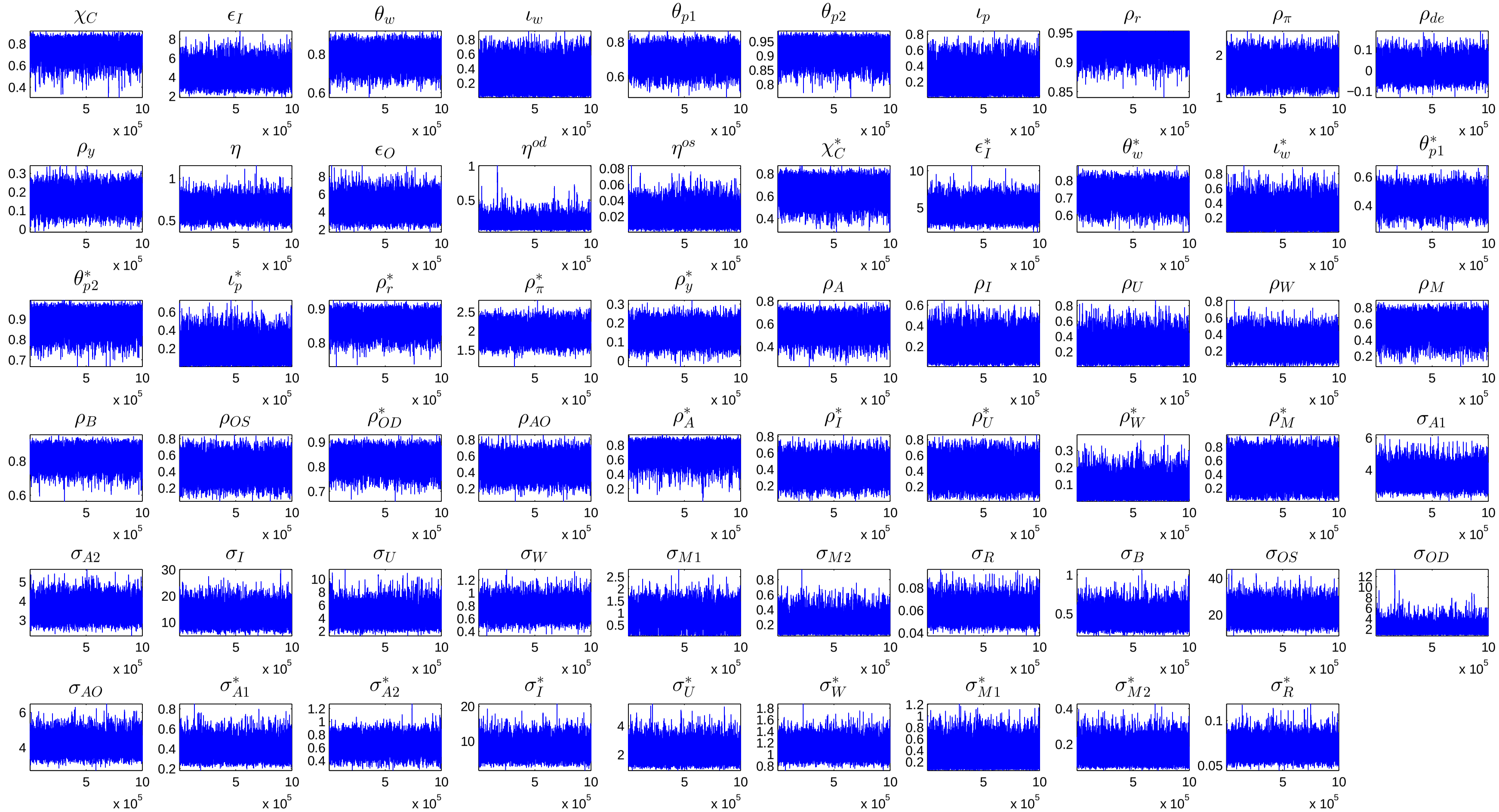
C.1 POSTERIOR MCMC CHAIN

Table C.1: Geweke convergence statistics (p-values)

		Domestic and oil			Foreign		
		4%	8%	15%	4%	8%	15%
χ_C	Habit	0.85	0.85	0.81	0.41	0.42	0.81
ϵ_I	Inv. adj. cost	0.48	0.47	0.47	0.26	0.26	0.47
θ_w	Calvo wages	0.71	0.73	0.74	0.01	0.03	0.74
ι_w	Indexation, π_w	0.63	0.59	0.54	0.33	0.33	0.54
θ_{p1}	Calvo prices 1	0.98	0.98	0.98	0.58	0.59	0.98
θ_{p2}	Calvo prices 2	0.27	0.26	0.23	0.39	0.33	0.23
ι_p	Indexation, π_p	0.94	0.94	0.94	0.28	0.28	0.94
ρ_r	Smoothing, r	0.30	0.29	0.22	0.61	0.55	0.22
ρ_π	Taylor, π	0.59	0.56	0.52	0.63	0.67	0.52
ρ_{de}	Taylor, Δe	0.40	0.37	0.35	–	–	–
ρ_y	Taylor, gdp	0.26	0.27	0.19	0.44	0.40	0.37
η	H-F elasticity	0.21	0.18	0.16	–	–	–
ϵ_O	Inv. adj. cost oil	0.51	0.47	0.41	–	–	–
η^{od}	Oil demand elast.	0.54	0.54	0.53	–	–	–
η^{os}	Oil supply elast.	0.62	0.63	0.63	–	–	–
ρ_A	Technology	0.24	0.17	0.14	0.96	0.96	0.96
ρ_I	Investment	0.67	0.66	0.57	0.47	0.47	0.45
ρ_U	Preferences	0.55	0.53	0.51	0.96	0.96	0.96
ρ_W	Wage markup	0.31	0.26	0.23	0.25	0.21	0.18
ρ_M	Price markup	0.60	0.57	0.58	0.93	0.93	0.93
ρ_B	UIP	0.89	0.89	0.87	–	–	–
ρ_{OS}	Oil investment	0.82	0.83	0.83	–	–	–
ρ^*_{OD}	Oil demand	0.77	0.75	0.70	–	–	–
ρ_{AO}	Oil supply	0.50	0.42	0.32	–	–	–
σ_{A1}	Sd technology 1	0.62	0.61	0.54	0.79	0.79	0.77
σ_{A2}	Sd technology 2	0.31	0.28	0.29	0.26	0.28	0.29
σ_I	Sd investment	0.61	0.59	0.58	0.84	0.84	0.82
σ_U	Sd preferences	0.60	0.60	0.56	0.85	0.86	0.84
σ_W	Sd labor supply	0.75	0.76	0.78	0.04	0.05	0.03
σ_{M1}	Sd markup 1	0.97	0.97	0.97	0.96	0.96	0.95
σ_{M2}	Sd markup 2	0.62	0.60	0.57	0.26	0.23	0.25
σ_R	Sd mon. pol.	0.08	0.07	0.08	0.81	0.80	0.76
σ_B	Sd UIP	0.50	0.50	0.47	–	–	–
σ_{OS}	Sd oil inv.	0.84	0.82	0.80	–	–	–
σ_{OD}	Sd oil price	0.42	0.40	0.38	–	–	–
σ_{AO}	Sd oil supply	0.55	0.55	0.55	–	–	–

Note: Geweke (1992) convergence test calculated from the full Markov chain after burn-in. H0: the first 20% draws (4000000-4200000) have equal mean as the last 50% draws (4500000-5000000). The columns represent p-values with 4, 8 and 15% tapering, respectively.

Figure C.2: MCMC draws



C.2 DATA AND SIMULATED MODEL MOMENTS

Table C.2: Data and model moments

		Standard deviation		Autocorrelation	
		Data	Model M(5%-95%)	Data	Model M(5%-95%)
			Domestic variables		
gdp	GDP	2.87	3.00(1.76-4.42)	0.91	0.85(0.69-0.95)
gdp_m	GDP manufacturing	4.06	4.41(2.95-6.17)	0.89	0.73(0.50-0.89)
gdp_s	GDP services	2.25	3.53(2.34-4.99)	0.87	0.75(0.55-0.90)
c	Consumption	1.34	3.54(1.89-5.45)	0.73	0.91(0.80-0.97)
i	Investment	7.08	11.33(5.98-16.96)	0.90	0.93(0.84-0.97)
π_w	Wage inflation	1.27	1.00(0.78-1.28)	0.77	0.80(0.69-0.88)
π	Price inflation	0.78	0.62(0.45-0.81)	0.85	0.86(0.79-0.92)
r	Interest rate	0.17	0.22(0.13-0.33)	0.96	0.89(0.80-0.96)
Δe	Exchange rate	2.69	2.62(2.10-3.17)	0.21	$-0.07(-0.28$-0.15)
o	Output oil	4.20	5.11(3.81-6.62)	0.32	0.47(0.22-0.71)
i_o	Investment oil	7.20	17.46(10.75-25.20)	0.56	0.86(0.75-0.94)
			International variables		
gdp^*	GDP	2.50	2.54(1.42-3.80)	0.90	0.91(0.82-0.97)
gdp_m^*	GDP manufacturing	3.16	3.06(1.73-4.63)	0.90	0.91(0.84-0.97)
gdp_s^*	GDP services	2.04	2.26(1.31-3.44)	0.90	0.89(0.79-0.96)
c^*	Consumption	1.83	2.00(1.22-2.94)	0.89	0.88(0.77-0.96)
i^*	Investment	5.62	7.66(4.14-11.81)	0.90	0.92(0.85-0.97)
π_w	Wage inflation	0.96	1.11(0.86-1.38)	0.59	0.73(0.60-0.83)
π^*	Price inflation	0.58	0.35(0.26-0.45)	0.90	0.84(0.77-0.91)
r^*	Interest rate	0.27	0.22(0.14-0.31)	0.98	0.85(0.74-0.93)
p_{ro}^*	Oil price	37.50	21.24(13.84-29.89)	0.93	0.76(0.58-0.89)

Note: Standard deviations and first order autocorrelations in data versus simulations from the estimated model. Standard deviations are expressed in percent. We report the posterior mean and the 90% highest probability intervals from the simulations. Posterior moments are computed based on every 1000 draw from the posterior MCMC chain.

Figure C.3: Empirical (black) and theoretical (blue) second moments, domestic economy

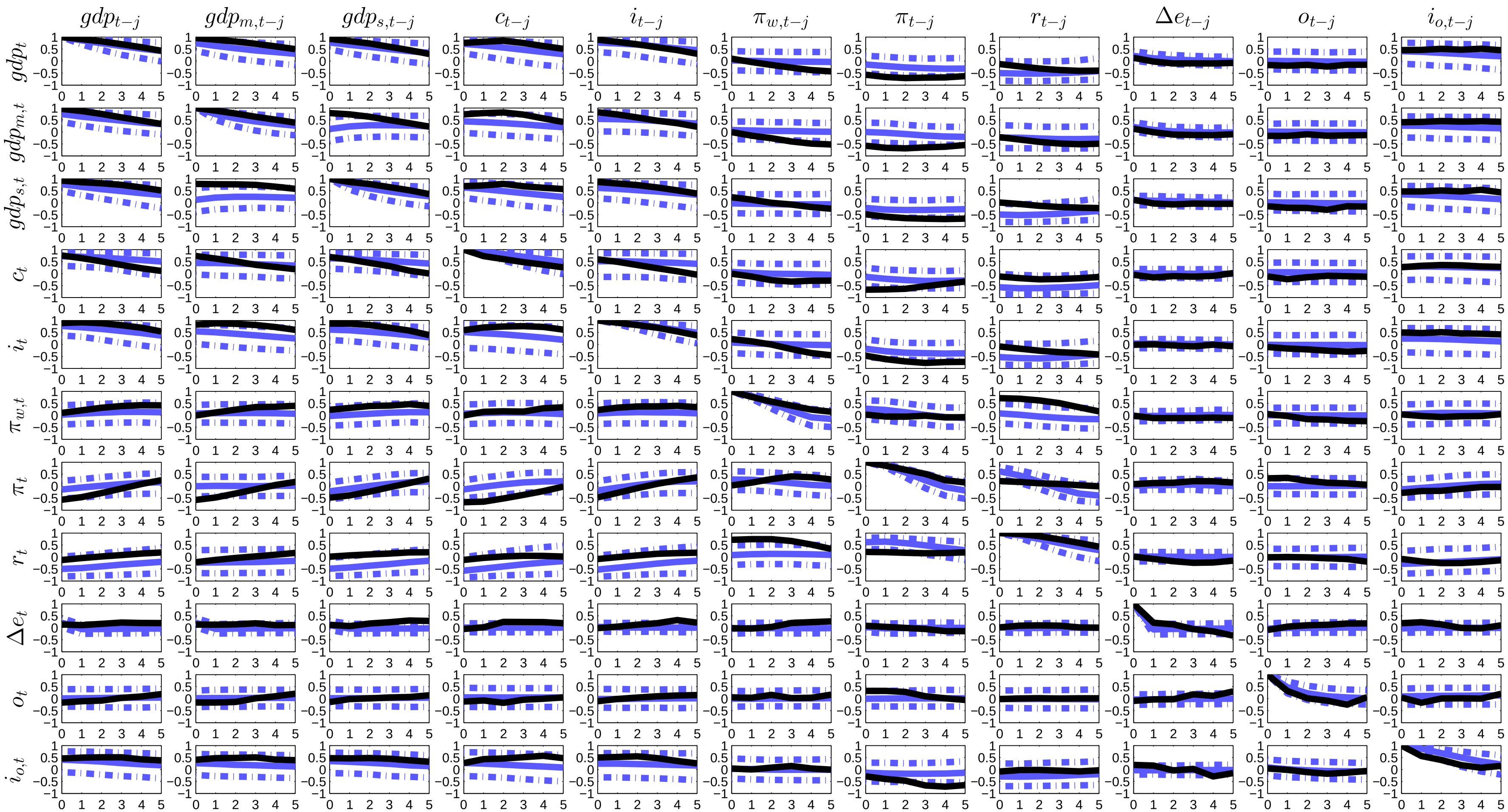


Figure C.4: Empirical (black) and theoretical (blue) second moments, foreign economy

