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Global oil prices and the macroeconomy: The role of tradeable manufacturing versus nontradeable services

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Non-technical summary

Research Question

In this paper, I argue that, for studying the relationship between oil prices and the macroeconomy of an oil-importing economy, a careful distinction should be made between the manufacturing sector, which exports a lot and uses oil heavily, and the services sector, which exports very little and does not use oil intensively. The production and distribution of manufactured goods constitute a major factor in shaping global oil demand. Also, manufacturing production not only requires a lot of oil but also uses a large amount of intermediate manufactured goods, implying a tight link between demand for these intermediate inputs and the demand for oil. Moreover, from the oil-importing country's perspective, shocks driving the oil price benefit domestic manufacturing relative to services if they are related to rising exports to, for instance, Asian emerging markets or – on account of international wealth transfers in times of oil price changes – major oil-producing countries (like OPEC).

Contribution

This paper studies the ability of shocks specific to the manufacturing sector to explain global oil prices. I estimate a business cycle model that includes three regions – the United States, OPEC, and the rest of world, incorporates two broad production sectors (manufacturing and services) in the oil-importing economies, and features cross-border manufacturing supply chains as well as oil inventories and variable oil supply.

Results

Shocks to the manufacturing sector are found to be a key demand-type source of real oil price movements. At a global level, such shocks rationalize the observed empirical pattern of a positive comovement between oil prices and the cyclical gap between manufacturing output and services provision. Given positive manufacturing technology shocks, – owing to the low substitutability of oil and non-oil intermediate inputs in production – oil demand and demand for intermediate manufactured goods as well as global trade decline in tandem. Of similar importance are shocks to final manufactured goods demand that are amplified by input-output linkages and international trade. From the US perspective, all foreign shocks that cause higher oil prices – including adverse oil supply shocks – have a positive impact on manufacturing relative to services as well as a positive impact on aggregate core inflation and policy rates. These dynamics rationalize, to a large extent, the observed pattern during major oil price hikes, and, correspondingly (with opposite signs), during important episodes of low oil prices.

Nichttechnische Zusammenfassung

Fragestellung

Die Analyse des Zusammenhangs globaler Ölpreise und der gesamtwirtschaftlichen Entwicklung ölimportierender Länder bedarf einer sorgfältigen Unterscheidung zwischen dem verarbeitenden Gewerbe und dem Dienstleistungssektor. Insbesondere ist das verarbeitende Gewerbe im Vergleich zum Dienstleistungssektor in der Produktion sehr ölintensiv und viel stärker vom Handel abhängig. Die Produktion und der Handel von gewerblichen Erzeugnissen sind dadurch wichtige Faktoren für die weltweite Ölnachfrage. Zudem spielen verarbeitete Zwischengüter genauso wie Rohöl für das verarbeitende Gewerbe eine wichtige Rolle als Vorleistungskomponenten, was für einen engen Zusammenhang zwischen diesen beiden Produktionsfaktoren spricht. Auch wirken sich Schocks, die den Ölpreis steigern, aus Sicht eines ölimportierenden Landes positiv auf das inländische verarbeitende Gewerbe aus, wenn sie mit steigenden Exporten einhergehen.

Beitrag

Der Beitrag untersucht die Rolle von Schocks, die für das verarbeitende Gewerbe spezifisch sind, für die globale Ölpreisdynamik. Es wird ein Konjunkturmodell mit drei Regionen (USA, OPEC, Rest der Welt) geschätzt. Das Modell berücksichtigt globale Wertschöpfungsketten, die weltweiten Erdölvorräte und das variable Ölangebot. Im Fall der ölimportierenden Länder werden zwei große Produktionssektoren einbezogen.

Ergebnisse

Schocks des verarbeitenden Gewerbes finden sich als wichtigste nachfrageseitige Quelle für Ölpreisschwankungen. Auf globaler Ebene erklären sie den positiven Gleichlauf der Ölpreise mit der zyklischen Lücke zwischen der Produktion im verarbeitenden Gewerbe und dem Dienstleistungsverbrauch, der auch aus den Daten hervorgeht. Ein wichtiger zugrundeliegender Kanal ist die geringe Substitutionsmöglichkeit von Rohöl und verarbeiteten Zwischengütern, was bei Produktivitätsschocks im verarbeitenden Gewerbe zum Tragen kommt. Ähnlich bedeutsam sind Schocks der Nachfrage von für den Endverbrauch bestimmten Gütern des verarbeitenden Gewerbes, die durch Input-Output Verknüpfungen und den internationalen Handel verstärkt werden. Aus Sicht der USA haben alle ausländischen Schocks, die zu einem Anstieg der Ölpreise führen (auch negative angebotsseitige Schocks am Ölmarkt) im Verhältnis zum Dienstleistungssektor einen positiven Effekt für das verarbeitende Gewerbe. Außerdem wirken sie sich über den zugrundeliegenden Preisdruck günstig auf die aggregierte Kerninflation und die Leitzinsen aus. Diese Dynamik erklärt in einem wesentlichen Ausmaß das Muster, das während bedeutender Ölpreisanstiege – sowie entsprechend mit umgekehrten Vorzeichen auch während bemerkenswerter Abschwünge am Ölmarkt – zu beobachten war.

DEUTSCHE BUNDESBANK DISCUSSION PAPER NO 60/2020

Global oil prices and the macroeconomy: The role of tradeable manufacturing versus nontradeable services*

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Abstract

This paper studies the ability of manufacturing-specific shocks to explain global oil prices. In an estimated three-region DSGE model (United States, OPEC, rest-of-world) incorporating two sectors (manufacturing and services) in the oil-importing economies and featuring cross-border manufacturing supply chains, oil inventories as well as endogenous oil supply, such shocks rationalize the observed empirical pattern of a positive comovement between global oil prices and the global cyclical gap between manufacturing output and services provision. Given positive manufacturing technology shocks, oil demand and demand for intermediate manufactured goods as well as global trade decline in tandem. Of similar importance are shocks to final manufactured goods demand that are amplified by input-output linkages and international trade. From the perspective of the US, all foreign shocks that cause higher oil prices – including adverse oil supply shocks – have a positive impact on manufacturing relative to services as well as a positive impact on aggregate core inflation and policy rates. These dynamics rationalize, to a large extent, the observed pattern during major oil price hikes, and, correspondingly (with opposite signs), during important episodes of low oil prices.

Keywords: Endogenous global oil price, trade channel, manufacturing and services, oil and the business cycle, oil intensity, intermediate inputs.

JEL classification: E32, F41, Q43

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1 Introduction

Large upswings and downswings in global oil prices since the mid-2000s have renewed interest in the causes and consequences of such dynamics. In the literature, there is a growing consensus about the need to differentiate between several underlying sources of oil price movements (cf. inter alia Barsky and Kilian 2002, Kilian 2009, Bodenstein, Guerrieri, and Kilian 2012). The trade channel plays an important role in this context, especially in the case of disturbances to the oil price that stem from shifts in economic activity. In a period in which, for example, Asian (oil demand) growth fuels global oil prices, US exports could be positively affected by increasing foreign demand (see, for example, Kilian 2008).

The recent literature considers models where there is only one aggregate production sector in oil-importing economies, a practice that has to be called into question when it comes to studying the role of the trade channel in the link between global oil prices and the macroeconomy. If it is, acknowledged that the oil price moves because of shifts in global oil demand, then this should be attributed mainly to the global production of tradeable manufactured goods. Manufacturing is a sector which, compared with services, is very oil-intensive in production.[1] Moreover, at a global level, the trade cycle tends to be highly correlated with the industrial cycle, whereas the correlation with GDP is more limited (cf. Bobasu, Manu, and Quaglietti 2019). In the case of business cycle shocks originating in the manufacturing sector, the trade channel therefore plays not only a role in the international transmission of such shocks but also in global oil use, as production of manufactured goods typically relies on means of transport that make heavy use of oil as an input.[2] Another important dimension that is usually neglected in open economy models but has been stressed more recently, is the relevance of global supply chain integration, both in explaining global trade dynamics as well as domestic production patterns. As the oil-intensive manufacturing sector is typically also using a large share of domestically sourced and imported manufactured goods as intermediate inputs, there is intuitively a tight link in demand for oil inputs and demand for intermediate manufactured goods. Finally, because oil-producing countries may shift their non-oil imports in response to oil price movements on account of international wealth effects (cf. Bodenstein, Erceg, and Guerrieri 2011 and Kilian, Rebucci, and Spatafora 2009), in times of rising oil prices the global manufacturing sector could additionally benefit from higher demand from oil exporting countries. From the US perspective, shocks driving the oil price benefit domestic manufacturing if they are related to rising external demand from, for instance, goods exporters (such as in the example of increasing Asian demand growth) or oil exporters (like the Organization of the Petroleum Exporting Countries, OPEC). The large and important US services sector – which does not export much – would, however, not benefit

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[1] According to input-output tables from the Bureau of Economic Activity, in 2012, the total requirement for oil-use was 6% in manufacturing and 1.4% in services. In the same tables, the share of exports in total production is 21.4% in manufacturing, compared with 2.9% in services.

[2] While transport might not use crude oil directly as input, the indirect exposure – i.e. the total requirements capturing input/output linkages – is relatively large. As documented in Dargay and Gately (2010) since the 1970s/1980s, the decomposition of overall oil use in the OECD (Organization of Economic Development and Cooperation) countries changed towards a large share of transport which is less responsive to oil prices changes than to other activities. The increased importance of transport might be related to the broader trend of globalization and increasing worldwide trade.

from the external sector. Additionally, during such episodes, the economy as a whole – including services – could face inflationary pressure triggered by the manufacturing sector.

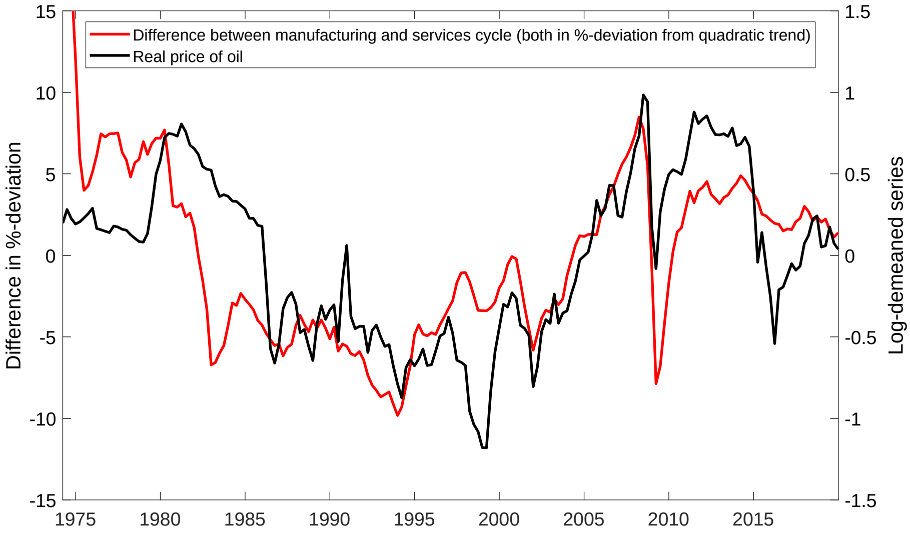

Figure 1: Left-hand axis: Difference between global manufacturing production and global services consumption expenditure (both measured as an index and as a percentage deviation from their respective quadratic trends). Right-hand axis: real oil price. See below for details on the construction of the series. Excluding the first year in the sample, the correlation coefficient of the two series is 0.67.