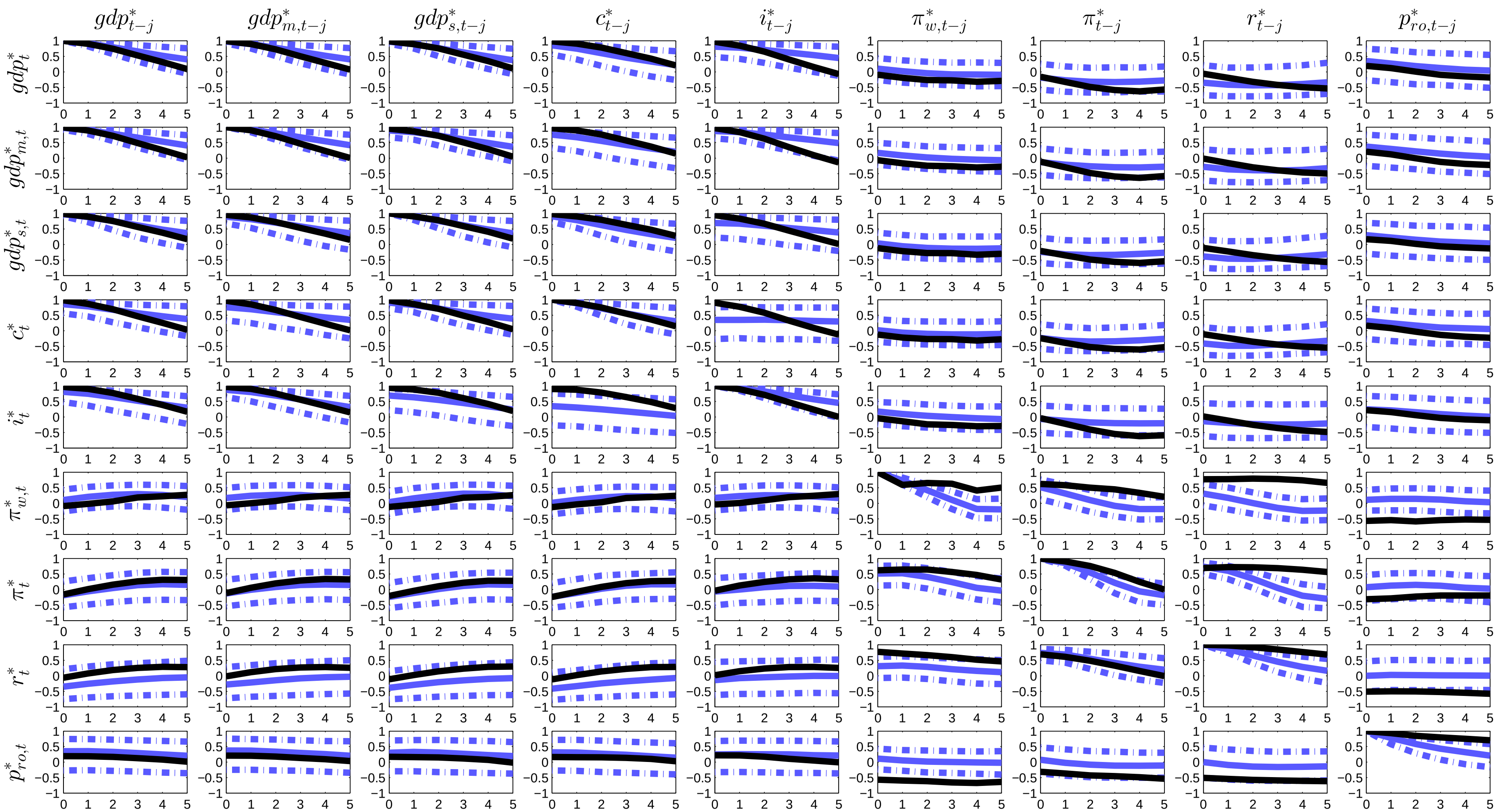


Table C.3: Unconditional (stationary) variance decomposition in percent

Variable	*All mainland shocks*	σ_{A1}	σ_{A2}	σ_R	σ_U	σ_I	σ_M	σ_S	σ_W	σ^*_{A1}	σ^*_{A2}	σ^*_R	σ^*_U	σ^*_I	σ^*_M	σ^*_S	σ^*_W	σ^*_B	σ^*_{OD}	σ^*_{OS}	σ^*_{AO}
		Decomposition																			
Panel A: mainland Norway																					
GDP	52.9	3.6	7.5	5.2	4.4	8.9	2.0	11.3	10.0	0.5	0.2	0.6	1.0	12.7	0.1	3.2	11.6	5.4	10.8	0.9	0.2
Consumption	41.1	1.1	2.9	3.1	16.0	3.3	2.3	6.1	6.2	0.2	0.0	0.6	1.1	13.6	0.1	3.1	9.9	3.5	25.3	1.1	0.5
Investment	72.7	2.7	2.2	3.3	0.4	31.9	13.0	11.4	7.8	0.2	0.0	0.2	0.3	6.2	0.0	1.1	4.9	4.7	9.2	0.1	0.2
Public spending	67.4	3.1	3.3	19.3	3.8	3.3	16.0	13.4	5.2	0.6	0.3	1.0	0.2	8.5	0.1	2.5	11.0	6.6	1.2	0.6	0.0
Trade balance	49.6	6.1	10.0	1.3	2.0	4.0	17.6	5.6	2.9	0.2	0.4	0.3	2.0	3.8	0.1	1.1	2.1	18.2	21.1	0.8	0.3
Hours	51.7	4.9	0.4	0.6	0.1	2.9	29.2	6.4	7.1	0.7	0.1	0.6	0.6	10.7	0.2	3.1	10.4	8.0	13.3	0.3	0.3
CPI inflation	71.2	4.4	4.2	10.6	0.8	3.2	17.8	22.5	7.6	0.2	0.0	0.3	0.5	4.8	0.1	1.5	4.2	6.3	10.2	0.4	0.2
Wage inflation	85.9	12.9	3.8	2.9	0.2	0.4	41.7	21.0	3.0	0.6	0.1	0.2	0.1	0.4	0.3	1.1	2.4	7.5	1.5	0.0	0.0
Real exchange rate	62.2	0.9	1.2	0.3	0.2	0.8	6.5	16.5	35.7	0.2	0.0	0.4	0.6	9.6	0.1	2.1	7.3	2.9	14.0	0.4	0.3
Panel B: Offshore Norwegian oil industry																					
Output	10.2	0.2	0.5	5.1	0.3	1.2	0.8	1.3	1.0	0.1	2.2	0.4	0.3	4.8	0.0	49.8	10.2	12.0	9.7	0.1	0.2
Gross revenues	2.5	0.0	0.1	0.2	0.0	0.8	0.2	0.3	0.8	0.0	0.0	0.0	0.1	0.6	0.0	0.0	0.5	0.2	1.0	10.9	84.2
Value added	3.0	0.1	0.0	0.3	0.0	0.3	0.9	0.9	0.5	0.2	1.5	0.4	4.2	2.4	0.1	1.8	2.3	2.0	77.0	0.5	4.7
Utilization	1.6	0.0	0.0	0.1	0.0	0.1	0.6	0.5	0.2	0.2	1.6	0.3	4.4	1.8	0.1	1.7	1.8	2.2	76.4	3.1	4.8
Materials	1.0	0.0	0.0	0.1	0.0	0.2	0.3	0.1	0.2	0.2	1.5	0.3	4.2	1.4	0.1	1.4	1.3	2.1	70.8	11.2	4.6
Hours	13.7	0.3	0.3	1.0	0.0	3.1	2.0	3.0	3.8	0.1	0.1	0.1	0.2	2.5	0.0	0.4	2.4	1.0	6.2	73.2	0.2
Investments	11.0	0.1	0.1	0.9	0.0	1.1	0.7	1.0	7.3	0.0	0.1	0.1	0.2	0.7	0.0	0.3	0.9	0.4	6.0	80.2	0.2

Note: Calculated at the posterior mean. Note that when the predictive horizon becomes large, the contribution of each shock converges to their contribution to the unconditional volatility. Thus, numbers in the table represent each shock's contribution to the unconditional volatility.

Figure C.5: Historical variance decomposition, mainland GDP

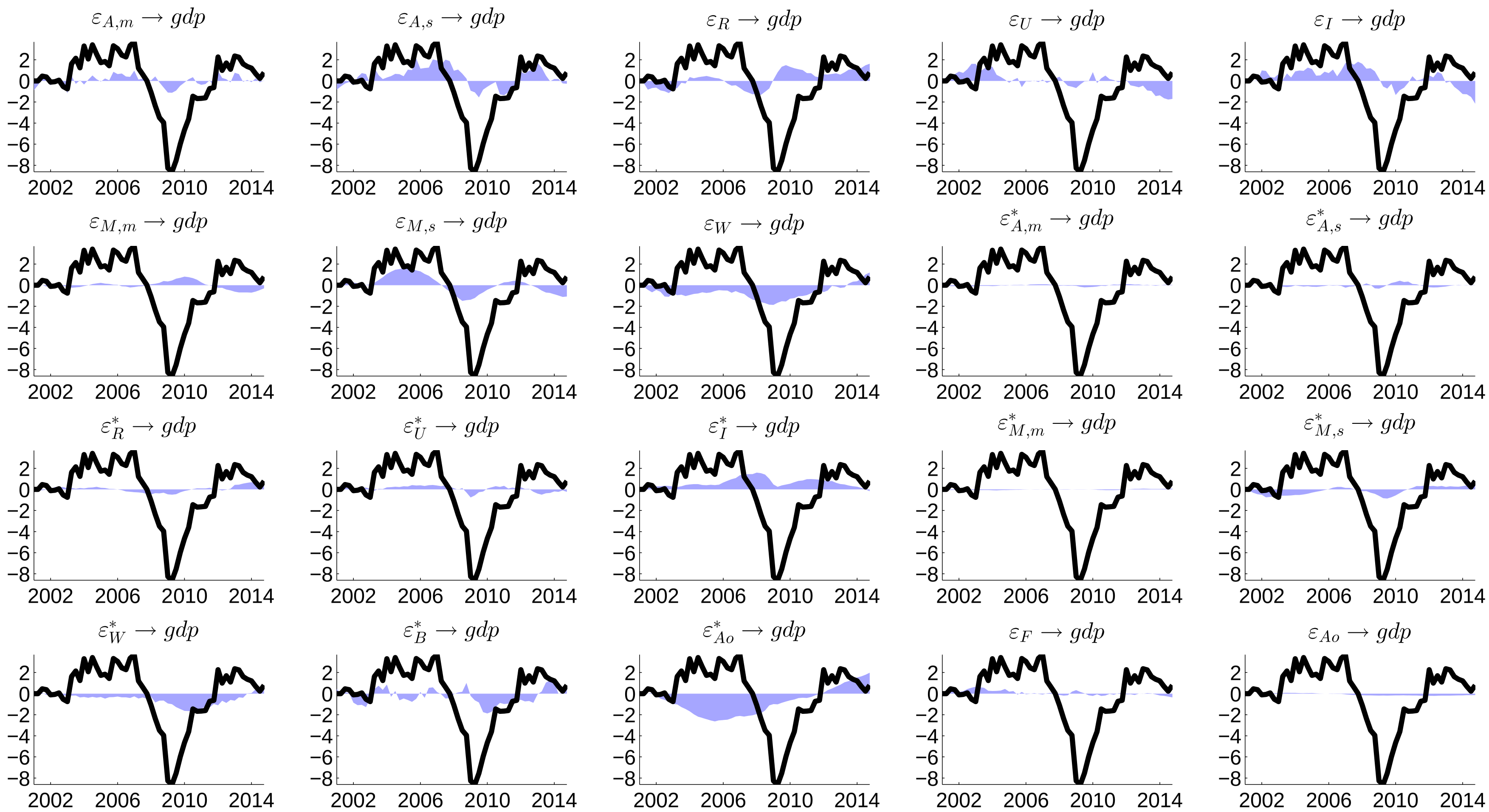


Figure C.6: Smoothed shocks (90% highest probability densities)