In this paper, I estimate a structural dynamic stochastic general equilibrium (DSGE) model which includes three regions – the United States (US), OPEC, and the rest of world (ROW) – and, in the US and the ROW, incorporates two broad production sectors facing nominal rigidity (manufacturing and services). In the model, manufacturing is the more oil-intensive sector and produces tradeable goods, whereas services is the nontradeable sector. The model has an input-output structure in order to distinguish between final goods and intermediate goods. It also incorporates cross-border supply chain linkages in the manufacturing sector (as in Georgiadis, Gräb, and Khalil, 2019). Building on Unalmis, Unalmis, and Unsal (2012) and Nakov and Nuño (2013), the model features global oil inventories as well as OPEC as a dominant oil producer with market power over a competitive fringe of non-OPEC suppliers. It incorporates a rich shock structure – of demand and supply shocks in the goods and oil market – and is estimated using data on sectoral output and inflation, nominal interest rates and nominal exchange rates for the US, as well as data on the global levels of real oil prices, oil production, oil storage, manufacturing output and services activity (1974Q1 until 2019Q4).

Three channels are especially relevant in the estimated model: (1) In oil-intensive manufacturing production, there is low substitutability of oil and manufactured intermediate inputs. Therefore, in the case of positive manufacturing technology shocks, demand for manufactured goods and oil demand, as well as global oil intensity and non-oil trade decline jointly. (2) Shifts in demand for final manufactured goods result in increased manufacturing output relative to services provision and larger oil demand of the the oil-intensive sector, which is amplified by input-output linkages and international trade.

(3) When oil prices rise there are wealth shifts from US and ROW towards OPEC that translate into higher OPEC's import demand.

The main findings of the analysis can be summarized as follows:

1. In the data, I find that, at a global level, the cyclical gap between manufacturing production and services activity comoves positively with global real oil prices (cf. Figure 1). Estimation of the structural DSGE model and employing historical shock decomposition reveals that the observed pattern can, to a large degree, be rationalized by shocks specific to the manufacturing sector (i.e. technology shocks in the manufacturing sector as well as shocks to demand for manufactured final goods). Such manufacturing-specific shocks are found to be a key driver of global oil prices.

2. Oil supply shocks are also found to be major drivers of oil prices and can, for some episodes to a quantitatively relevant extent, also rationalize positive comovement between the global manufacturing/services wedge and real oil prices (as found in Figure 1). Oil supply shocks move oil prices and affect the income of oil exporters as well as import demand in those regions. Negative oil supply shocks thus positively affect global manufacturing production worldwide.[3]

3. From the perspective of the US, because of the trade channel, all shocks to ROW activity that fuel global oil demand (including – in addition to manufacturing-specific demand and technology shocks, for example – non-manufacturing specific technology shocks, and shocks that add a risk premium to the spread between US and ROW interest rates – i.e. "exchange rate shocks") lead to a positive wedge between manufacturing and services output in the US, higher aggregate inflation – due to underlying cost pressure arising from higher factor prices, in particular also wages – and higher US nominal interest rates. According to historical decomposition, such dynamics are typically in line with the observed pattern of these variables during many major oil market events throughout the sample. Notably, oil supply shocks impose, qualitatively, similar dynamics and sectoral patterns as foreign activity shocks that move the oil price.[4]

The empirical results uncover movements in the – global and US – wedge between production in manufacturing and services as a vital dimension of macroeconomic transmission of oil-related shocks. On a global level, manufacturing-specific shocks are found to be a key driver of global oil prices, especially in the short to medium run. For instance, between 2003 and 2006 manufacturing-specific shocks originating outside the US are identified to be responsible for most of the marked oil price increase. The estimation reveals that, during this episode, such shocks can explain the observed expansion in OPEC production and a modest pickup in US manufacturing relative to services. Explicitly modeling the OPEC region reveals that the trade channel importantly affects the impact of oil supply

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[3] This channel can rationalize why economic activity in some regions increases in response to an adverse oil supply shock (cf. Caldara, Cavallo, and Iacoviello 2019 and discussions below). Similar dynamics occur in presence of oil storage demand shocks but they play a relatively small quantitative role as compared to OPEC and non-OPEC oil supply shocks.

[4] This quantifies and aligns with the mechanism in Bodenstein et al. (2011) where in a two-country model, the US non-oil trade balance improves in response to adverse oil supply shocks as a general equilibrium outcome.

shocks – as well as oil storage demand shocks – on aggregate production because the manufacturing sector is exposed to exports. For instance, between 2014 and 2016, low oil prices – that are in a relevant extent found to be the consequence of non-OPEC and OPEC oil supply shocks – markedly dampened global and US manufacturing relative to services because of lower demand for manufactured goods from oil exporters.

The results challenge the popular view that especially the output of oil-intensive manufacturing industries is adversely affected when oil prices rise. Also, they are not consistent with the narrative that the 1970s are very different from the 2000s, as the US economy is found to be affected by similar channels in more recent oil-related events compared to earlier episodes. Earlier studies have sometimes suggested that an increase of the global oil price driven by global activity is – from the US point of view – always like an exogenous oil supply shock (cf. inter alia Blanchard and Gali 2010 and Blanchard and Riggi 2013). In this view, the trade channel does not play much of a role and the direct effects of changing oil prices dominate, which is challenged by the results presented here and reaffirms findings in Bodenstein et al. (2012) and Bodenstein and Guerrieri (2018) based on different DSGE models. Still, qualitatively, from the US perspective oil supply shocks and demand-type shocks in the oil market share common features when they originate outside the US.

My formal analysis corroborates the insights of Kilian (2008). The empirical work complements the evidence provided in Kilian (2009), Kilian and Hicks (2013), and Baumeister and Hamilton (2019) among others, based on different methodologies. The resulting historical shock sequences obtained from the estimated DSGE model accord well with the sequence of corresponding shocks in the structural vector autoregressive (S-VAR) model of Baumeister and Hamilton (2019).[5] Also, the findings of the paper advocate the use of a measure of global manufacturing activity as an indicator of shifts in oil demand related to economic activity, which contributes to the debate on how (structural) oil models should be specified (cf., for instance, Kilian and Zhou, 2018).

The paper adds to many more studies that analyze the relationship between the oil price and the macroeconomy (see, for example, Barsky and Kilian 2002, Hamilton 2003, Kilian, 2008, Kilian 2014, and Baumeister and Kilian 2017). Some papers incorporate oil prices in DSGE models in order to study the effects of exogenous oil price shocks in closed economy settings (*inter alia* Leduc and Sill, 2004; Carlstrom and Fuerst, 2006; Natal, 2012). The role of openness in the context of macroeconomic effects of oil prices was first addressed theoretically by Backus and Crucini (2000) in a flexible price model and later in models with sticky prices (cf. Balke, Brown, and Yucel 2010, Bodenstein and Guerrieri 2018 and Bodenstein et al. 2012). None of these studies includes a nontradeable sector or cross-border manufacturing supply chains in the analysis.[6] Also, contrary to earlier contributions, this paper aims at capturing the most relevant features of the oil market

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[5] Interestingly, the annualized series of manufacturing-specific shocks (weighted US and ROW averages) in the DSGE model moves similarly as the corresponding oil-specific "consumption" demand shocks in Baumeister and Hamilton (2019). In Baumeister and Hamilton (2019), however, the oil-specific consumption demand shocks – which explain most of the demand variation behind oil price movements in the SVAR – are, by virtue of their construction, fundamentally unrelated to industrial activity shocks. In the DSGE model, the most relevant demand-type source of oil price movements are shocks fundamentally related to the manufacturing sector and thereby industrial activity.

[6] One notable exception in earlier literature is Bergholt, Larsen, and Seneca (2017), who, in a different context, study the link between oil price movements and the business cycle of an oil exporting economy.

emphasized in recent VAR literature – global oil storage, endogenous oil production, as well as the role of the US dollar exchange rate – in a unified DSGE framework.

Most closely related are probably the studies by Bodenstein et al. (2012) and Bodenstein and Guerrieri (2018) who estimate two-country DSGE models (one country being the US) featuring endogenous global oil prices. They find exogenous oil-efficiency shocks to have quantitative relevance for the business cycle and as a demand-type source of global oil price movements. Contrary to these earlier studies, this paper contributes by highlighting the role of supply and demand channels in the manufacturing sector that lead to endogenous shifts in oil intensity and are thereby a key source of global oil price movements. As an example, for the mid-2000s, Bodenstein and Guerrieri (2018) identify an important role played by lowering ROW oil efficiency in rationalizing large oil price movements. In the estimated model studied here, between 2003 and 2006 shocks to final manufactured goods demand that raise ROW oil intensity can partly rationalize this finding. In addition, according to the model results, especially in 2004/2005 ROW manufacturing technology shocks led to a greater use of labour, oil and intermediate manufactured inputs for a given amount of output, which also implied higher ROW oil intensity. These results are in line with evidence that during the mid-2000s rapid industrialization in China was a major factor behind rising oil prices. Distinguishing between manufacturing and services makes it possible to directly identify shifts in oil demand in the oil-intensive manufacturing production sector as a key driver of global oil prices. Moreover, the sectoral distinction allows the identification of a direct link between these economic activity shocks and international trade. Also, in contrast to Bodenstein et al. (2012), and Bodenstein and Guerrieri (2018), oil is assumed to be storable, and global oil production is endogenous and price-elastic, which means that the results of the DSGE estimation can be set against complementary evidence from recently discussed SVAR models. While Bodenstein et al. (2012) and Bodenstein and Guerrieri (2018) attribute most of the variation in oil prices to foreign oil efficiency shocks, according to variance decomposition, I find a more balanced mix of various demand-type as well as supply-type shocks in the oil market.

The remainder of this study is organised as follows. The detailed model structure is described in section 2, while the data and structural estimation approach are discussed in section 3. Details on the most relevant transmission mechanisms and the identified link between global oil prices and the global wedge between manufacturing output and services activity are discussed in section 4. Section 5 presents shock decomposition for important historical episodes. Finally, section 6 concludes. The appendix contains detailed data and model descriptions, further empirical results, as well as a comparison of the identified shocks of the DSGE model with the shock series obtained with the S-VAR model of Baumeister and Hamilton (2019).

2 Manufacturing and services in a model of endogenous global oil prices

I incorporate global oil markets in a relatively standard New Keynesian (NK) framework employed in the New Open Economy Macroeconomy (NOEM) literature. In the model there are three regions: Home (US), OPEC, and rest of world (ROW). US and ROW are of unequal size with the population size in the US given by n and and in ROW by $1-n$. In production in Home and ROW a distinction is made between a tradeable (manufacturing) and a nontradeable (services) sector (in the spirit of Stockman and Tesar 1995). I build on contributions in the NOEM literature that introduce sticky prices in such a framework (cf. in particular Rabanal and Tuesta, 2013, among others). Manufactured goods are traded internationally while services are not. The model features an input-output structure in both sectors. Moreover, firms in the manufacturing sector are integrated in global value chains as intermediate inputs are not only sourced domestically but are also imported from abroad (similar as in Georgiadis et al., 2019).

Departing from the model of Nakov and Nuño (2013), the OPEC region is specified as an economy owning a dominant oil producing firm and, for simplicity, having only the oil sector. It exports crude oil and imports tradeable goods for consumption and as intermediate inputs to oil production from the other two countries. The relative country size of OPEC is determined by the oil use of the trading partners.[7] US and ROW proportionally own a global oil supplier that trades oil against manufactured goods with OPEC and, additionally, is endowed with non-OPEC oil supplies. This specification allows for the possibility of different elasticities of OPEC and non-OPEC oil supply with respect to oil prices as emphasized in recent contributions. Oil extraction is subject to exogenous disturbances. Moreover, the oil market features global storage of oil and oil speculation shocks (as in Unalmis et al. 2012).

The decision making of households and firms is relatively standard. Below I present these parts of the model that are the most relevant for understanding the key mechanism. A more detailed description of the structural model is provided in the appendix. The Home (US) and the Foreign (ROW) economy have the same structure. Below, it is mainly the Home economy that is described and, if not otherwise indicated, the same relations hold equivalently for the ROW economy. ROW variables are denoted by an asterisk. The OPEC region differs in several dimensions and is described explicitly. Log-linearized variables are denoted by hats and lowercase letters.