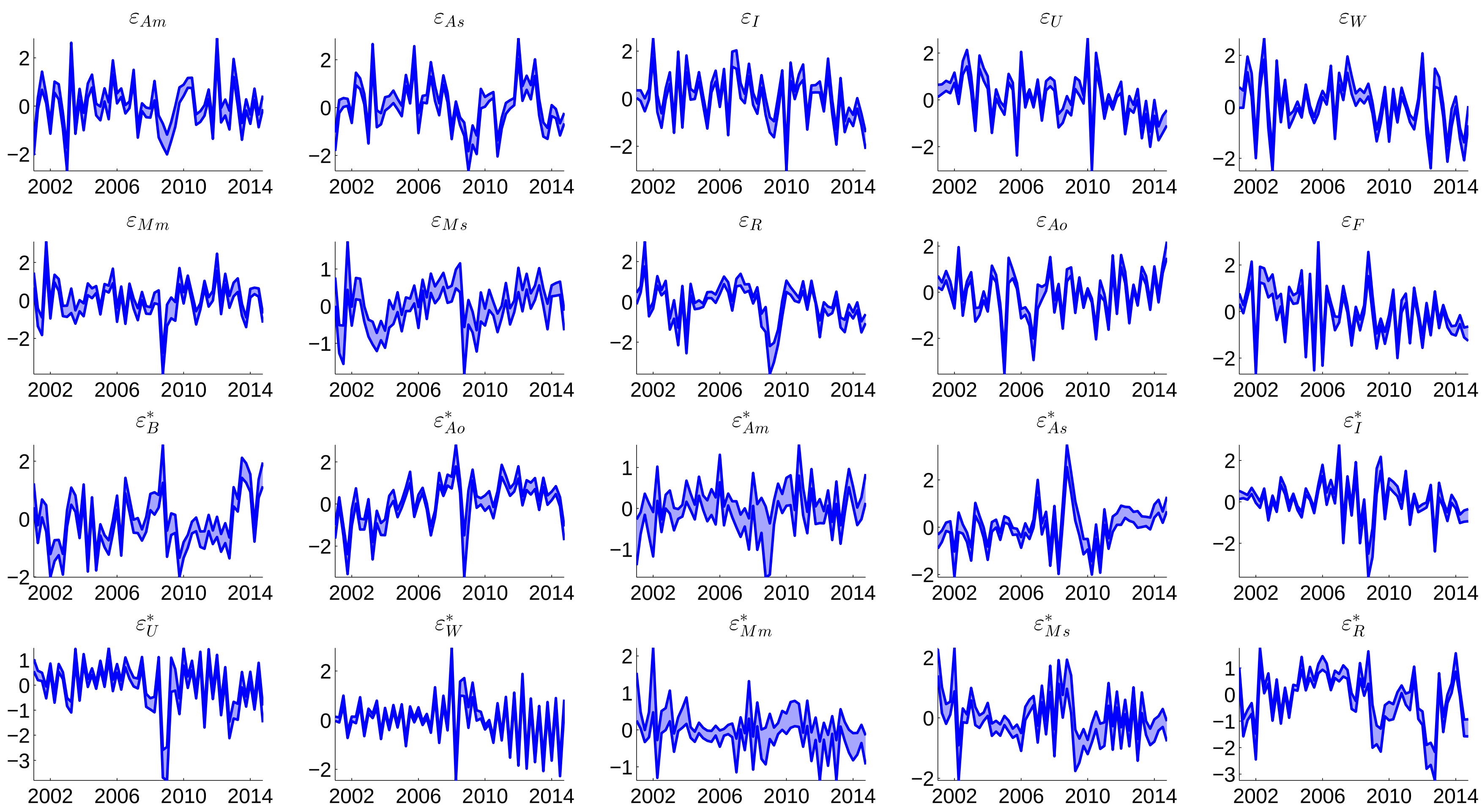
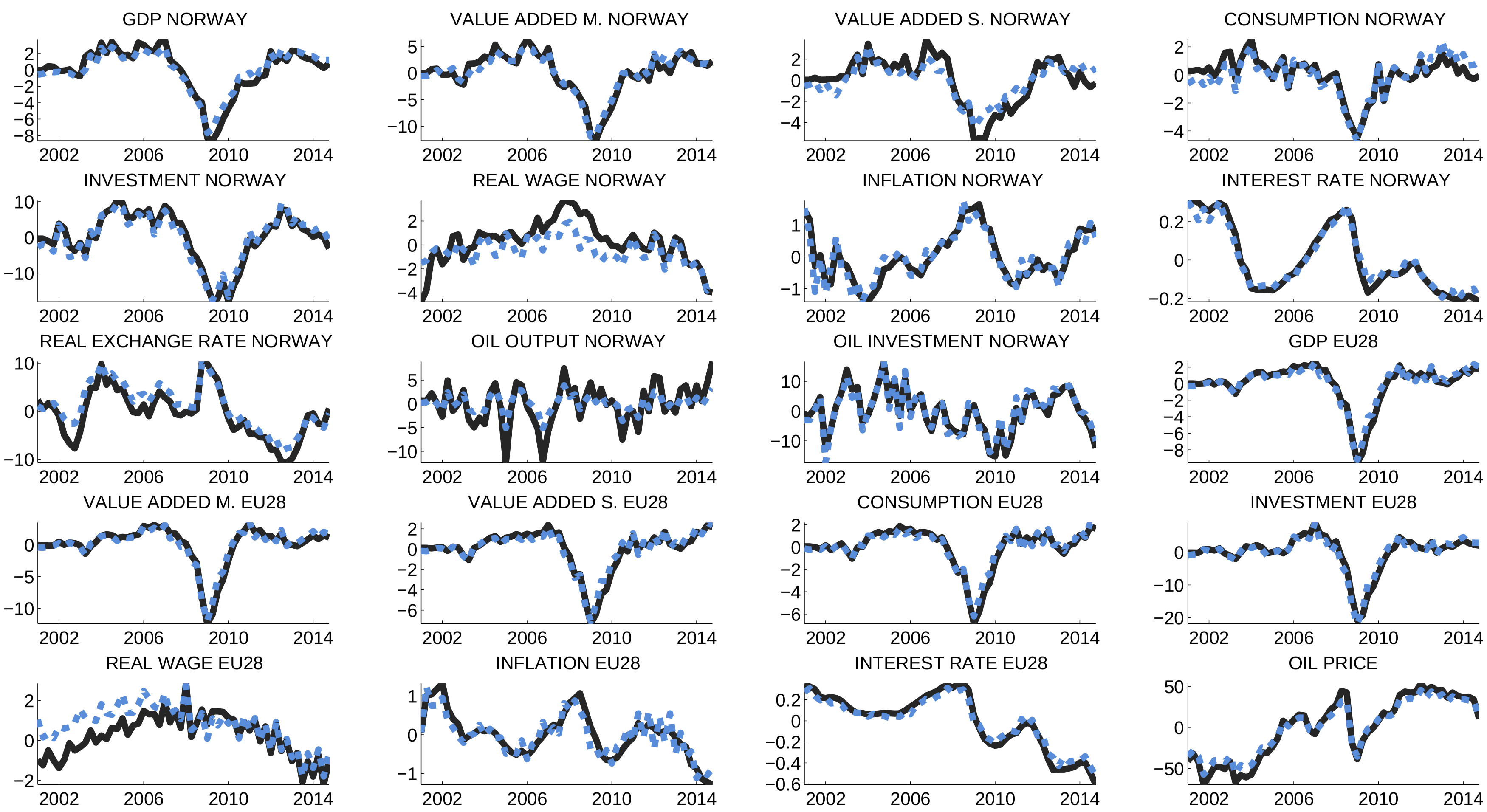
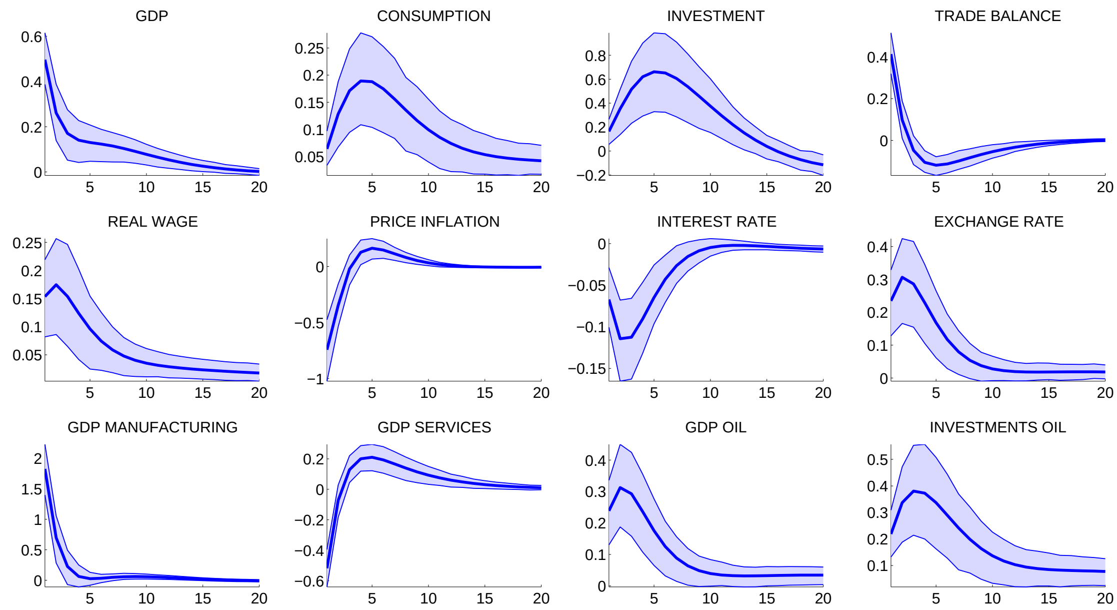


Figure C.7: Data (black) and 1-step ahead forecasts (blue)



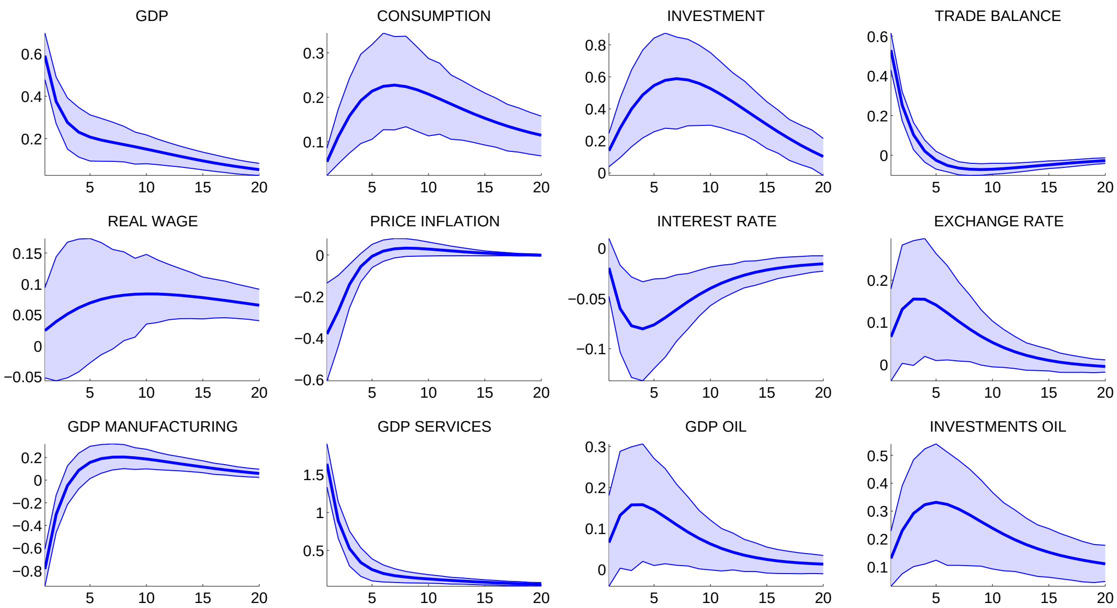
C.3 FULL SET OF BASELINE IMPULSE RESPONSES

Figure C.8: Domestic TFP manufacturing



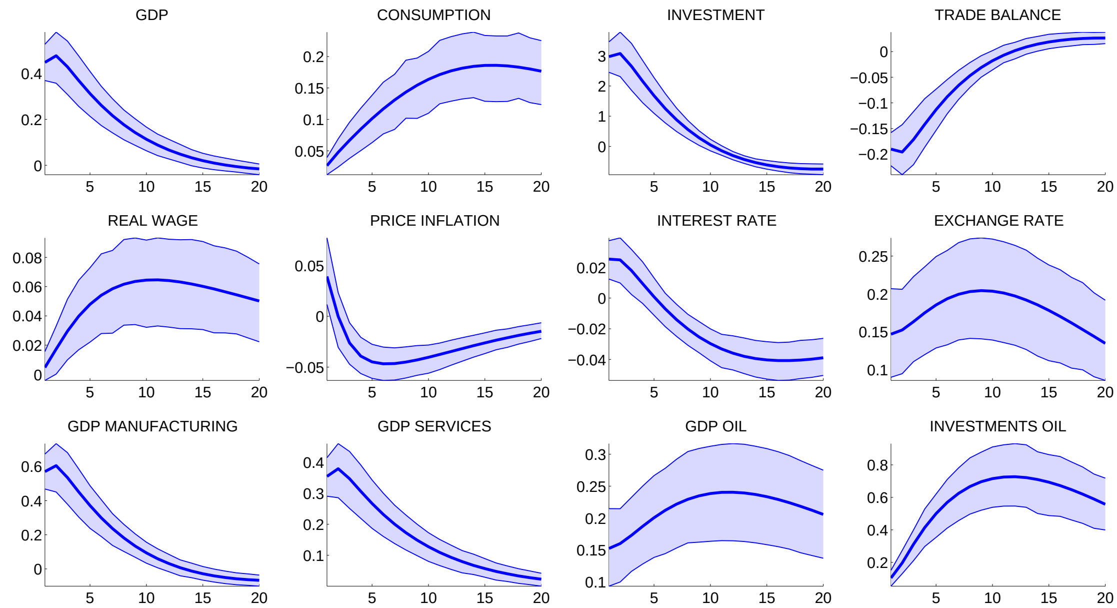
Note: See Figure 7 for details.