2.1 The model

Household's consumption

The domestic representative agent consumes each period the following consumption goods bundle

$$C_t \equiv \left[(1-\gamma)^{1/\phi}(C_{T,t})^{\frac{\phi-1}{\phi}} + \gamma^{1/\phi}(C_{N,t})^{\frac{\phi-1}{\phi}}\right]^{\frac{\phi}{\phi-1}} \tag{1}$$

where γ is the share of services (nontradeable goods) in the consumption basket and ϕ is the elasticity of substitution between final manufactured consumption goods (tradeables) $C_{T,t}$ and final services (nontradeables) $C_{N,t}$. The corresponding consumer price index is given by $P_t = \left[(1-\gamma)(P_{T,t})^{1-\phi} + \gamma(P_{N,t})^{1-\phi}\right]^{\frac{1}{1-\phi}}$.

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[7] In particular only by use of oil from the OPEC region as, in the model, a major share of 59% of global oil use is provided by non-OPEC suppliers (cf. calibration below).

Final manufactured goods bundling

It is assumed that Home-produced and ROW-produced final manufactured goods are combined according to

$$\tilde{C}_{T,t} \equiv \left[(1-\delta)^{1/\theta}(C_{TH,t})^{\frac{\theta-1}{\theta}} + \delta^{1/\theta}(C_{TF,t})^{\frac{\theta-1}{\theta}}\right]^{\frac{\theta}{\theta-1}} \tag{2}$$

where δ denotes the share of foreign goods in the consumption of manufacturing and θ is the elasticity of substitution between Home-produced $C_{TH,t}$ and ROW-produced manufactured goods $C_{TF,t}$. The varieties of home tradeable goods are indexed by $f_{TH} \in [0, n)$, while the varieties of foreign tradeable goods are indexed by $f_{TF} \in [n, 1]$. The respective varieties are aggregated with a standard constant elasticity of substitution (CES) technology.

Total final manufactured goods demand in US and ROW follows $\tilde{C}_{T,t} = C_{T,t} + G_{T,t}$, $G_{T,t+1} = (G_{T,t})^{\rho_{G_T}} exp(\xi_{G_T,t+1})$ and $\tilde{C}^*_{T,t} = C^*_{T,t} + G^*_{T,t}$, $G^*_{T,t+1} = (G^*_{T,t})^{\rho_{G^*_T}} \exp(\xi_{G^*_T,t+1})$ where G_T and G^*_T are exogenous shocks. The shocks to final manufactured goods demand can be interpreted as government-led increases in manufacturing output (financed by lump-sum taxation). More generally, they explain unexpected shifts towards demand for manufactured goods that cannot be explained by changes in the interest rate or other relative prices (cf. Rabanal and Tuesta 2013).[8]

Firms, price and wage setting

Domestic production takes place with a CES technology such that output in a single firm f_l is produced according to

$$Y_{l,t}(f_l) = Z_{l,t}\left[\alpha_N N_{l,t}(f_l)^{\frac{\tau-1}{\tau}} + \alpha_O O_{l,t}(f_l)^{\frac{\tau-1}{\tau}} + \alpha_M M_{l,t}(f_l)^{\frac{\tau-1}{\tau}}\right]^{\frac{\tau}{\tau-1}} \tag{3}$$

for $l \in \{T, N\}$ denoting a sector, $f_l \in [0, n)$ is a domestic firm producing a specific variety, α_N, α_m, and α_O are parameters determining labour, non-oil intermediate input, and oil use in production (same for all firms within a sector), $Z_{l,t}$ denotes sector-specific technology and $N_{l,t}(f_l)$, $O_{l,t}(f_l)$, $M_{l,t}(f_l)$ are firm specific-labour, oil, and non-oil intermediate goods demand. The parameter τ denotes the elasticity of substitution between the factor inputs. Technology $Z_{l,t}$ evolves according to an AR(1) process in logs.

Price setting is introduced a la Calvo (1983). In each period only a fraction of $(1 - \varphi_l) \in [0, 1]$ firms is allowed to readjust prices. Exchange rate pass-through is assumed to be incomplete as in Corsetti and Pesenti 2005. Households provide differentiated labour, which gives rise to nominal inertia in wages (in a standard specification a la Erceg, Henderson, and Levin 2000).

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[8] To keep the model simple it does not feature capital and investment. In the data, the manufacturing specific demand shocks would, however, capture demand specific to investment goods which are typically manufactured final goods. In the same vein, observed goods imports from the OPEC region include investment goods used in oil production. For simplicity, in the model it is assumed that imports are either final goods or intermediate goods. Nevertheless, bringing the model to the data allows a broader interpretation.

Intermediate manufactured goods bundling

It is assumed that US-produced and ROW-produced intermediate inputs for the manufacturing sector include only manufactured goods and are combined according to

$$M_{T,t} \equiv \left[(1-\omega)^{1/\theta}(M_{TH,t})^{\frac{\theta-1}{\theta}} + \omega^{1/\theta}(M_{TF,t})^{\frac{\theta-1}{\theta}}\right]^{\frac{\theta}{\theta-1}} \tag{4}$$

where ω denotes the steady state share of imported intermediate goods in the total use of non-oil intermediate goods in manufacturing. θ is the elasticity of substitution between US-produced $M_{TH,t}$ and ROW-produced non-oil intermediate goods $M_{TF,t}$.

Goods and services market clearing

Services markets clear such that $Y_{N,t} = C_{N,t} + M_{N,t}$, and $Y^*_{N,t} = C^*_{N,t} + M^*_{N,t}$. The market for manufactured goods clears such that $Y_{T,t} = C_{TH,t} + \frac{1-n}{n}C^*_{TH,t} + M_{TH,t} + \frac{1-n}{n}M^*_{TH,t} + C_{dom,TH,t} + X_{dom,TH,t}$ and $Y^*_{T,t} = C^*_{TF,t} + \frac{n}{1-n}C_{TF,t} + M^*_{TF,t} + \frac{n}{1-n}M_{TF,t} + C_{dom,TF,t} + X_{dom,TF,t}$ where $C_{dom,TH,t}$ and $C_{dom,TF,t}$ denote OPEC's consumption demand of US-produced and ROW-produced goods and $X_{dom,TH,t}$ and $X_{dom,TF,t}$ denote OPEC's corresponding intermediate goods demand.

Global oil market

Given the ability to store oil, global oil markets clear every period such that

$$O_{demand,t} + INV_t = O_{supply,t} + INV_{t-1} \tag{5}$$

where $O_{demand,t}$ is global oil demand determined in each period by factor demand of the tradeable (manufacturing) and the nontradeable (services) sector of US and ROW, and $O_{supply,t}$ is the global oil supply. The optimal choice on inventories INV_t builds on the model of Unalmis et al. 2012 which is described in the appendix.[9]

Global oil production is characterized by a fringe of oil suppliers and a dominant oil producer. In particular, I build on the model of Nakov and Nuño (2013) by allowing for the presence of a dominant producer that takes into consideration global supply and demand

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[9] In the DSGE model, global oil demand is equal to the sum of oil-demand from the large service sector and oil demand in the manufacturing sector, whereas, for simplicity, I refrain from incorporating a transportation sector, a sector producing gasoline, or a utility sector, which are all oil-intensive. Oil use in these sectors can be partly captured indirectly by using input-output requirement tables for calibrating manufacturing and services oil use. Moreover, not explicitly modeling these sectors is probably not a large issue in identifying short and medium-term demand-type shocks in the global oil market. Intuitively, transport services, gasoline production, or utilities provision are complements to production in the two main sectors of manufacturing and services. Dynamics of these smaller sectors probably cannot be decoupled from services activity or manufacturing production. For instance, transportation activity and energy production is likely to increase with economic output. Also, private commuting is likely to be higher during economic booms than during economic busts, and therefore tightly linked to manufacturing and services activity.

conditions when adjusting production.[10] Oil production of the dominant producers follows a Cobb-Douglas technology that combines labour $N_{oil,j,t}$ and imported intermediate inputs $X_{oil,j,t}$ to produce oil for a given level of productivity $Z_{oil,j,t}$ (AR(1) process in logs), such that

$$O_{supply,dom,t} = Z_{oil,dom,t} N_{oil,dom,t}^{\alpha_{N,dom}} X_{oil,dom,t}^{\alpha_{X,dom}} \tag{6}$$

where $\alpha_{N,dom}$ and $\alpha_{X,dom}$ denote the share of labour and intermediate goods use in total oil production. The dominant producer incorporates global oil demand $O_{demand,t}$, oil supply provided by fringe producers $O_{supply,fringe,t}$ as well as the level of global storage INV_t to decide upon the level of oil production while optimizing domestic utility. As in Nakov and Nuño (2013), the dominant producer constitutes an oil-exporting economy that trades oil revenues against tradeable imports under financial autarky.[11]

$O_{supply,fringe,t}$ is modeled as an exogenous AR(1) process in logs, i.e. oil production of fringe production is inelastic to global oil price movements.[12] The global oil supply is given by $O_{supply,t} = O_{supply,dom,t} + O_{supply,fringe,t}$.

3 Data and structural estimation

The model is estimated structurally employing a Bayesian approach and data on the US economy, the global oil market as well as global manufacturing activity and services provision.[13] US data for inflation and output in the manufacturing and services sector (in the latter case proxied by service consumption expenditure) as well as short-term interest rates and US dollar (USD) nominal exchange rates are available for a long time span. There is, however, a lack of data for the same variables of the other regions. To map global demand forces, many studies have used the index of global real economic activity proposed in Kilian (2009), which is based on data for dry bulk cargo ocean freight rates. In this paper, I instead use a proxy for global manufacturing production because

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[10] There are differences from the framework of Nakov and Nuño (2013). I assume that the dominant producer is located in the OPEC region instead of Saudi Arabia. This is motivated by a close comovement of the cyclical oil production data of Saudi Arabia and the OPEC region as a whole (cf. Figure 15 in the appendix). Distinguishing between OPEC and non-OPEC production requires corresponding exogenous shock processes. Therefore, I assume that the productivity of the dominant producer is subject to exogenous supply shocks and not constant. Also, there is no capital, but labour is utilized to produce oil instead. Finally, oil is assumed to be storeable. This implies that the dominant producer's decision depends on the global level of oil storage. Cf. appendix D for more details.

[11] In a two-country model of the US economy and an oil-exporting economy, Bodenstein et al. (2011) find that US external adjustment in response to oil supply shocks is very similar in the case of financial autarky rather than under the more realistic assumption of incomplete markets.

[12] Caldara et al. (2019) find empirical support in favour of this assumption. Also, in the detrended time series data, non-OPEC supply is rather persistent and does not move in the same direction as oil prices or economic activity during major episodes like the in mid-2000 (cf. Figure 15). I.e. the series does not seem responsive to overall oil market conditions. Profits of the oil supplier are distributed proportionally to the US and ROW economies as lump sum transfers (similar to the specification of Campolmi, 2008).

[13] The model is estimated with Dynare. For a detailed explanation of the Bayesian estimation approach the reader is referred to An and Schorfheide (2007) among many other sources. One early example of an application of a Bayesian estimation of a two-country model is Lubik and Schorfheide (2005). Other studies related to the New Keynesian two-country framework employed here include *inter alia* Rabanal and Tuesta (2010) and Rabanal and Tuesta (2013). The latter study incorporates a nontradeable sector.

this measure coheres most closely with the production of global tradeables in the DSGE model.[14] Additionally, I construct a similar measure for global services activity based on service consumption expenditure data.[15] The employed oil market data (real oil price, oil inventories, oil production) is relatively standard (see for instance Kilian and Murphy, 2014), with the exception that oil production is additionally separated into OPEC and non-OPEC production. The sample is restricted by the availability of the refiner import oil price series from 1974Q1. The estimation of the model presented below is conducted for the time span 1974Q1 to 2019Q4.[16]

The observable variables have to be mapped into the stochastic stationary model, which is log-linearized around a deterministic steady state such that variables have the interpretation of percentage deviations from steady state. The non-stationary series are transformed by quadratically detrending the logarithm of the observed time series.[17] The inflation variables, the real oil price (in log level) as well as the domestic interest rate and the depreciation of the exchange rate are assumed to be stationary, so in these cases the original data are not detrended. All variables are demeaned. The model counterpart of the observed global manufacturing production index is the country size-weighted sum of US and ROW manufacturing real output. Accordingly, US and ROW services are weighted to match the observed index. There are twelve structural shocks and twelve observational variables, i.e. the empirical model is just identified.