Figure C.9: Domestic TFP services



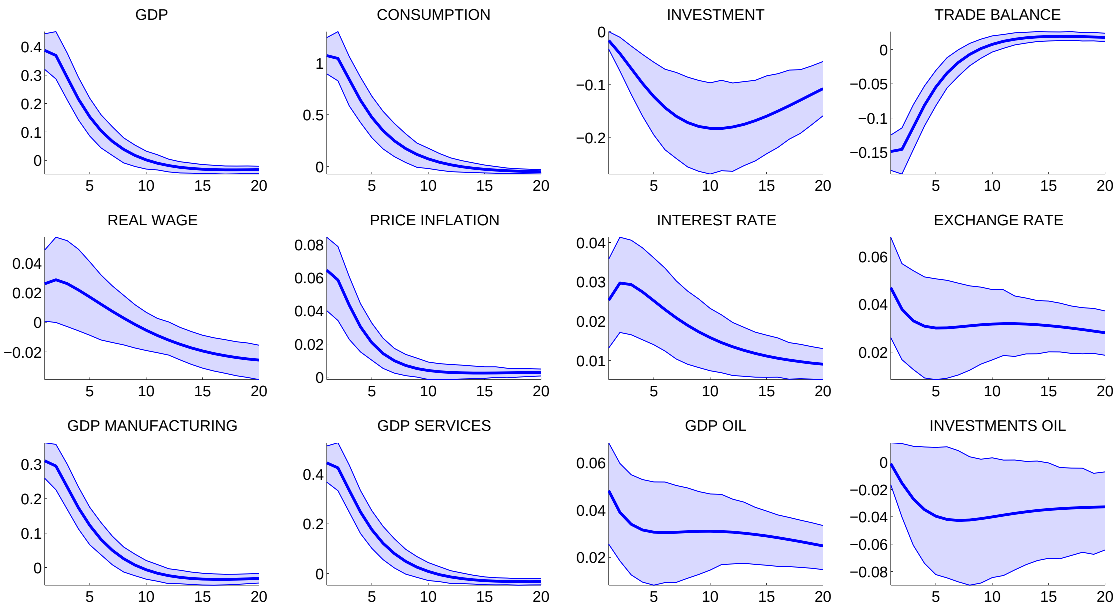
Note: See Figure 7 for details.

Figure C.10: Domestic MEI



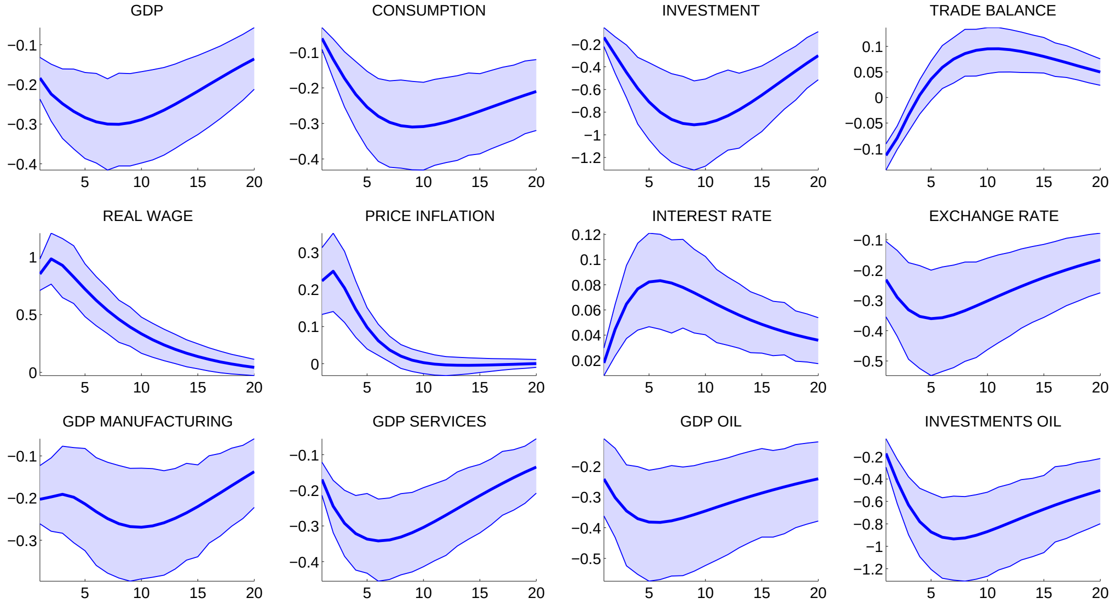
Note: See Figure 7 for details.

Figure C.11: Domestic preference



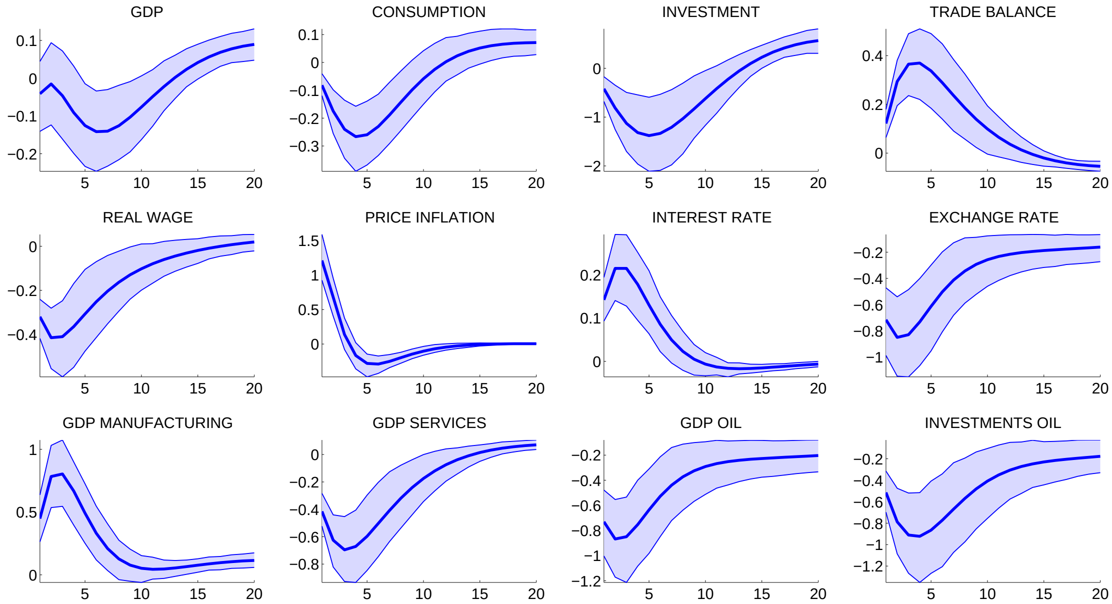
Note: See Figure 7 for details.

Figure C.12: Domestic wage markup



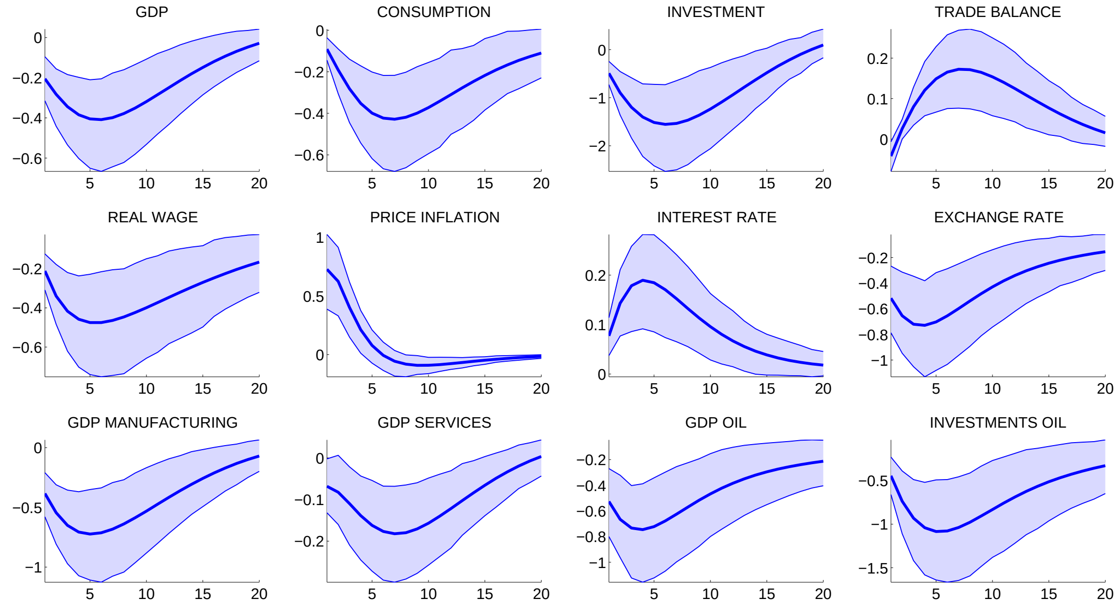
Note: See Figure 7 for details.

Figure C.13: Domestic markup manufacturing



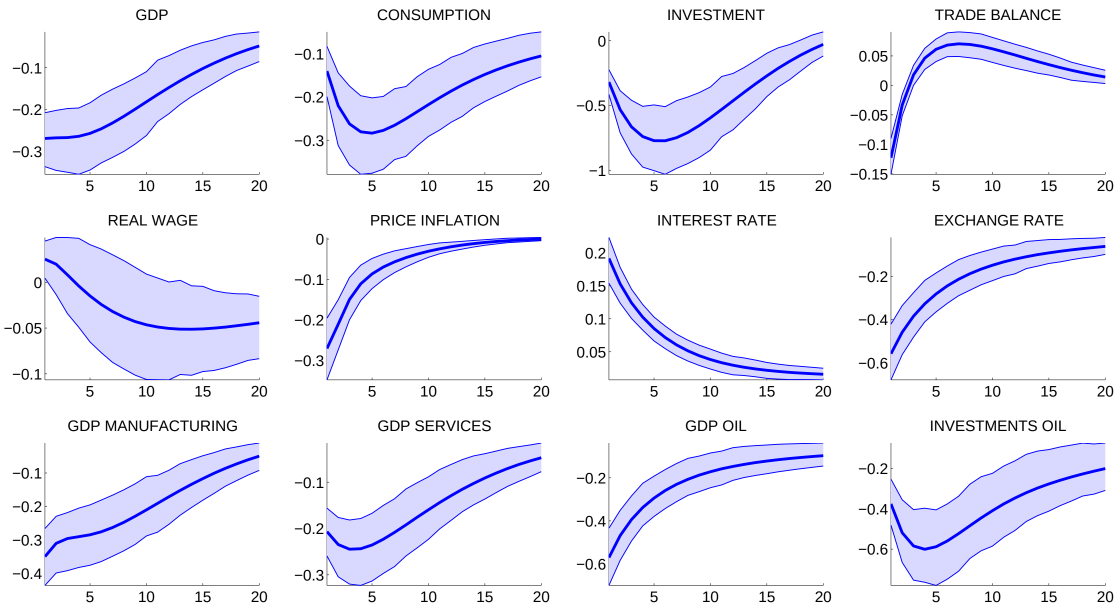
Note: See Figure 7 for details.

Figure C.14: Domestic markup services



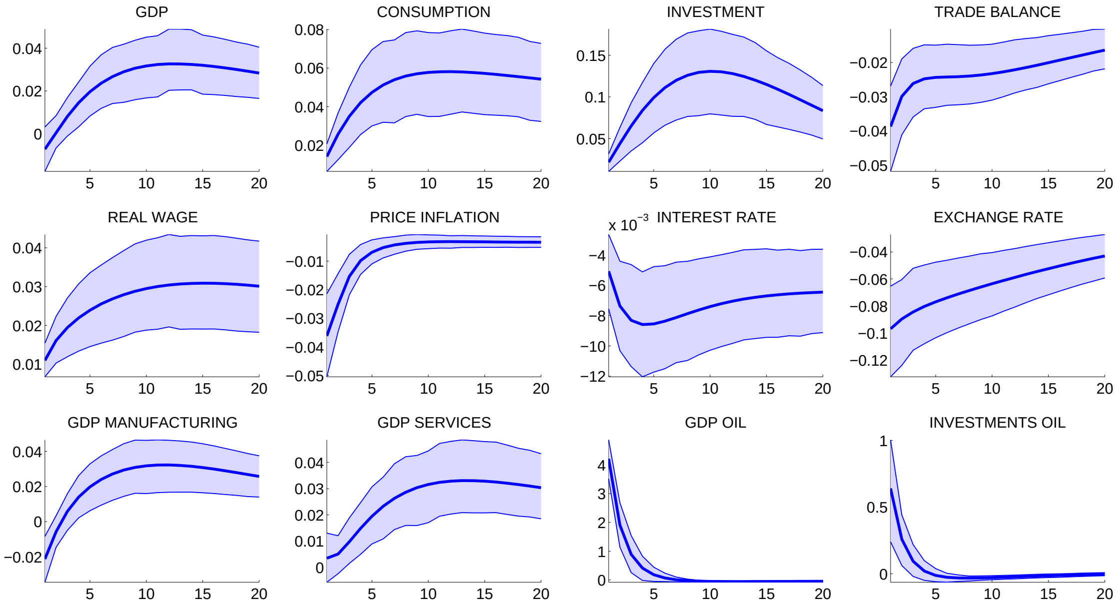
Note: See Figure 7 for details.