3.1 Calibration, Bayesian prior and posterior

Some parameters in the model remain calibrated. The discount factor is set to $\beta = \beta^* = 0.99$ and relative risk aversion to $\sigma = \sigma^* = 2$. The inverse of the Frisch elasticity of labour is set to to $\varphi = \varphi^* = 2$. The elasticity between varieties of differentiated labour is calibrated to $\varepsilon_w = 4.5$ as in Born and Pfeiffer (2020). The size of the Home economy (US) relative to the ROW economy is set to $n/(1-n) = 0.28/0.72$ so as to match the share of US GDP in global GDP (excluding OPEC member countries).[18] The steady state share of services in production is set to 60 %.[19] The steady state share

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[14] In particular, I construct a global index of manufacturing production similar to the index of global industrial production computed by Baumeister and Hamilton (2019). The index covers OECD and six major non-OECD countries. Details can be found in the appendix.

[15] For constructing sectoral activity indices of the the ROW aggregate, there is a lack of data especially early in the sample when only data for a few countries (including the US) are available. This caveat is more pronounced for the services consumption expenditure series than for the proxy of manufacturing production (see data description in the appendix). Still, for a major part of the sample there is a large pool of countries available to have a balanced panel of different advanced and emerging countries included.

[16] All data sources and the observable variables are reported in the appendix (Table 2). The sample for the benchmark estimation ends in the fourth quarter of 2019 and excludes periods related to the Covid-19 pandemics. It is left as an issue for future research weather the disruptions in the first half of 2020 should be considered as outliers or not. In the appendix, bearing potential caveats, the model is estimated with all available data including observations up to the second quarter of 2020.

[17] Quadratic detrending aims at capturing potentially lowering trend growth rates of economic activity over the sample.

[18] The share of US GDP in global GDP (excluding OPEC member countries) is measured using data from the International Monetary Fund's (IMF) world economic outlook (WEO) for the time span 1980-2018. Nominal GDP in all countries is measured in US-Dollar.

[19] It should be noted that the implied share of services in total output is lower than indicated by recent input-output tables. Proxying total output of the economy by services and manufacturing production

of ROW-produced manufactured goods in US manufacturing expenditure (both of final goods and intermediate goods) is set to $\delta = \omega = 0.223$ in order to match the observed average trade openness of the US economy between 1974 and 2018 provided by the World Bank. To be consistent with balanced trade in steady state and relative prices of one, the corresponding share in ROW is calibrated to $\delta^* = \omega^* = n\delta/(1-n) = 0.0867$. Consistent with the estimates of Rabanal and Tuesta (2010) the financial intermediation cost is set to $\chi = 0.007$. The relative importance of the sector-specific demand shock is $\iota_T = \frac{G_T}{Y_T} = \frac{G_T^*}{Y_T^*} = 0.1$.[20] Moreover, I assume that ROW exporters operate under USD pricing $\zeta = 0$. The oil cost share is set to $\tilde{\alpha}_{O,T} = \tilde{\alpha}^*_{O,T} = 0.060$ in manufacturing and $\tilde{\alpha}_{O,N} = \tilde{\alpha}^*_{O,N} = 0.014$ in services, which corresponds to values obtained from 2012 US input-output tables (cf. footnote 1).[21] The share of manufactured intermediate inputs in total manufacturing production is set to $\tilde{\alpha}_{M,T} = \tilde{\alpha}^*_{M,T} = 0.40$ and the share of service inputs in the service sector $\tilde{\alpha}_{M,N} = \tilde{\alpha}^*_{M,N} = 0.29$.[22] For the dominant oil producer, the production function parameters governing labour input as well as intermediate input are calibrated to $\alpha_{N,dom} = \alpha_{X,dom} = 0.15$. In the model, these parameters govern the supply elasticity of OPEC oil production (which then – absent of market power of the dominant producer – would be 0.3). The calibration is motivated by estimation results of Caldara et al. (2019) who, using monthly data, estimate an elasticity of around 0.2 for OPEC production and not different from zero for non-OPEC production. The steady state share of OPEC output in global oil production is calibrated to 41 %, based on data from the US Energy Information Administration. Accordingly, the steady state ratio of global oil inventories to global oil supply is set to 0.33.

Altogether, 30 parameters are estimated. It is assumed that the elasticity between services (nontradeables) and manufactured goods (tradeables), the elasticity between US and ROW manufactured goods, as well as the parameters shaping the technology shocks and the Taylor rule are identical in US and ROW. The posterior mean is used for the remaining calibration of the model. All estimated prior and posterior distributions are reported in Table 5 in the appendix. The elasticity between services (nontradeables) and man-

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(excluding other broader sectors like retail trade and transport, mining and agriculture, construction, or utilities) results in manufacturing having a share in total production of around 30 %. Still, the average share of manufacturing in total production over the whole sample is likely to be higher than the most recent values because of a well-known structural change in the US economy towards a large share of services activity. Moreover, in the context of this paper, the retail trade might be seen as a complement to manufacturing production since manufactured goods rely on distribution services.

[20] It is assumed that there are no demand shocks specific to services as manufacturing-specific demand shocks are able to rationalize diverging output patterns between the two sectors which are not captured by other business cycle shocks.

[21] The implied aggregate oil intensity is around 3 % of gross output. At that time, oil prices were relatively high, implying that the oil share were overestimated. Nevertheless, abstracting from valuation effects, the average aggregate intensity of oil use is likely to be higher than more recent values due to structural changes towards lower oil-intensity over the sample.

[22] The values are also obtained from the 2012 US input/output tables. The model abstracts from service inputs in manufacturing and manufactured intermediate inputs in the services sector in order to keep the model simple. According to the input/output tables, the share of service inputs in total manufacturing production is 13%, while the share of manufactured inputs in total service output is around 3%. As these numbers are comparatively small, including these cross-sectional linkages would likely not affect the results to a relevant extent.

ufacturing (tradeables) consumption is $\phi = 0.43$[23], indicating that service consumption expenditure and manufacturing are complements. The elasticity between US-produced and ROW-produced manufactured goods is found to be lower than one ($\theta = 0.83$). The Calvo parameters relevant for the New Keynesian Phillips curves are $\varphi_N = 0.71$ and $\varphi_T = 0.65$. The Calvo parameter for nominal wages is estimated at $\varphi_w = 0.85$. The parameter governing exchange rate pass-through in ROW is estimated to be low at $\zeta^* = 0.06$, close to the case of local currency pricing. The estimated policy coefficients are also within a reasonable range ($\nu_r = 0.84, \kappa_\pi = 1.33, \kappa_y = 1.54$).

In line with intuition, the posterior mean of the elasticity of substitution between oil and labour supply is rather low ($\tau = 0.11$). The negative value of the convenience yield is estimated at $-\kappa = 0.60$, indicating a lower sensitivity of oil storage to changes in expected oil prices as found in Unalmis et al. (2012). The markup of OPEC producers is implicitly given by the estimated parameters and found to be around 17%.[24]

4 The identified link between the manufacturing/ services activity wedge and real oil prices

The particular focus of this study is the extent to which global oil price movements are differently related to the dynamics in the oil-intensive manufacturing sector that trades a lot compared with to the service sector which does very little trading and is less oil-intensive. Computing the global manufacturing cycle and global service cycle by assuming that the non-stationary time series follows a quadratic trend, I find that the difference in two cycles comoves with the evolution of the real oil price – computed as the demeaned level of the nominal oil price relative to the US CPI – over the entire sample (cf. Figure 1).[25,26] Also, as discussed in detail in the next section, during many major historical episodes, the corresponding cyclical wedge in the US also tended to widen

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[23] As the estimation does not include manufacturing consumption data, the parameter cannot clearly be pinned down by the estimation. One way to deal with this issue would be to calibrate the parameter (following for instance Stockman and Tesar, 1995). I follow a similar approach, and use the calibration of Stockman and Tesar, 1995 ($\phi = 0.44$) as an upper bound of the estimation of this parameter that is ultimately almost reached. Not taking this approach would eventually not affect the main conclusions of the paper. However, then, given manufacturing technology shocks, the identified channel between declining oil prices and declining demand for intermediate manufactured goods demand (see below) would dominate only in the short-run (2-3 quarters) while in the medium-run there are offsetting forces from higher manufacturing consumption relative to services consumption. This latter medium-run phenomenen is not very important for oil price dynamics but would still make the interpretation of the historical decomposition more difficult.

[24] Cf. Appendix D for details. Nakov and Nuño (2013) who assume a markup of 20%. In contrast to Nakov and Nuño (2013) the model features oil storage and assumes OPEC, rather than Saudi Arabia, to be an oil producer having market power.

[25] The correlation coefficient of the two series is 0.67 (excluding the first year in the sample). The correlation coefficient is still above 0.5 if the two series are transformed to y-o-y changes (computed as the difference between the current percentage deviation and the percentage deviation four quarters before). The manufacturing cycle is – only to a slightly lower degree – also positively correlated to the real oil price series. Services activity and the real oil price have, however, a correlation coefficient of close to zero.

[26] Throughout the paper, services activity is proxied by services consumption expenditure also due to data limitations. The advantage of using this measure in the context of this study is that it excludes

with rising oil prices. Furthermore, aggregate US core inflation and the nominal interest rate picked up. Moreover, some important episodes show a positive link between the manufacturing/services wedge and OPEC production.

4.1 Illustration of the main theoretical channels

Before discussing the insights gained from the fully fledged estimated model, and to better grasp the underlying economic intuition, the main channels are discussed by inspecting model-implied, log-linearized relations based on simplifying assumptions. Three main channels are highlighted: (1) In oil-intensive manufacturing production, oil and – imported as well as domestically sourced – manufactured intermediate inputs cannot be easily substituted in the short run. In the case of productivity shocks in the manufacturing sector, this implies close comovement between global manufactured output relative to services expenditure, as well as global oil demand and thus oil prices. (2) Shifts in demand for final manufactured goods result in increased manufacturing output relative to services provision and higher demand for oil in the oil-intensive sector. This is amplified by the input-output structure in the manufacturing sector. (3) In times when global oil prices are high, oil-producer's relative wealth is large, as is therefore also oil-producer's import demand for manufactured goods. For trading partners of oil-producers (in the model, US and ROW) the manufacturing sector benefits from additional demand, rationalizing a link between the difference in the cycle of manufacturing and services, global non-oil trade and oil prices.

Supply chain linkages, oil use, and productivity in manufacturing production

To highlight the first channel (1), let us assume that the elasticity of substitution between manufactured final goods and services is close to zero $\phi \to 0$, which implies $\hat{c}_t = \hat{c}_{T,t} = \hat{c}_{N,t}$ and $\hat{c}^*_t = \hat{c}^*_{T,t} = \hat{c}^*_{N,t}$ in all periods and that the share of non-oil intermediates in production is equal across sectors $\tilde{\alpha}_M = \tilde{\alpha}_{M,T} = \tilde{\alpha}_{M,N}$. For the sake of argument, it is assumed that no oil is used in services and that oil and intermediates are full complements in production (i.e. $\tau \to 0$; in this case, we have $\hat{o}_{T,t} = \hat{m}_{M,t}$ and $\hat{y}_{T,t} = \hat{m}_{T,t} - \hat{z}_{T,t}$ and equivalent relations for ROW). Then, – ignoring, for the moment, the exogenous component in final manufactured goods demand and the role of trade with the OPEC region, which are both discussed below – the log-linearized cyclical wedge between global manufacturing output and services consumption expenditure can be expressed as

$$\begin{aligned}\hat{wedge}_t &= n(\hat{y}_{T,t} - \hat{c}_{N,t}) + (1-n) * (\hat{y}^*_{T,t} - \hat{c}^*_{N,t}) = \\ &= n * \hat{c}_{T,t} + (1-n)\hat{c}^*_{T,t} - \frac{\tilde{\alpha}_M}{(1-\tilde{\alpha}_M)}(n * \hat{z}_{T,t} + (1-n) * \hat{z}^*_{T,t}) - n * \hat{c}_{N,t} + (1-n)\hat{c}^*_{N,t},\end{aligned}$$

$$\Leftrightarrow \hat{wedge}_t = -\frac{\tilde{\alpha}_M}{1-\tilde{\alpha}_M}(n * \hat{z}_{T,t} + (1-n)\hat{z}^*_{T,t}). \tag{7}$$

The underlying intuition of equation (7) is the following: In the case of a productivity

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service activities that are closely related to manufacturing production such as outsourced business support activities.

shock in the manufacturing sector in the US or in ROW, the same amount of output can be produced with a smaller amount of factor inputs which include labour, oil and manufactured goods. Demand for these – domestically and foreign-sourced – inputs falls. Because of the fall in demand for intermediate manufactured goods, the wedge between global output in manufacturing and services activity declines.[27] Notably, in the case of shocks other than manufacturing technology shocks there is no change in $\widehat{wedge}_t$.

When productivity in the manufacturing sector changes, oil demand is also affected. Since I assume in this example that the oil share in the service sector is zero and that oil and intermediates are close complements in production as $\tau \rightarrow 0$, global oil demand is equivalent to US and ROW demand for manufactured intermediate inputs

$$\widehat{oildemand}_t = [n * (\hat{m}_T) + (1-n) * (\hat{m}_T^*)] = \\ = -\frac{1}{1-\tilde{\alpha}_M}(n * \hat{z}_T + (1-n)\hat{z}_T^*) + \hat{c}_t^{US/ROW}. \quad (8)$$

Expression (8) shows that, ceteris paribus, $\widehat{oildemand}_t$ declines in response to positive shifts in technology in the manufacturing sector with a relatively large elasticity of $-\frac{1}{1-\tilde{\alpha}_M} \leq -1$. Implicitly assuming an oil supply curve that increases in the price of oil, the real oil price also declines when oil demand falls. Still, the direct effect of technology shocks on oil demand can be offset by the response of US and ROW private consumption $\hat{c}_t^{US/ROW} = n * \hat{c}_t + (1-n) * \hat{c}_t^*$, which is typically positive in the case of positive productivity shocks. While it is not straightforward analytically to show that this latter effect is dominated by the direct effect of the technology shock, in the estimated model this is clearly the case. More generally, the basic mechanism described here prevails in the estimated model with a different parameter configuration.

The role of shifts in demand for manufactured final goods

Whereas the first channel (1) is especially important in the case of shifts in oil input demand in the presence of supply shocks, i.e. technology shocks, another channel resulting in a positive link between the global manufacturing/services wedge and global oil prices is related to exogenous shifts in demand for final goods in the manufacturing sector $\hat{g}_T$ and $\hat{g}_T^*$ (2). These shocks induce a wedge between output in global manufacturing and services. This can be illustrated by again assuming Leontief preferences for final goods consumption of tradeables and nontradeables and a low elasticity of substitution in production $\tau \rightarrow 0$ and focusing on manufacturing demand shocks while setting technology shocks to zero. In this case, aggregate output in manufacturing is equal to factor input demand, i.e. $\hat{y}_T = \hat{n}_T = \hat{o}_T = \hat{m}_T$ and $\hat{y}_T^* = \hat{n}_T^* = \hat{o}_T^* = \hat{m}_T^*$. The global manufacturing/services wedge

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[27] Services activity is captured in the estimated model by services consumption expenditure. Nevertheless, the corresponding wedge would also decline in presence of such shocks if the wedge is measured as the difference between manufacturing aggregate output and services aggregate output. This becomes clearer in the discussion of the fully fledged estimated model.

and global oil demand can be written as[28]

$$wedge_t = \frac{G_T}{Y_T}\left(n * (\hat{g}_T - \hat{c}_t) + (1-n) * (\hat{g}^*_T - \hat{c}^*_t)\right), \tag{9}$$

$$oildemand_t = \frac{G_T}{Y_T}\left(n * (\hat{g}_T - \hat{c}_t) + (1-n) * (\hat{g}_T - \hat{c}_t)\right) + \hat{c}_t^{US/ROW}. \tag{10}$$

Equations (9) and (10) show that the global manufacturing/services wedge and global oil demand comove after positive shocks to final goods demand $\hat{g}_T$ and $\hat{g}^*_T$ if global private consumption $\hat{c}_t^{US/ROW} = n*\hat{c}_t + (1-n)*\hat{c}^*_t$ does not respond too strongly. In the estimated impluse-response functions, the impact is indeed found to be relatively small. In line with intuition, the manufacturing demand shocks in US and ROW lead to an increase in global manufacturing activity relative to services provision and $\widehat{oildemand}_t$, implying positive comovement between $\widehat{wedge}_t$ and oil prices.

OPEC's trade response to oil price movements

A similar rationale as in the case of increased demand for final manufactured goods prevails due to wealth shifts between US/ROW and the OPEC region as a general consequence of oil prices movements (3). Denoting steady-state exports of manufactured goods to the OPEC region relative to US and ROW total manufacturing output by $\mathcal{O} = \frac{n*(C_{dom,TH}+X_{dom,TH})+(1-n)*(C_{dom,TF}+X_{dom,TF})}{nY_T+(1-n)Y^*_T}$, and ignoring, for the sake of clarity, the possibility of exogenous technology shocks and of final manufactured goods demand shocks, then

$$\widehat{wedge}_t = \frac{O}{1-\tilde{\alpha}_m}\left((1-\alpha_{x,dom})\hat{c}_{dom,t} + \alpha_{x,dom}\hat{x}_{dom,t}\right) - \frac{O}{1-\tilde{\alpha}_m}\hat{c}_t^{US/ROW}. \tag{11}$$

The term $(1-\alpha_{x,dom,})\hat{c}_{dom,t} + \alpha_{x,dom}\hat{x}_{dom,t}$ expresses OPEC's demand for imports of manufactured final goods ($\hat{c}_{dom,t}$) and intermediate goods ($\hat{x}_{dom,t}$). Because of OPEC's financial autarky, it is equal to $\hat{p}_{Oil,t} + \hat{o}_{s,t} - \hat{p}_{x,dom,t}$. Given a change in the oil price that is not offset by changes in OPEC's oil supply $\hat{o}_{s,t}$ or manufactured goods prices $\hat{p}_{x,dom,t}$, OPEC's demand for manufactured imports increases. This is due to a positive valuation effect of OPEC's output against the rest of the world. When oil prices rise, US and ROW have to compensate for this valuation effect by a higher amount of exports to OPEC, which, all else equal, increases activity in the manufacturing sector relative to services. Notably, in the estimated model consumption in the US and ROW $\hat{c}_t^{US/ROW}$ declines when oil prices rise after adverse (OPEC and non-OPEC) supply shocks, and the shift of wealth between US/ROW and OPEC related to higher oil prices leads to an increase in $\widehat{wedge}_t$.

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[28] Note that $n\hat{y}_{T,t} + (1-n)\hat{y}^*_{T,t} = (1-\tilde{\beta}) * \left((1-\frac{G_T}{Y_T}) * (n * \hat{c}_t + (1-n)\hat{c}^*_t) + \frac{G_T}{Y_T}(n\hat{g}_T + (1-n)\hat{g}^*_T)\right) + \tilde{\beta} * (n * \hat{y}_T + (1-n) * \hat{y}^*_T)$ where it is assumed that $\hat{c}_t = \hat{c}_T = \hat{c}_N$, and $\hat{c}^*_t = \hat{c}^*_T = \hat{c}^*_N$ as $\phi \to 0$.

4.2 The trade channel, sectoral dynamics, and the transmission of oil-related demand and supply shocks in the estimated model

In the historical decomposition of the estimated model (cf. below) it turns out that shocks specific to the manufacturing sector, i.e. manufacturing technology shocks and shocks to the demand for manufactured goods, are found to be a major demand force for global oil prices. For this reason I focus on these demand-type disturbances in the global oil market and start with total factor productivity shocks in manufacturing. As discussed above, such shocks have the potential to rationalize comovement between oil prices and the global wedge between manufacturing and services. Figure 2 reports the impulse response functions for a one standard deviation shock to ROW manufacturing technology $\xi_{z_T^*}$.[29]

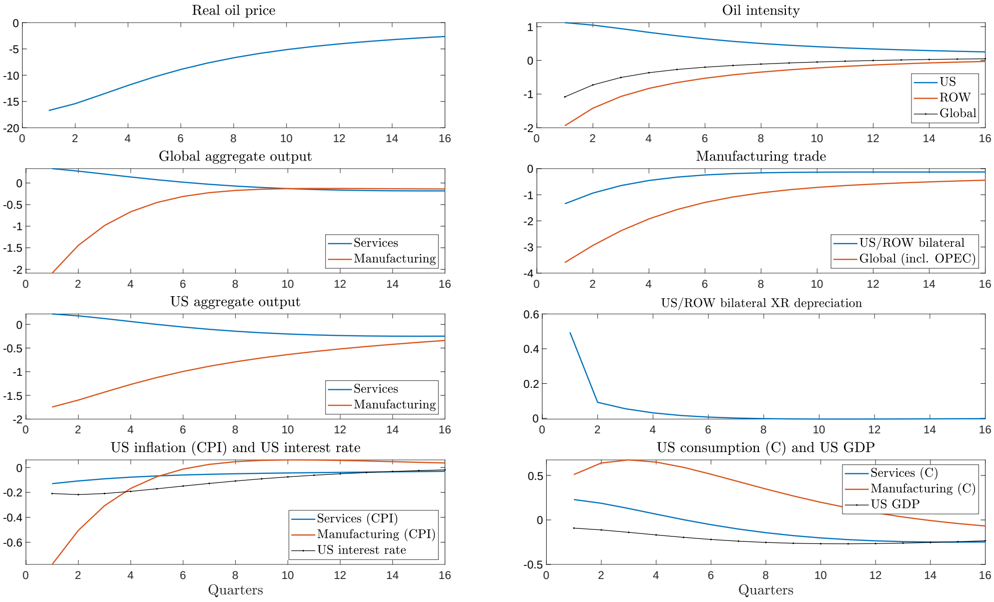

Figure 2: Impulse response function for a ROW manufacturing technology shock ξ^*_{ZT}. Expressed as percentage deviation from steady state.

A priori, the effect of a technology shock on global oil prices is ambiguous in the model. As outlined above, a shock to productivity lowers the demand for all factor inputs, and, if oil is a complement to the other factors of productions, oil demand should go down as well. At the same time, factor demand in this sector might go up because of more final good demand arising in response to a technology shock that lowers the price of ROW-produced manufactured goods. The estimated impulse response function shows that the first effect plays a dominant role and oil prices are lowered for around four years.[30] In a one-sector model, Bodenstein and Guerrieri (2018) and Bodenstein et al. (2012) specify

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[29] ROW manufacturing-specific shocks are more important in the historical decomposition than US-specific shocks and, therefore, the focus is on these shocks. Nevertheless, the rationale can be translated to the corresponding US shocks.