Figure C.15: Domestic monetary policy



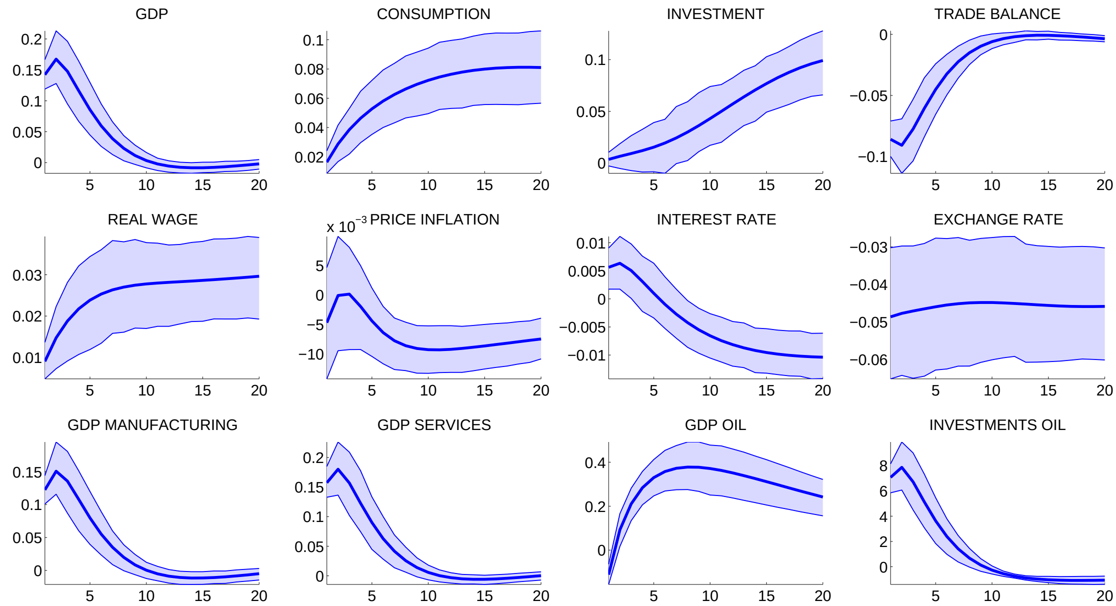
Note: See Figure 7 for details.

Figure C.16: Domestic oil supply



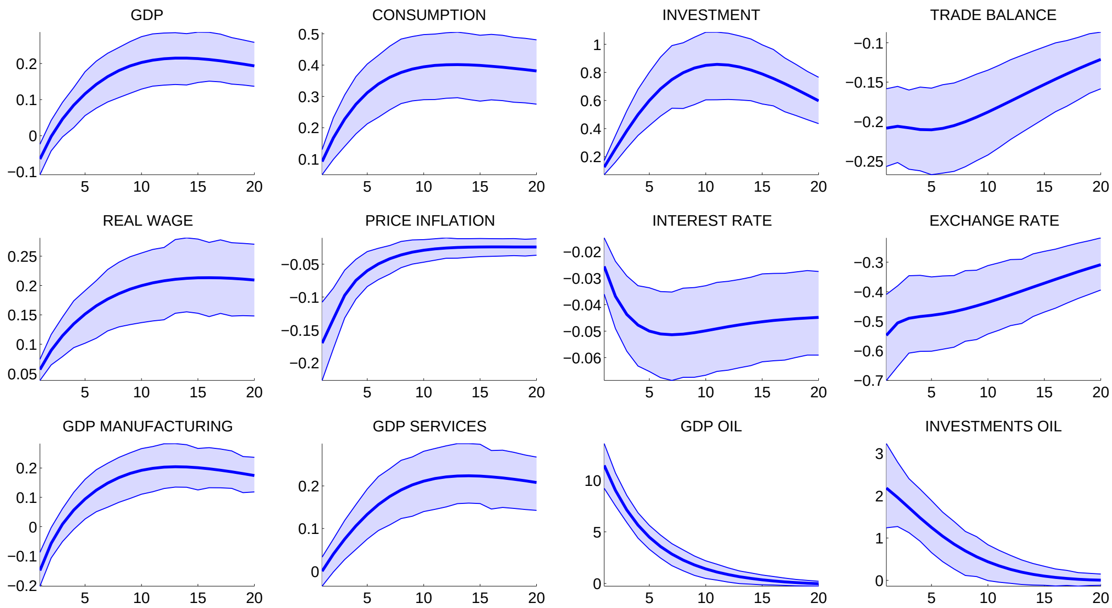
Note: See Figure 7 for details.

Figure C.17: Domestic oil capacity



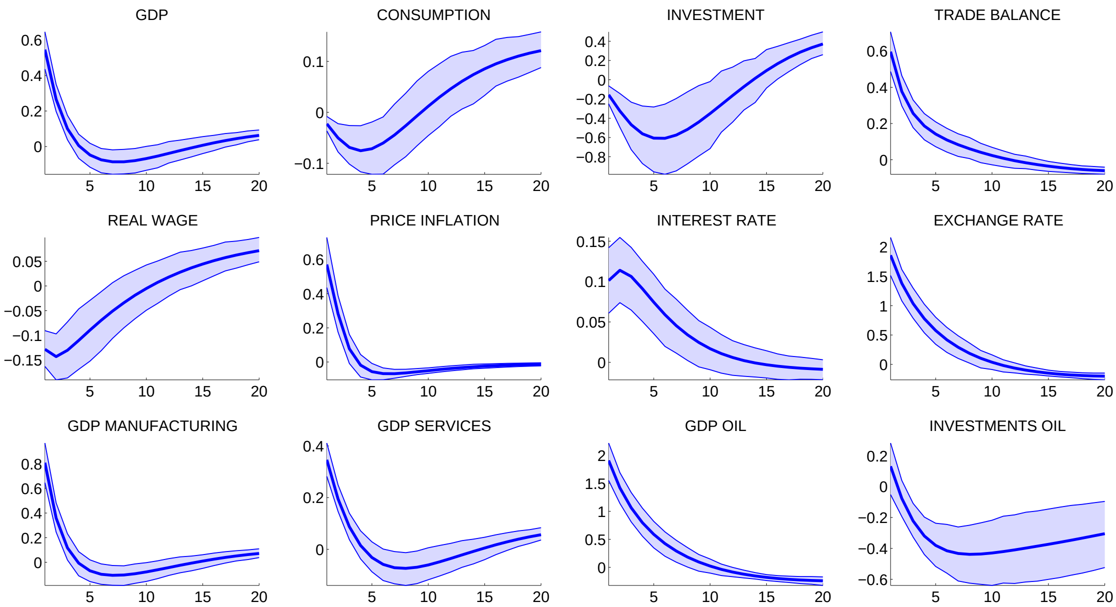
Note: See Figure 7 for details.

Figure C.18: International oil supply



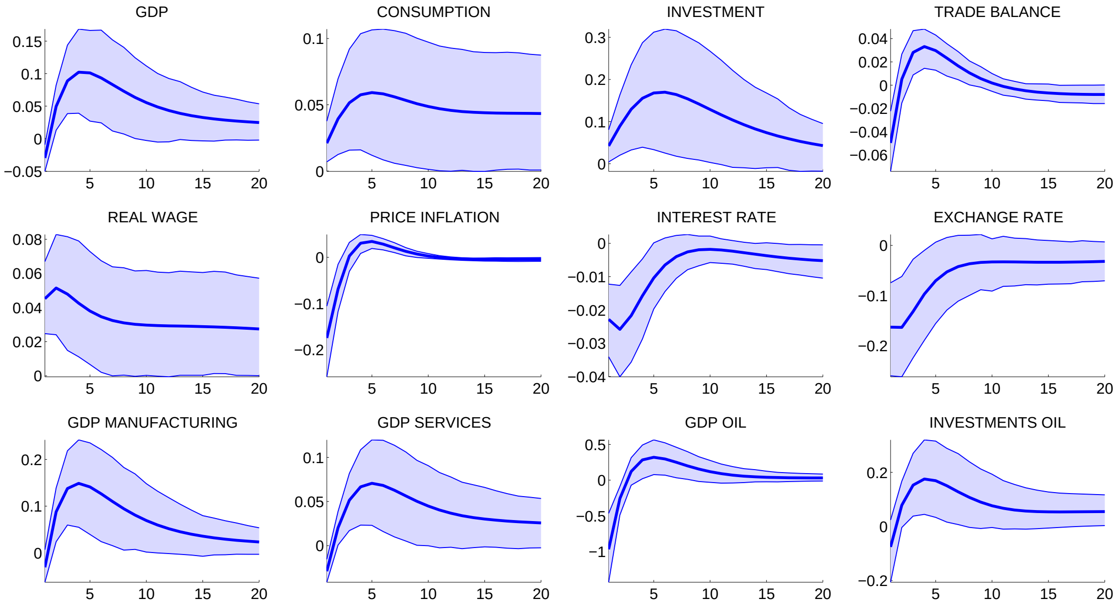
Note: See Figure 7 for details.

Figure C.19: International risk



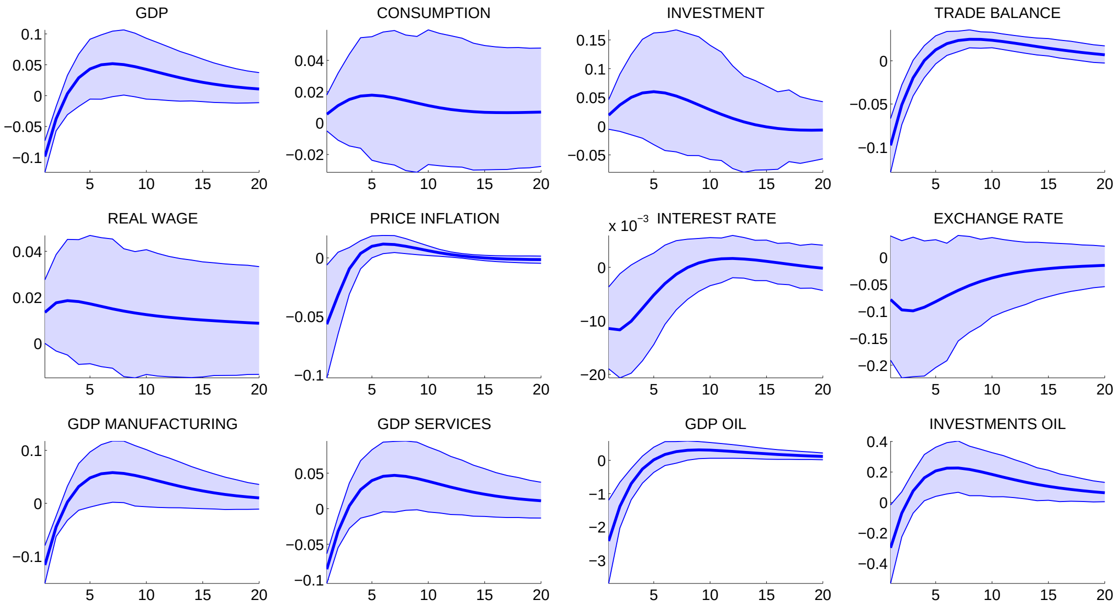
Note: See Figure 7 for details.

Figure C.20: International TFP manufacturing



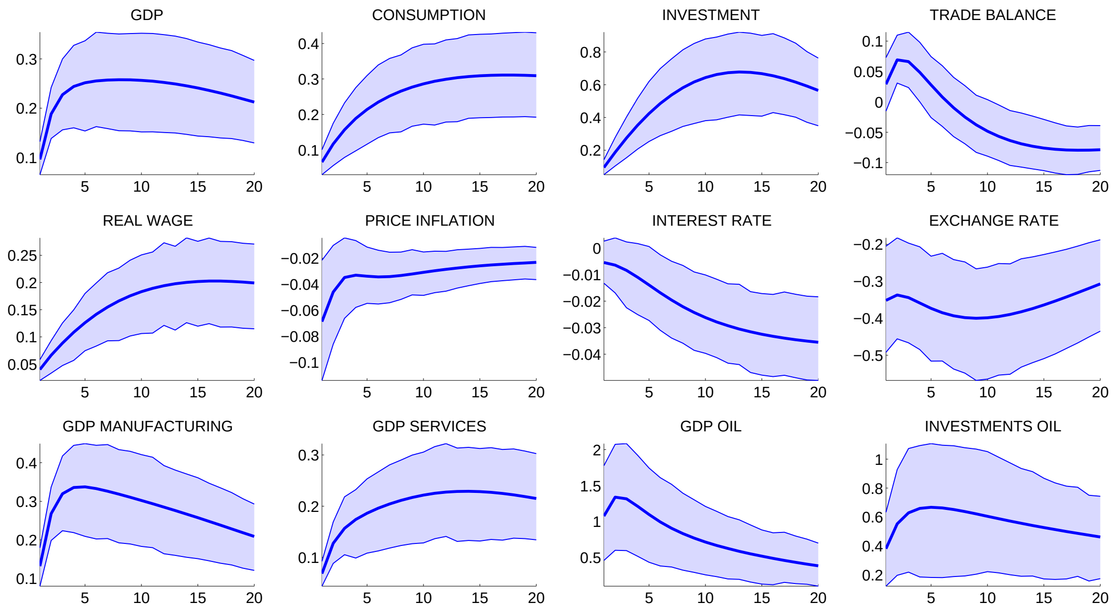
Note: See Figure 7 for details.

Figure C.21: International TFP services



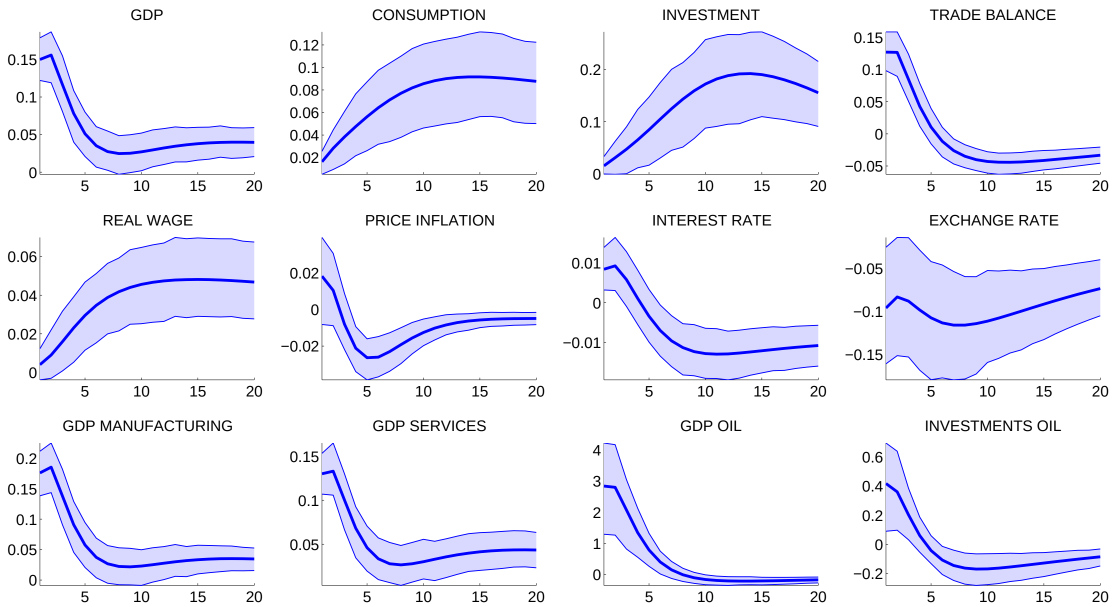
Note: See Figure 7 for details.

Figure C.22: International MEI



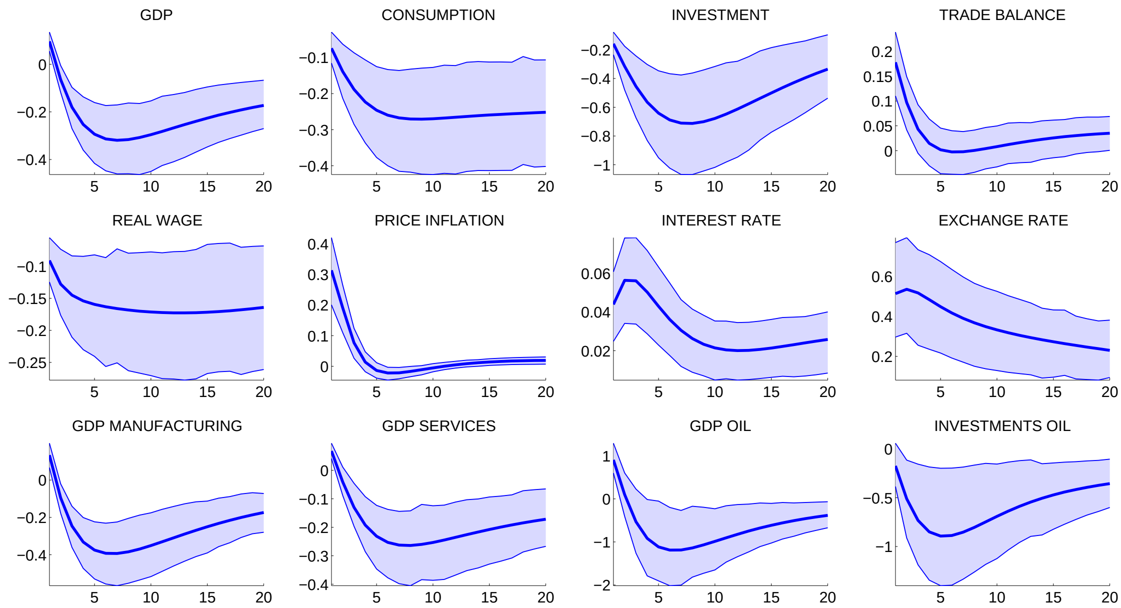
Note: See Figure 7 for details.

Figure C.23: International preference



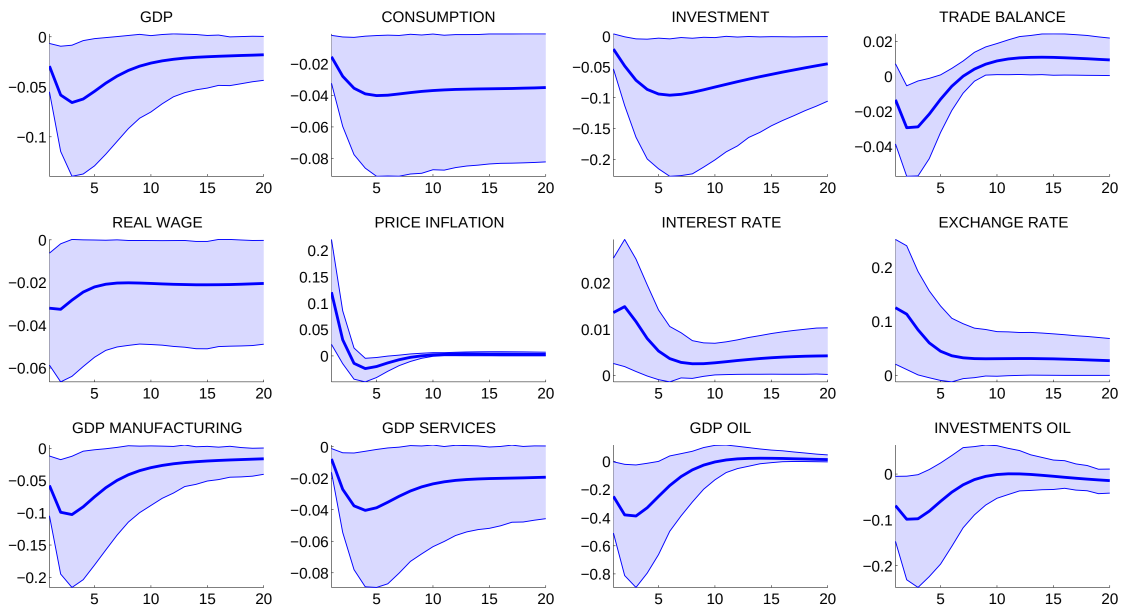
Note: See Figure 7 for details.

Figure C.24: International wage markup



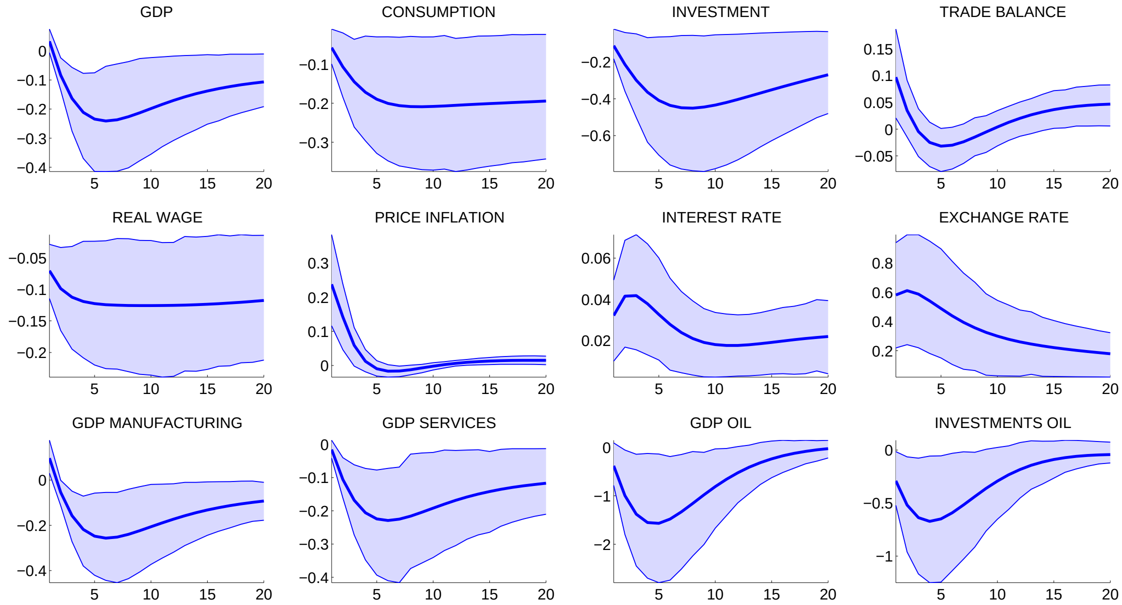
Note: See Figure 7 for details.

Figure C.25: International markup manufacturing



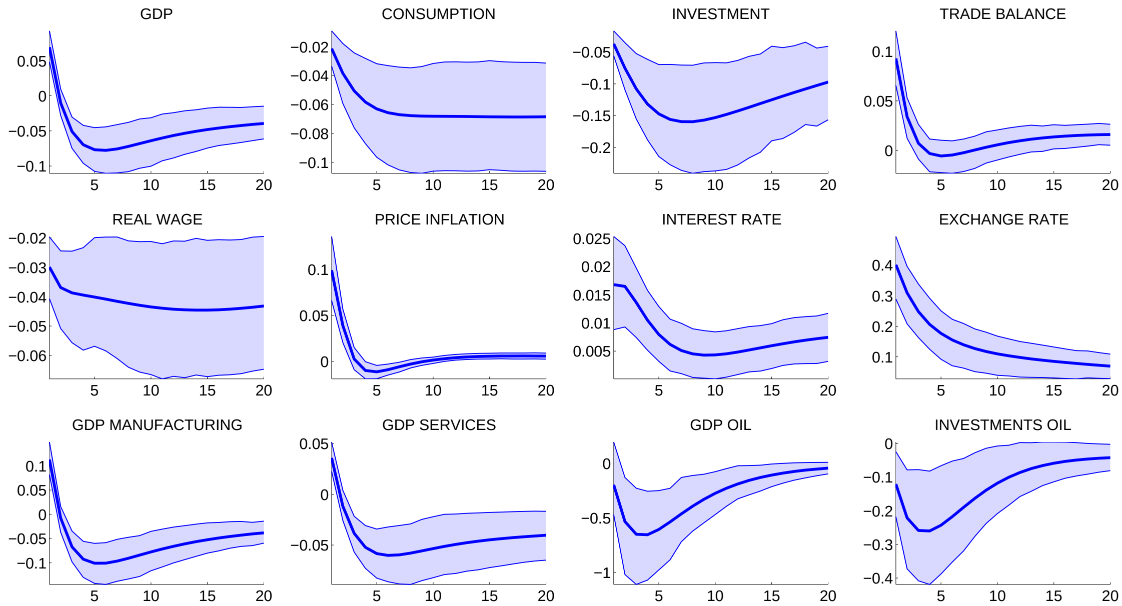
Note: See Figure 7 for details.

Figure C.26: International markup services



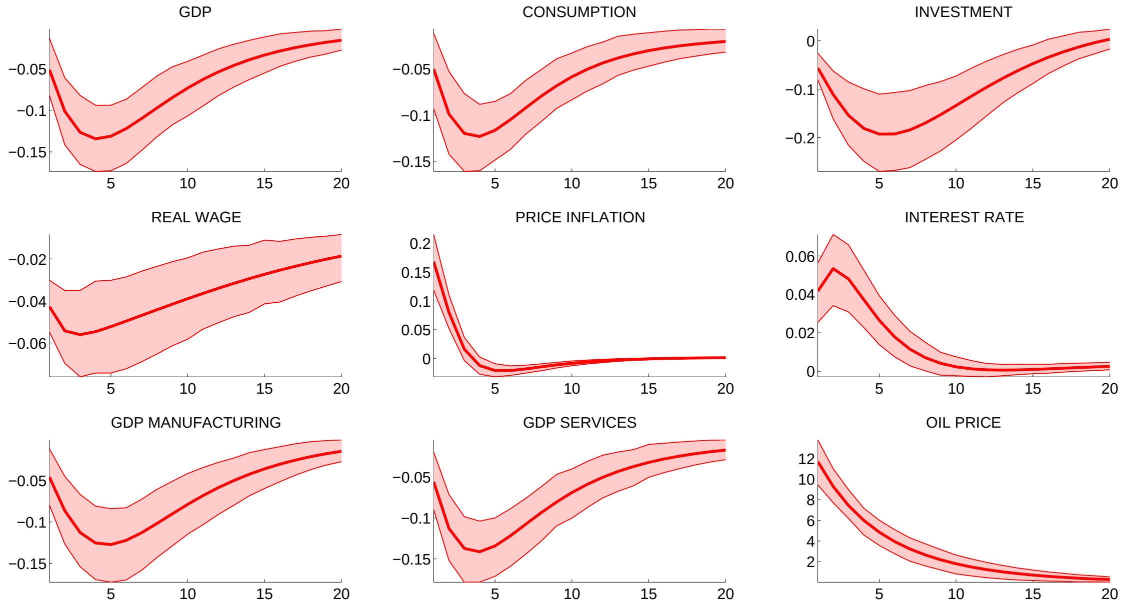
Note: See Figure 7 for details.