[30] As an estimation outcome, the elasticity of substitution between oil, labour, and intermediates is estimated at a rather low value (cf. section 3).

shocks of oil-input specific technology (i.e. oil-efficiency shocks), which are found to be major demand-type driver of oil prices. Because of the complementary of the inputs of production, the standard total factor productivity shock as introduced here delivers a similar rationale about shifts in global oil demand. ROW aggregate oil intensity, measured as oil use in barrel per one unit of aggregate output, and ROW intermediate manufactured goods demand decline jointly. In the calibrated model intermediate manufactured goods represent a large fraction of aggregate output in the manufacturing sector of around 40%. While the manufacturing technology shock leads to higher consumption of final manufactured goods – and, through income effects, also higher global services activity and higher ROW's GDP –, the decline in manufactured intermediate goods demand is sufficient to lower aggregate manufactured output. Notably, manufacturing contracts relative to service. The trade channel is also important. ROW's demand for US-produced intermediate manufactured goods declines. Also, the lowered demand for ROW's oil imports translates into lower OPEC imports of manufactured goods from the rest of the world. Moreover, manufacturing producers in the US face tighter conditions due to higher relative prices in comparison to their ROW competitors. US demand for US-produced goods as well as corresponding exports are dampened and manufacturing output in the US contracts. For the US economy, a manufacturing technology shock occurring in ROW still imposes positive income effects because of improving terms of trade. As shown in Figure 2, in the first 1½ years these income effects lead to an increase in US consumption and results in an expansion of services activity. Overall, the gap between manufacturing output and services activity declines jointly with the oil price. US GDP is relatively little affected and decreases only modestly. Marginal cost in both US sectors go down relative to sector-specific goods prices because of lower factor prices. To a large degree also because of cheaper imports of manufactured goods, aggregate consumer price inflation decreases, and, consequently, short-run interest rates are lowered.

Figure 3 reports a one standard deviation shock to the ROW demand for manufactured final goods $\xi_{G^*_T}$. This ROW demand shock triggers an increase in the price of oil and a rising wedge between global manufacturing and services in the US and globally. In ROW, manufacturing expands markedly while service activity contracts slightly in the first two years after the shock. The increased demand for final manufactured goods translates not only in higher oil demand but also in increased demand for manufactured inputs. Thereby input-output linkages amplify the impact of the demand shock. Because of the trade channel, manufacturing output in the US benefits. The rise in output in US manufacturing stems especially from ROW demand; private consumption of the domestic agents shows relatively little movement in short-run response to the shock. In the first year after the shock, the adjustment of manufactured goods consumption is even negative. Notably, inflation remains for many periods at a positive level in both US sectors. Optimizing firms adjust sector-specific prices in response to changes in their marginal cost, and wages and the oil price increase in nominal terms due to pressure originating in the global manufacturing sector. Moreover, the input-output structure imposes strategic complementarities among price setters. It amplifies the aggregate price increase as competitor's prices enter directly into producer's marginal cost.[31] Monetary policy responds to rising aggregate

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[31] On impact, nominal oil prices pick up more pronounced than nominal wages that increase relatively persistently. In the medium term, both cost factors add to underlying price pressure. In US manufacturing, in the first 8 quarters, nominal wages add to marginal cost by roughly 0.025 percentage points

inflation and output growth by raising interest rates in line with the standard Taylor rule response.[32]

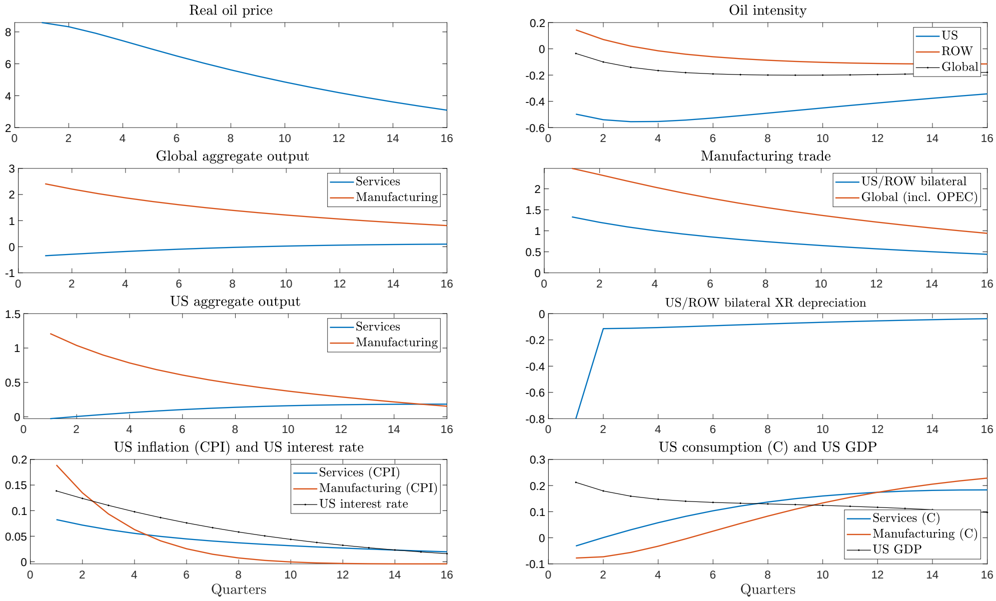

Figure 3: Impulse response function for a ROW manufacturing demand shock ξ_{GT^*}. Expressed as percentage deviation from steady state.

The other demand-type shocks are not discussed in every detail. It should, however, be noted that, from the US perspective, all shocks originating outside the US can explain the pattern of a widening of the gap between manufacturing output and services activity, as well as increasing aggregate and sectoral inflation and nominal interest rates in times of rising oil prices. This is in line with intuition that in general shocks to activity in one region have spillover effects to other regions because of the trade channel.

As outlined above, because OPEC is a net importer of manufactured goods – which are used in consumption and oil production, the dynamics of the wedge between manufacturing and services play a major role in the transmission of standard oil supply shocks to the ROW and US economies. This can be seen in Figure 4, which reports the effects of a one-standard deviation (positive) shock to the oil supply in the OPEC region.[33] As expected, an expansion in the global production of oil leads to an – indeed sizeable – decrease in the price of oil. In response to this shock, global manufacturing output contracts relative to global services activity. Manufacturing has a relatively high oil-intensity

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on average, while oil prices contribute by 0.045 percentage points. Additionally, prices for non-oil intermediate goods also rise, adding another 0.028 percentage points. Oil prices have less of an impact on inflation in the US services sector where the increase in nominal wages is more relevant for the evolution of marginal cost.

[32] Cf. Rabanal and Tuesta (2013) for a more detailed discussion of the mechanism related to tradeable demand shock in a model without oil and intermediate goods in production. They find that a tradeable sector demand shock can explain a negative relation between private consumption and the real exchange rate. This is in the medium term also observed here.

[33] OPEC supply is endogenous in the model. Nevertheless, production can be disrupted by exogenous supply shocks.

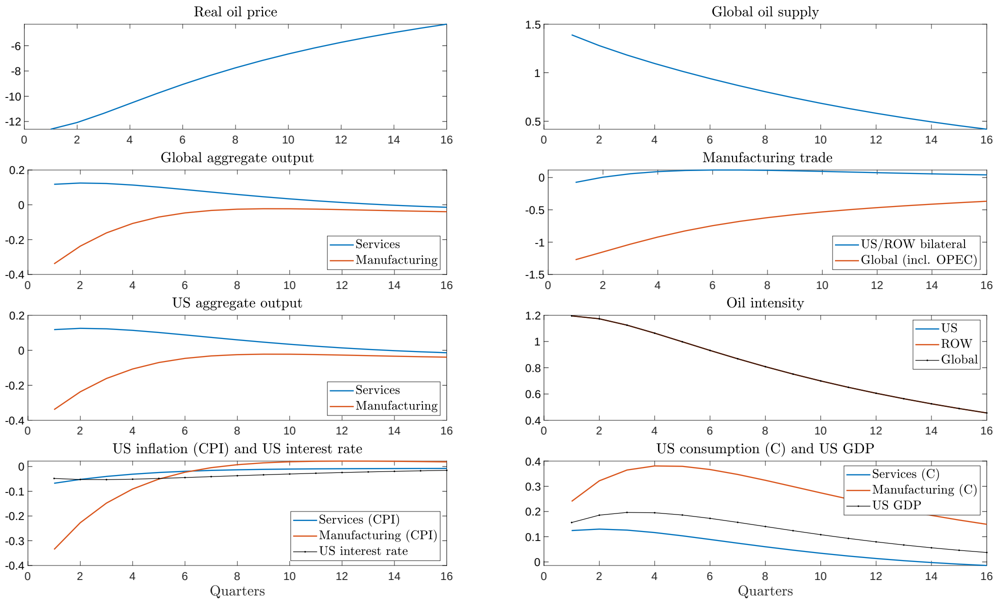

Figure 4: Impulse response function for an OPEC supply shock $\xi_{os,OPEC}$. Expressed as percentage deviation from steady state.

and faces decreased cost pressure after a positive exogenous oil supply shock. Still, the oil price increase also implies exports of the OPEC region to the US and ROW have a lower value, which is consistent with lower OPEC imports of manufactured goods from the other two countries in order to stabilize the trade balance.[34] At a global level, the manufacturing/services wedge declines. A similar pattern emerges in the US. Moreover, nominal prices in both US sectors are dampened – again not only due to lower oil prices but also because of a persistent decline in nominal wages – together with the policy rate.[35]

As an interesting byproduct of the estimation, manufacturing activity proxied by manufacturing output in the US and in the ROW is found to expand in response to adverse oil supply shocks, but GDP is slightly negatively affected. There is mixed empirical evidence on the impact of oil supply shocks for industrial production and real GDP in studies employing SVAR models. For instance, Caldara et al. (2019) find that industrial production in emerging economies rises after an adverse oil supply shock, which relates to the "Asian puzzle" documented in Aastveit, Bjørnland, and Thorsrud (2015). Also, industrial production in the advanced economies is not affected significantly in the first year after the shock and slightly negatively afterwards. Peersman and Robays (2012) find heterogeneity across different countries regarding the sign of the response of GDP. In Baumeister and

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[34] To keep the model tractable, it is assumed in the model that OPEC is financially autarkic, which implies that trade has to be balanced along the transition. The results of Bodenstein et al. (2011) indicate that, even under a more realistic assumption of incomplete financial markets the trade balance is not very responsive to oil supply shocks when the elasticity of substitution of oil is low.

[35] Oil storage demand shocks as well oil supply shocks not originating in the OPEC region share features of the dynamics of OPEC supply shocks. For shocks that lower oil prices, the value of OPEC exports declines, which implies spillovers to global manufacturing. Nevertheless, OPEC production declines endogenously in response to positive non-OPEC supply shocks as well as to shocks that decrease the demand for oil inventories.

Hamilton (2019) the impact of global oil production shocks on global industrial production measured by the posterior median is negative – as is the 68 present posterior credible set after around 6 periods, although the response is not significant within the 95 percent posterior credible set. In the same study the posterior median of an inventory demand shock that increases oil prices on industrial production is positive in the first year and then reverts only after around two years. According to the the credible sets, the effect is not, however, different from zero. In the DSGE model, the trade channel can rationalize why especially the response of industrial production to exogenous oil supply shocks – as well as to oil inventory shocks – is not necessarily negative as often a priori assumed.[36]

4.3 The relative importance of the identified shocks

Figures 5 and Figure 6 show the historical shock decomposition for the real price of oil and for the global wedge between manufacturing and services for various groups of shocks. They describe how, at every point in time, real prices and quantities are explained by the various exogenous disturbances. The graphs reveal that the manufacturing-specific shocks – manufacturing technology shocks and manufacturing demand shocks – explain most of the evolution in the wedge between manufacturing and services, while leading to large movements in the price of oil. These shocks are found to be a key source of global oil price movements.[37] The pattern is, for instance, pronounced in the 2000s, which is discussed in more detail below. Non-manufacturing-specific demand-type shocks can still explain a sizeable percentage of global oil price movements and, to a small extent, variation in the cyclical wedge.

The comovement between oil prices and the sectoral wedge can also partly be rationalized by the mechanism that oil price shocks induce wealth shifts towards oil exporters. For instance, after 2014 in response to positive oil supply shocks and oil storage demand shocks that led to declining oil prices, oil producers decreased their demand for manufactured goods, and, as a result, the cyclical wedge between manufacturing and services deteriorated – which becomes even clearer once year-on-year changes are discussed in more detail below. A similar pattern emerged in 1986. In an earlier study, Bodenstein et al. (2011) use a calibrated model to emphasize that the non-oil trade balance of the US improves in response to an adverse oil supply shock because of valuation and trade channels are also at work here. In the historical decomposition of the estimated model, I find that this channel is quantitatively relevant.[38]

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[36] It should, however, be noted that aggregate output in the model is proxied by the weighted average of production in manufacturing as well as services consumption expenditure, neglecting sectors like transportation, construction, agriculture and mining.

[37] The manufacturing-specific shocks also have large explanatory power according to variance decomposition (cf. Table 1).

[38] Using VAR models, Kilian et al. (2009) estimate the response of the (non-oil) trade balance of oil-importing and oil-exporting economies in response to oil supply shocks, among other exogenous drivers in the global oil market. For oil-importing economies, they find an increase in the non-oil trade balance in response to an adverse oil supply shock in the first year after the shock, comparable in magnitude to the decline of the oil trade balance on impact. For oil exporters, they find an increase in the oil trade balance on impact and a small decline in the non-oil trade balance in the first and second year after the shock. Nevertheless, in the VAR, in the first few years after the shock the described responses for oil exporters are statistically insignificant.

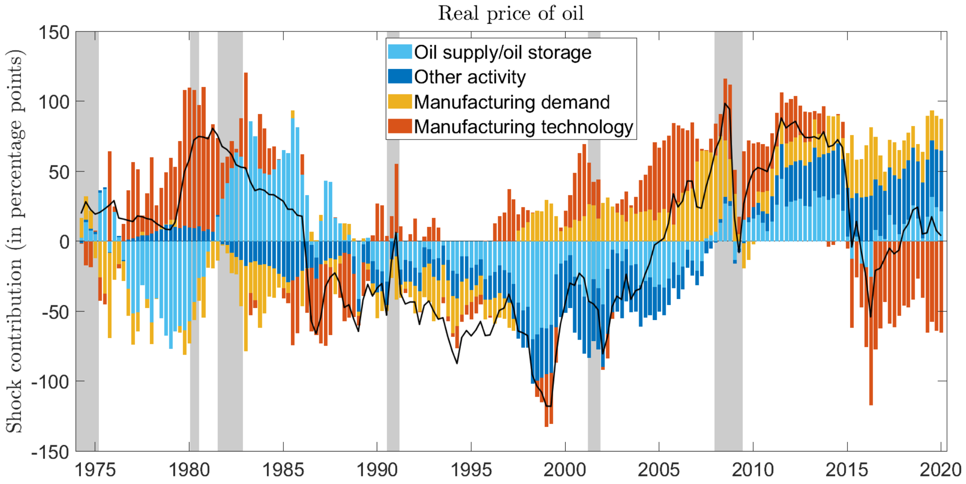

Figure 5: Historical decomposition of the real oil price. (*)
(*) The demand-type shocks (business cycle shocks) in the oil market are distinguished between shocks specific to the global manufacturing sector, i.e. US and ROW manufacturing technology shocks (red bar) and manufacturing-specific demand shocks (yellow bar) as well as other global activity shocks not specific to manufacturing, which include US impatience shocks, US monetary policy shocks, as well as US and ROW service sector technology shocks and shocks to the risk premium for US-denominated bonds (dark blue bar). The remaining group includes oil supply and oil storage demand shocks (light blue).

Earlier contributions to the DSGE literature discuss the role of oil efficiency as a major demand-type source in the global oil market (cf. Bodenstein et al. 2012 and Bodenstein and Guerrieri 2018). In the model, I refrain from assuming shocks specific to oil factor demand and focus on relatively standard business cycle shocks. To conserve space, the model-implied oil-intensity, measured by oil use in barrel for one unit of aggregate output, for the US and ROW are plotted in the appendix (cf. Figure 18 and 19). For some major episodes, the impact of manufacturing technology shocks to oil intensity corresponds to changes in oil efficiency identified in Bodenstein and Guerrieri (2018). For instance, Bodenstein and Guerrieri (2018) find an important role of oil-efficiency shocks for driving global oil prices in the mid-2000s, whereas, in the DSGE model, manufacturing-specific shocks are the main driver of oil prices and shift ROW oil-intensity upwards. The results also correspond with regard to other episodes in the 1990s and 2000s.[39] Nevertheless, other shocks than manufacturing technology shocks (including shocks to the demand for manufactured final goods and services technology shocks) likewise affect oil-intensity in a quantitatively important way and thus oil prices (see Figures 18 and 19 in the appendix and Table 1). More generally, several (US and non-US) goods market and oil market demand and supply type shocks are found to be of importance for the link between oil prices and the macroeconomy – especially also for the wedge between manufacturing and services – while Bodenstein and Guerrieri (2018) attribute most of the evolution – around 88% – in global oil prices to foreign oil efficiency shocks.

4.4 The role of the US dollar exchange rate

From the US perspective, diverging patterns in the manufacturing sector relative to services could intuitively be related to the rise in global oil prices because of shocks affecting

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[39] The estimation of Bodenstein and Guerrieri 2018 is restricted to the sample 1984-2008.

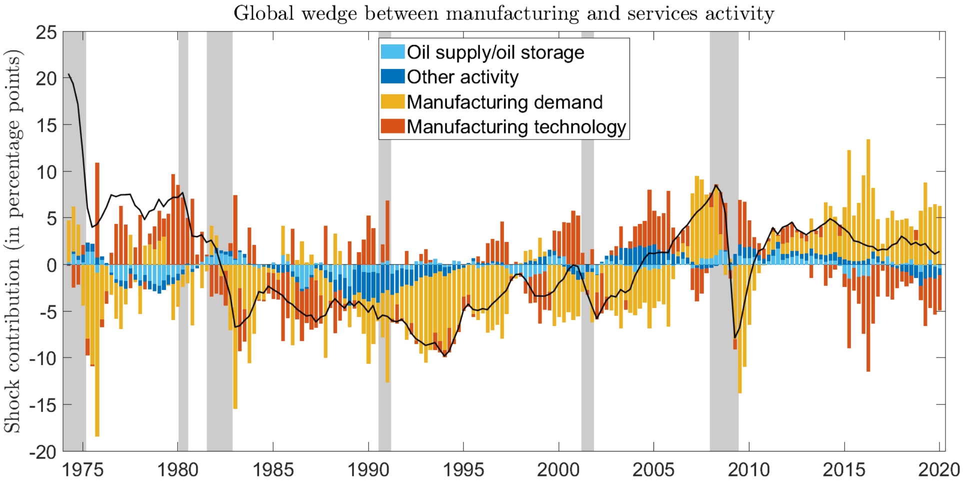

Figure 6: Historical decomposition of the global gap between manufacturing output and services activity. (*)

Table 1: Variance decomposition real oil price (in %, at different horizons in quarters)

	4	8	12	20	40
Manufacturing technology shocks (US)	6.55	6.00	5.68	5.43	5.34
Manufacturing-specific demand shocks (US)	3.53	4.11	4.54	5.06	5.57
Manufacturing technology shocks (ROW)	42.44	38.95	36.56	34.19	32.71
Manufacturing-specific demand shocks (ROW)	13.07	14.37	15.06	15.45	15.22
Manufacturing-specific economic activity shocks	65.59	63.43	61.84	60.13	58.84
Other activity shocks (US)	0.86	0.97	1.04	1.09	1.11
Other activity shocks (ROW)	0.14	0.13	0.14	0.16	0.21
Shocks to uncovered interest rate parity US/ROW	0.60	0.74	0.88	1.13	1.43
Non-manufacturing-specific economic activity shocks	1.61	1.84	2.06	2.38	2.75
OPEC oil supply shocks	27.34	29.26	30.23	30.88	30.87
Non-OPEC oil supply shocks	3.35	3.95	4.47	5.26	6.21
Total oil supply shocks	30.70	33.21	34.70	36.15	37.09
Oil storage demand shocks	2.10	1.51	1.40	1.35	1.33

the value of the US dollar. Ceteris paribus, an appreciation of the dollar makes US tradeable goods more expensive in the rest of the world, thereby leading to a contraction of the manufacturing sector relative to services. Also, demand for oil is directly affected by exchange rate movements due to dollar-denomination of the commodity.

In the model, exchange rates and oil prices are endogenously affected by business cycle and oil market shocks. The model also incorporates shocks to the standard uncovered interest rate parity (UIP) condition.[40] Itskhoki and Mukhin (2019) discuss the capacity of such shocks for rationalizing exchange rate disconnect. Interestingly, a consistent finding arises in the estimation of the DSGE model. A large percentage of exchange rate movements is explained by shocks to the UIP condition but the impact on macro variables and the global oil price is rather limited. For further reference, the impulse response function of the UIP

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[40] The log-linearized model-implied uncovered interest rate parity condition is given by $\hat{r}_t - \hat{r}_t^* = E_t \triangle \hat{s}_{t+1} + \varsigma_t$ where ς_t is an exogenous disturbance (risk premium shock).

shock is plotted in Figure 17 in the appendix. When such a shock positively affects the spread between the US and the ROW interest rates, the US real exchange rate appreciates markedly. The terms of trade improve, which is less favourable for US manufacturing production through decreased competitiveness, but expansionary for services. Also, in the ROW oil demand depends on the global oil prices denominated in US dollar. Therefore, an appreciation dampens global oil demand, and, in the short run, ROW manufacturing activity. The increase in the value of the US dollar does, however, deteriorate the terms of trade of the ROW, which leads, over the medium term, to higher output in the ROW manufacturing sector (also relative to the services sector).[41]

According to variance decomposition in Table 1, a rather limited percentage in global oil price movements can be rationalized by shocks to the uncovered interest rate parity – which are the main driver of USD exchange rates. The historical decomposition is discussed in greater depth in the next section and relates to findings in Kilian and Zhou (2019), who employ a benchmark SVAR model of the global oil market encompassing identified exchange rate shocks. During major episodes, exchange rate shocks contribute to oil prices in the expected way. After 2003, for instance, the depreciation of the USD reinforced manufacturing-specific activity shocks, as is shown in more detail below.

5 Dynamics of the oil price, sectoral patterns and the aggregate economy during important historical episodes

In this section, I zoom into the transmission of oil-related shocks during interesting episodes by means of historical decomposition. Below, for illustrative purposes, I shall discuss year-on-year changes in these specific variables (which are plotted in the historical decomposition).[42]

The mid-2000 surge in oil prices and the Great Recession

The episode after around 2003 was characterized by surging global real oil prices and global activity. Notably, manufacturing output was growing faster than services, as was indicated by a widening gap in the sectoral output of these two sectors, both globally and in the US. US aggregate inflation and the US nominal interest rates increased steadily (cf. Figure 7).

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[41] Note that this paper studies the link between global oil prices and the trade channel in a three-region framework (US, ROW, OPEC). The US dollar might, however, also play a role in the trade of many country pairs that do not include the US as trading partner since the USD has a special role in the international price system (cf. inter alia Gopinath, 2016). In this way, the global wedge between manufacturing and services could be affected to a larger extent by USD exchange rate shocks than is identified in this three-region framework. This issue is, however, outside the scope of this study and left for future research.

[42] Since variables are expressed as a percentage deviation from steady state, the measure is given in percentage points. For the non-stationary real variables, this expression would correspond to the annualized quarterly growth rate if the data were not detrended. In the appendix, for further reference, I also plot the historical decomposition of quarter-on-quarter changes in the real oil price, US consumer prices and aggregate US output.