Figure C.27: International monetary policy



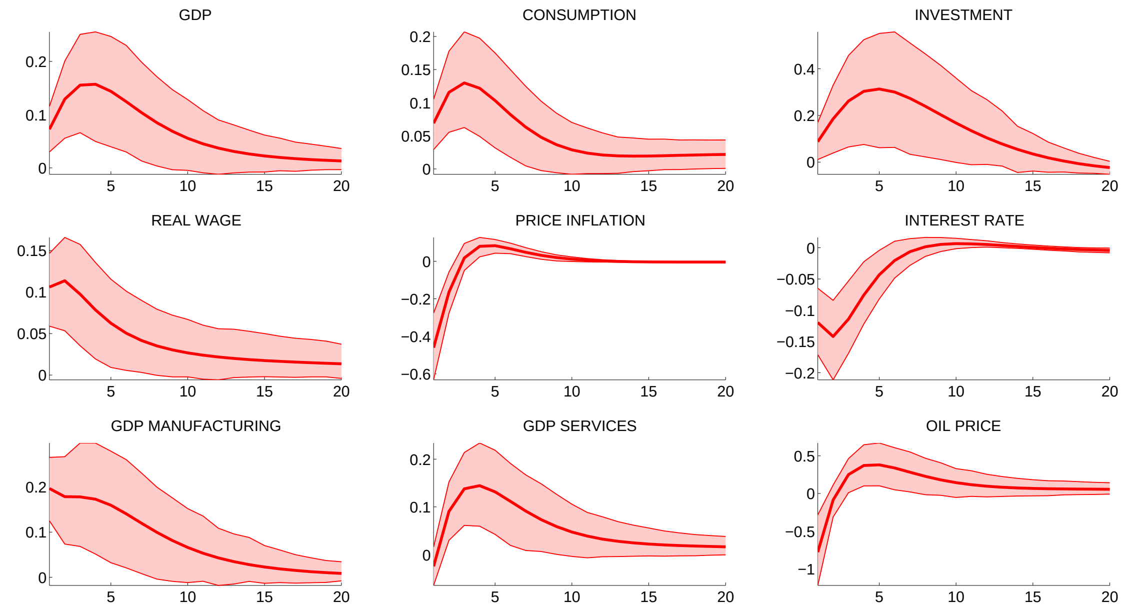
Note: See Figure 7 for details.

Figure C.28: International economy: international oil price shock



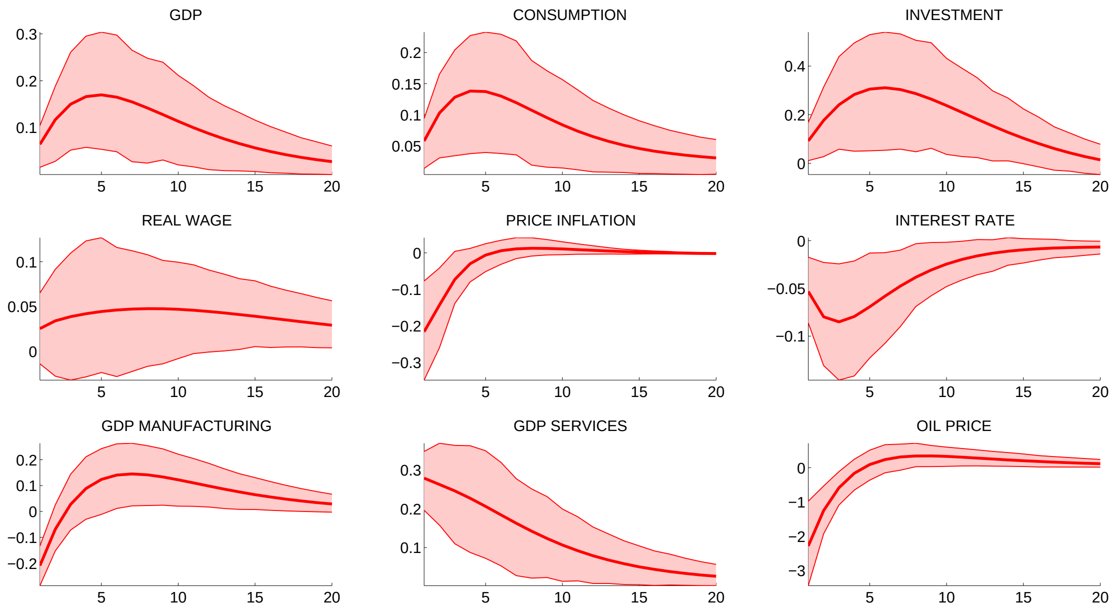
Note: See Figure 7 for details.

Figure C.29: International economy: international TFP manufacturing



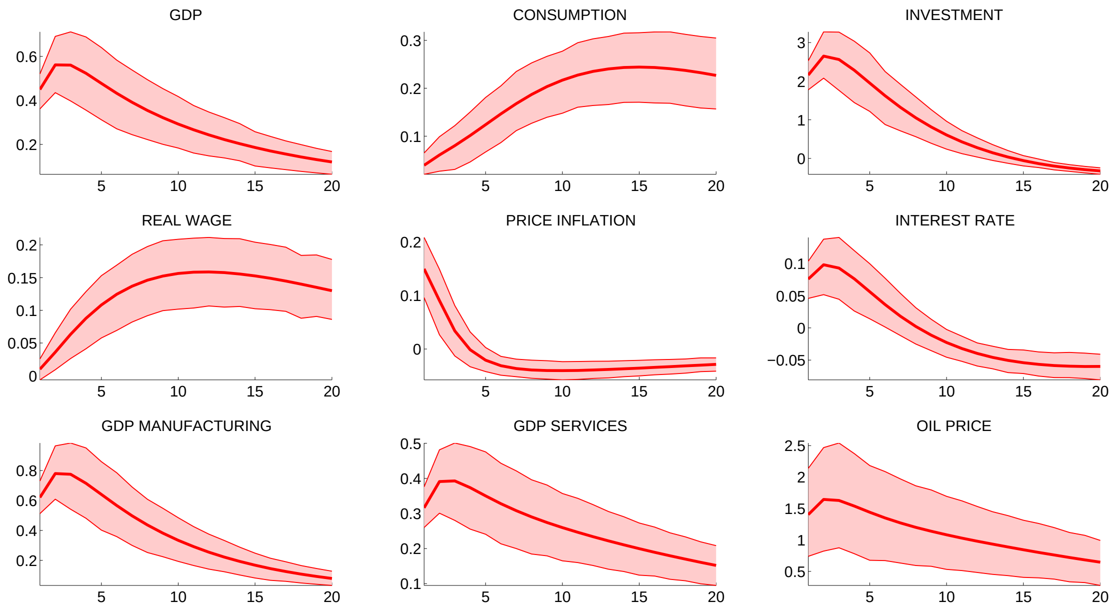
Note: See Figure 6 for details.

Figure C.30: International economy: international TFP services



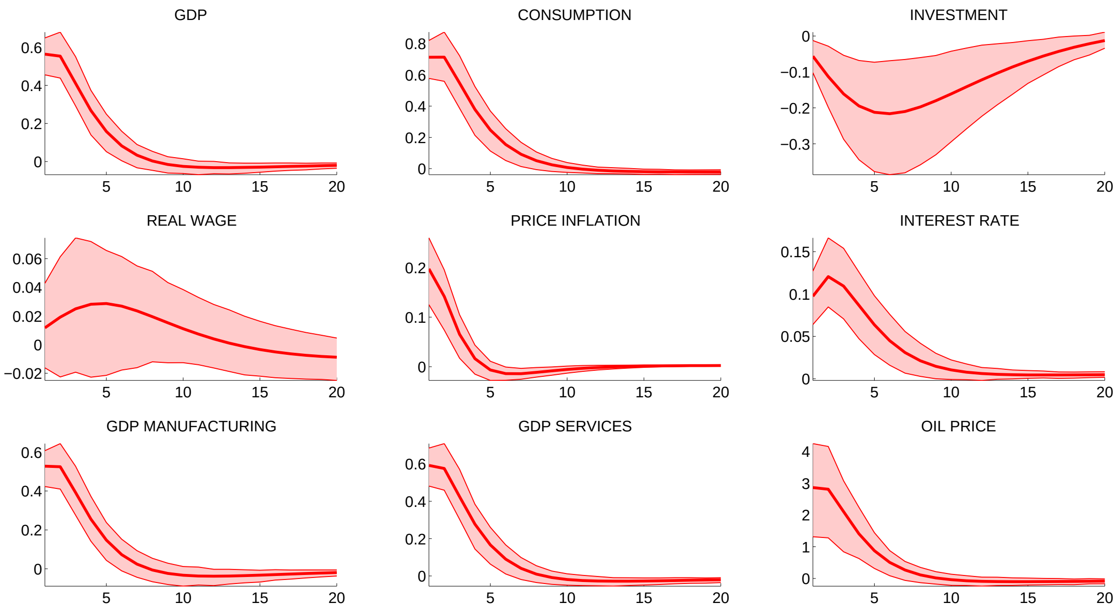
Note: See Figure 6 for details.

Figure C.31: International economy: international MEI



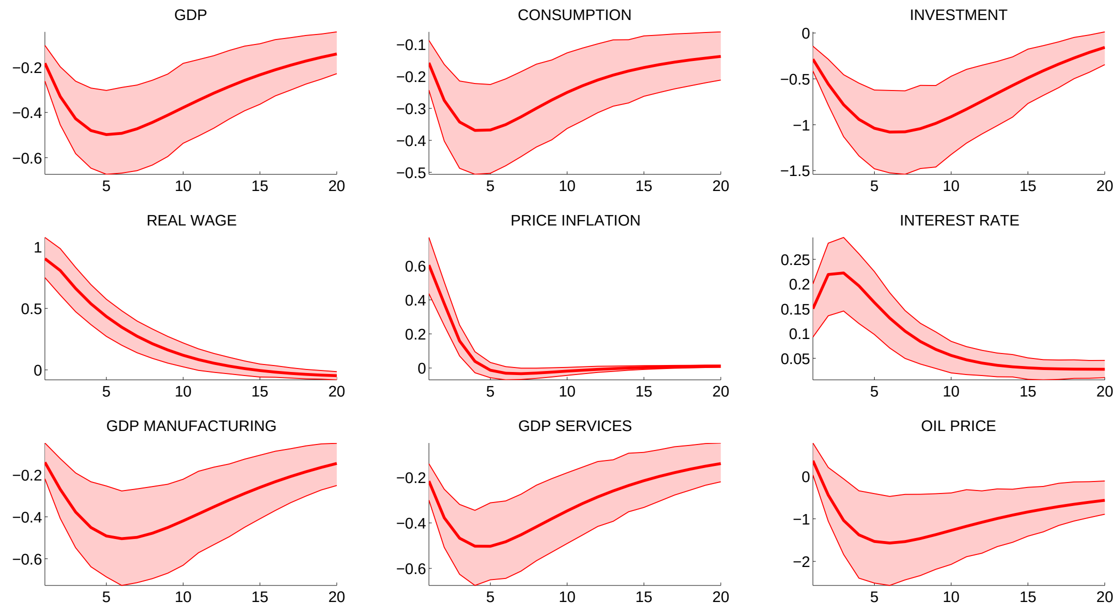
Note: See Figure 6 for details.

Figure C.32: International economy: international preference



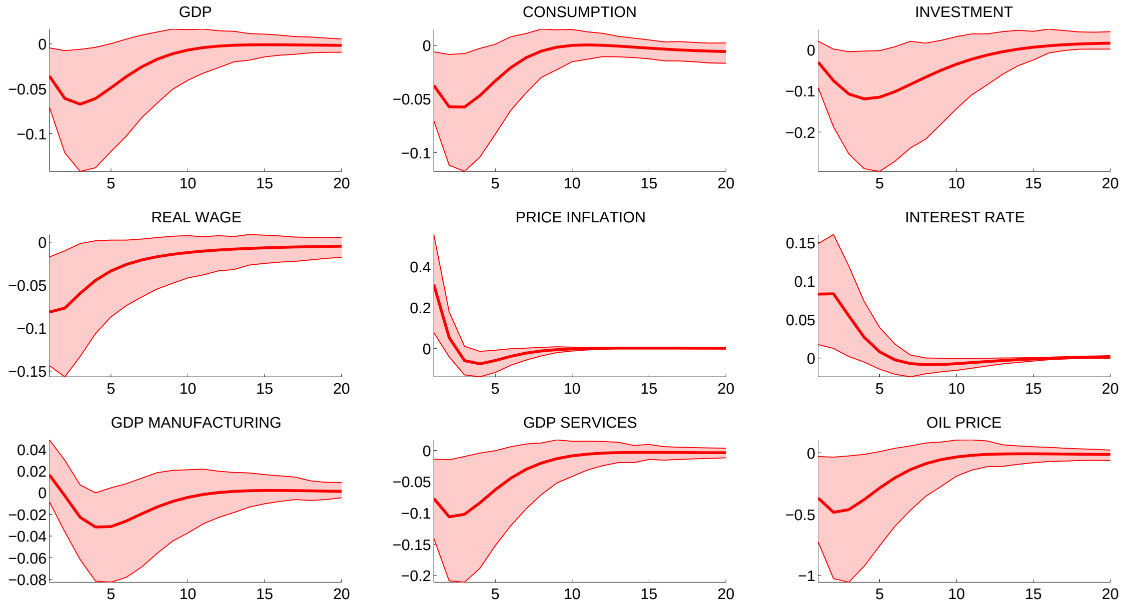
Note: See Figure 6 for details.

Figure C.33: Domestic economy: international wage markup



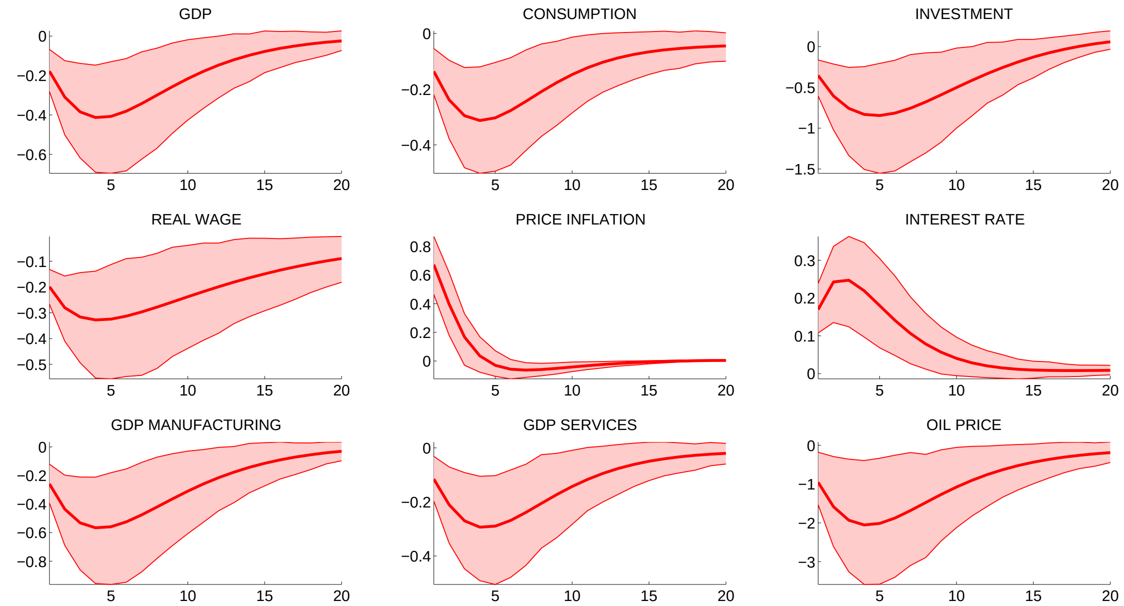
Note: See Figure 6 for details.

Figure C.34: International economy: international markup manufacturing



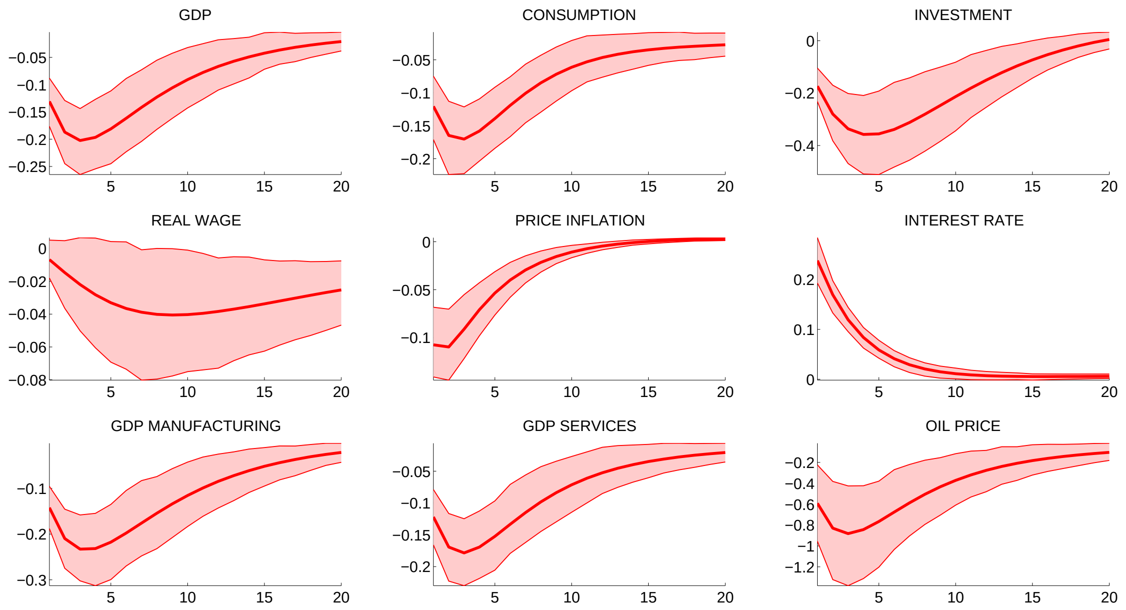
Note: See Figure 6 for details.

Figure C.35: International economy: international markup services



Note: See Figure 6 for details.

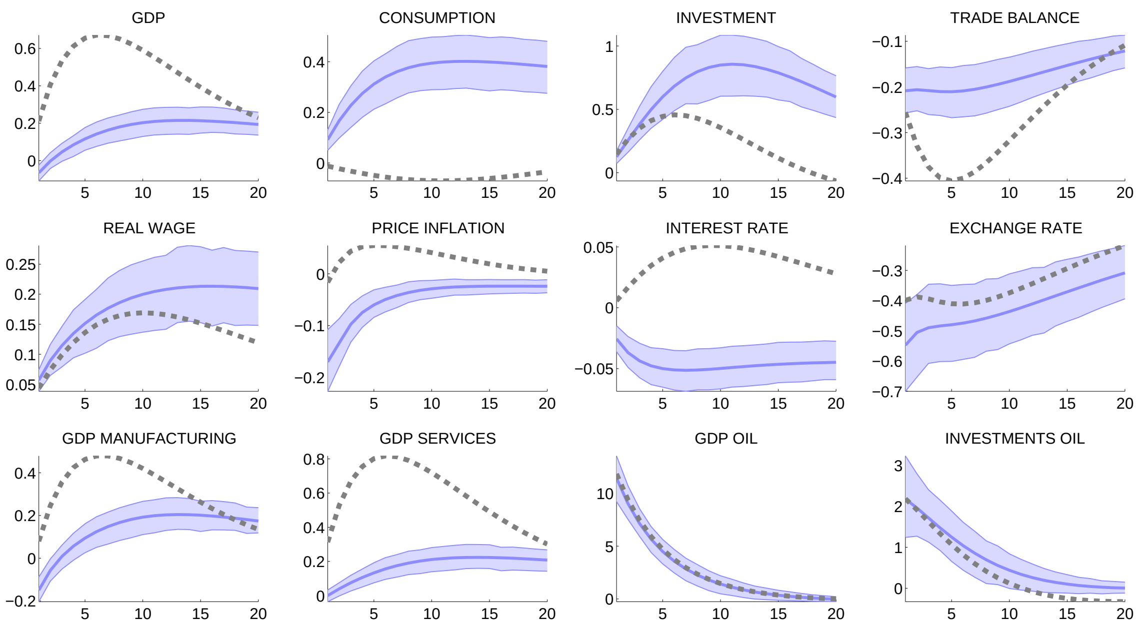
Figure C.36: International economy: international monetary policy



Note: See Figure 6 for details.

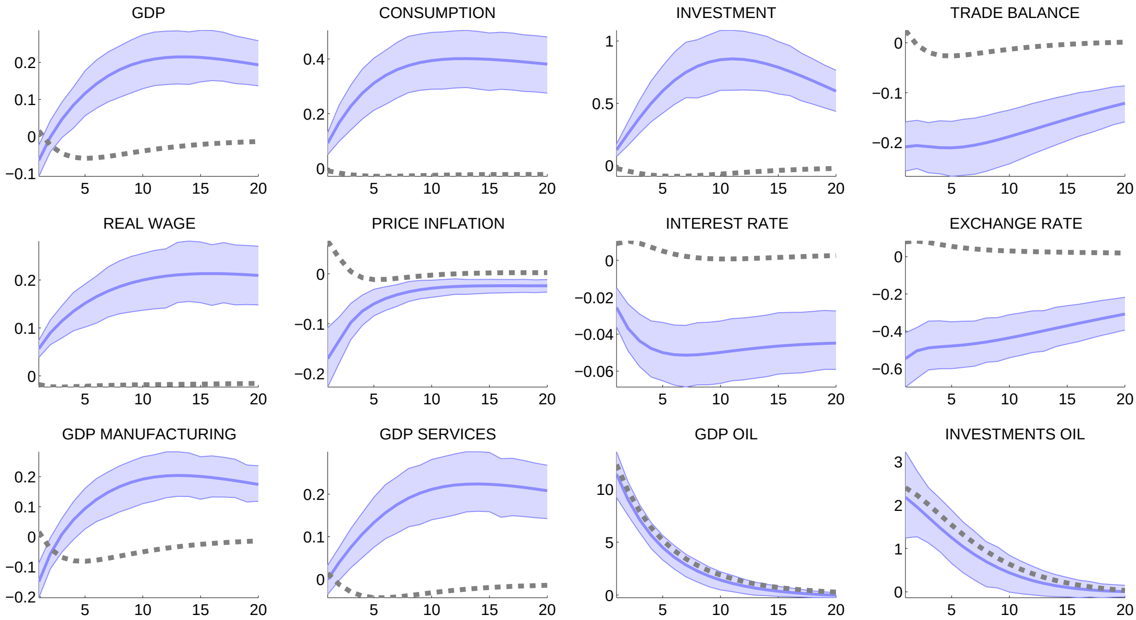
C.4 Counterfactual impulse responses

Figure C.37: An international oil price shock without the sovereign wealth fund



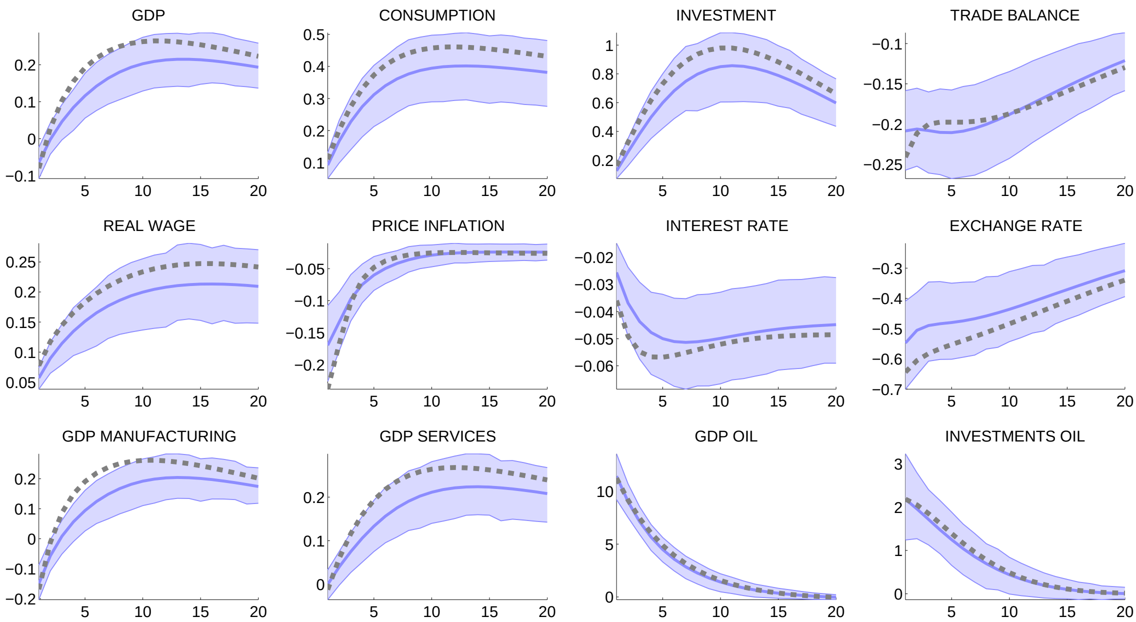
Note: Bayesian impulse responses to an international oil price shock (one standard deviation). Blue areas represent the baseline responses while gray dotted lines represent the counterfactual. See Figure 7 for details.

Figure C.38: An international oil price shock without the supply chain



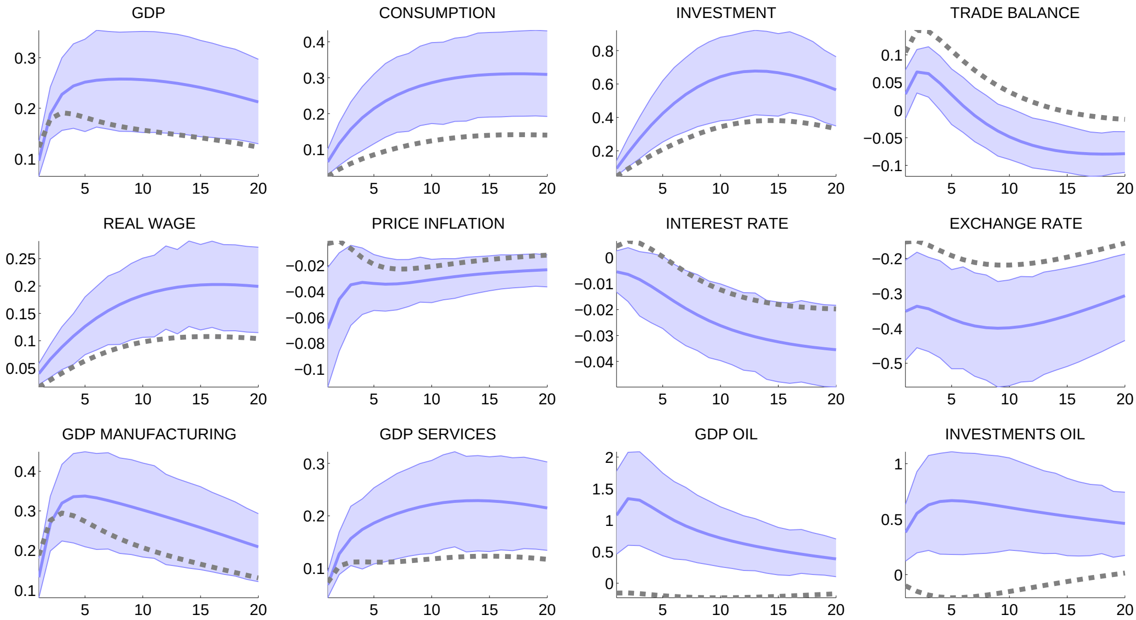
Note: Bayesian impulse responses to an international oil price shock (one standard deviation). Blue areas represent the baseline responses while gray dotted lines represent the counterfactual. See Figure 7 for details.

Figure C.39: An international oil price shock without feedback to macro



Note: Bayesian impulse responses to an international oil price shock (one standard deviation). Blue areas represent the baseline responses while gray dotted lines represent the counterfactual. See Figure 7 for details.

Figure C.40: An international investment shock without feedback to oil



Note: Bayesian impulse responses to an international oil price shock (one standard deviation). Blue areas represent the baseline responses while gray dotted lines represent the counterfactual. See Figure 7 for details.