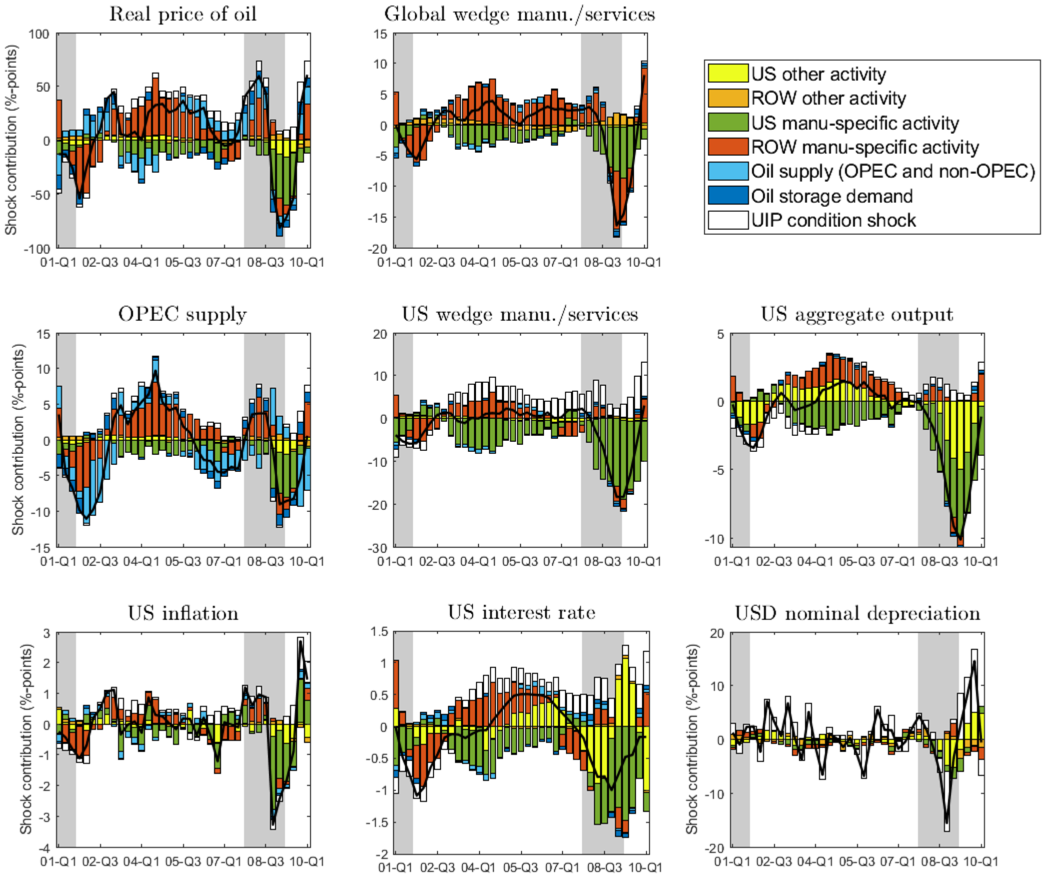

Figure 7: Dynamics in 2003-2009; for variables with a trend the values can be interpreted as percentage deviations from the trend. (**)
(**) Details on legend: (1) US other activity shock (light yellow): US services technology shocks, US impatience shocks, US monetary policy shocks, (2) equivalent for ROW (orange); (3) US manufacturing-specific shocks (green): US manufacturing technology shocks and US manufacturing-specific demand shocks, (4) equivalent for ROW (red); (5) oil supply shocks (light blue): OPEC and non-OPEC exogenous supply shocks; (6) oil storage demand shocks (dark blue); (7) shocks to the US/ ROW UIP condition (white). The variables are expressed in y-o-y changes (%-deviation in time t minus %-deviation in $t-4$).

The estimation procedure identifies manufacturing-specific shocks originating in ROW – both manufacturing technology and shocks to final manufactured goods demand[43] – as an explanation for a large percentage of the global gap between manufacturing and services as well as the steep rise in global oil prices. The findings are in line with evidence from a wide range of empirical studies finding that oil prices were driven by global business cycle factors during these episodes, including Kilian (2008,2009), Kilian and Hicks (2013), and Kilian and Murphy (2014).

From the perspective of the US, manufacturing-specific shocks originating in ROW contribute to the widening of the gap between manufacturing and services. The US manu-

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[43] The relative importance of ROW manufacturing-specific demand shocks in comparison to ROW manufacturing technology shocks for y-o-y changes in oil prices varies for the specific periods. For example, around end of 2003/ beginning of 2004 manufacturing-specific demand shocks explain a relatively larger fraction of rising oil prices, while from mid-2004 to mid-2005 ROW manufacturing technology shocks are more important. In the last quarter of 2005 and the first half of 2006, ROW manufacturing demand shocks explain again a relatively larger fraction.

facturing sector and US aggregate output benefit from additional global demand because of higher exports to the rest of the world, as hypothesized by Kilian (2008). In the US, aggregate inflation goes up and labour is allocated from the services sector to the manufacturing sector. Monetary policy responds by raising short-term nominal interest rates.

Interestingly, global activity shocks (i.e. especially ROW manufacturing-specific shocks) rationalize the large expansion in OPEC production during the mid-2000s. It can be noted that exogenous global oil production shocks contributed to high oil prices in 2007 and 2008. This relates to findings in Hamilton (2009). Also, the rise in oil demand lowered the level of oil storage, which was partly offset by speculative demand shocks in expectation of a tighter future oil market.[44] The results do, nevertheless, contradict the common view that oil-intensive industries are hit first by higher oil prices induced by exogenous supply shocks because of the former's cost structure. The trade channel as operative here has the interesting implication of an expanding oil-intensive manufacturing sector in times of high oil prices.

During the Great Recession, oil price fell sharply, while manufacturing contracted far more than services. The relationship between oil price movements and sectoral output is again well captured by manufacturing-specific shocks in this periods originating in the US, especially by shocks to the demand for manufactured final goods. This is consistent with anecdotal evidence for 2009 when a large fall in global trade was related to dynamics in US manufacturing – for example, the US automobile sector, and, at more aggregate level, physical investment and capital goods.[45]

Low oil prices around 2014-2016 and recovery in 2017

Oil prices recovered quickly after the Great Recession and remained at a relatively high level until they declined quite sharply in 2014 (cf. Figure 8). This decline and the following episode of low oil price levels is often attributed to the "shale oil revolution" in the US as well as a related increase in crude oil inventories and OPEC production increases. In the historical decomposition, oil-supply shocks are indeed identified as one main factor explaining the y-o-y change in real oil prices. Non-OPEC supply increased at a rapid pace, while cyclical OPEC supply remained relatively low. Low OPEC supply growth in 2014 is found to be, in part, an endogenous reaction to non-OPEC supply shocks, and found

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[44] Overall, during the mid-2000 surge in oil prices the role of storage demand shocks is, however, very limited. Kilian and Murphy (2014) as well as well as Baumeister and Hamilton (2019), among others, study the presence of speculative pressures in the market for oil in order to identify unobserved shifts in expectations about oil demand. They also do not find evidence for speculative pressure in the 2000s. It is discussed in more detail in the appendix that the oil storage demand shocks in the DSGE model correspond well to corresponding shocks in Baumeister and Hamilton's SVAR. Baumeister and Hamilton (2019) argue that measurement error in inventories should be taken into account to avoid misspecification that could affect the results for this particular episode. Including such an error in the observational equation of oil storage in the DSGE model, does not, however, affect the relative proportion of the shocks in Figure 7.

[45] In the earlier periods of the 2000s, immediately after the recession ending in 2001, demand-type shocks as well as positive oil supply shocks explain oil prices. Around 2002, oil prices changes are positively affected by oil supply shocks, with one possible explanation for this finding being be the Venezuelan crisis of 2002. I find no fundamental effect of the 2003 Iraq war on OPEC production.

to be partly an exogenous OPEC supply shock. The OPEC production increase in 2015 is mainly attributed to OPEC supply shocks.[46] Beginning in 2014, oil inventory shocks played a part in explaining negative oil price growth, gaining in importance with the sharpest decline in 2015. This finding indicates that expectations about future shifts in oil market conditions were also a driver of oil prices during this episode. The quantitative importance of this shock is, however, small compared to other shocks.

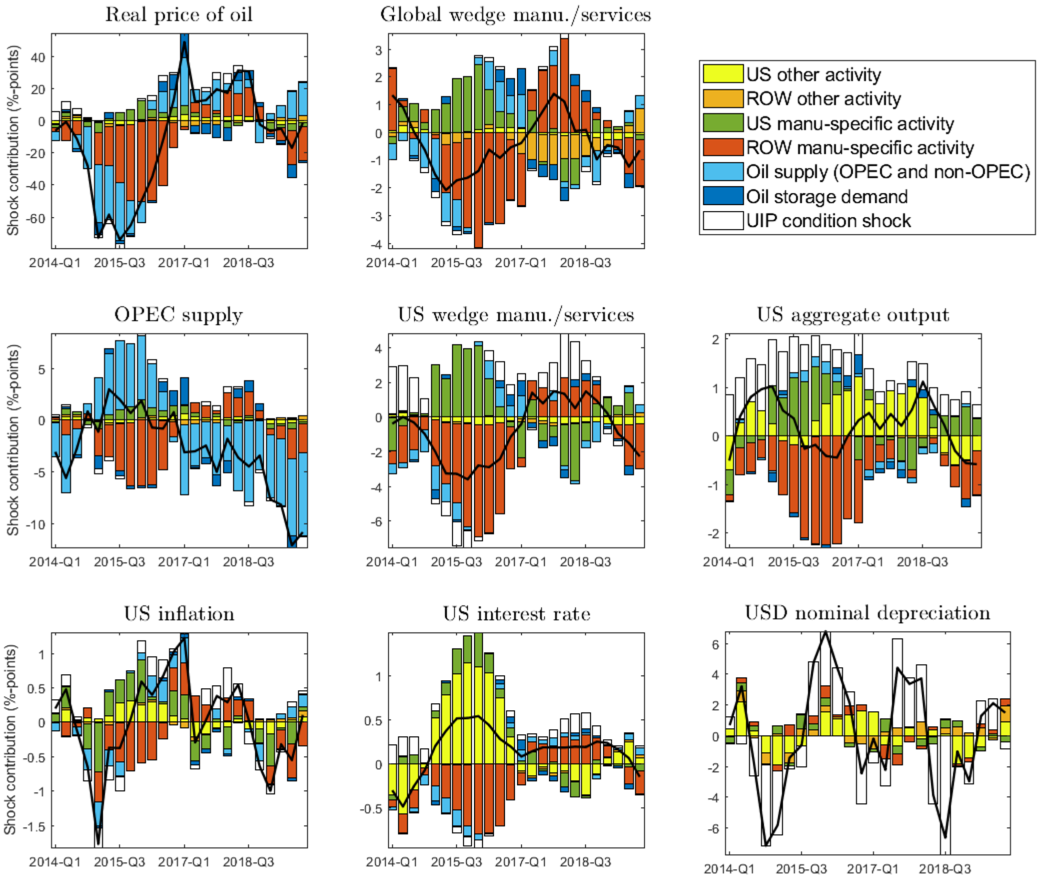

Figure 8: Dynamics in 2014-2018; for variables with a trend the values can be interpreted as percentage deviations from the trend. (**)

Importantly, in the context of this study, the global gap between manufacturing and services declined after 2014 because of oil supply and oil storage demand shocks. The fall in oil prices implied a negative wealth shock and lower consumption for the OPEC region. The region demanded fewer manufactured goods from abroad.[47] In the US, this translated into a declining manufacturing/services wedge. To a small extent, US aggregate inflation as well as US aggregate output declined in response to oil supply and oil storage demand shocks, putting downward pressure on short-term interest rates.

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[46] To limit the number of groups of the shocks in the graph, Figures 7 to 8 do, however, not separate OPEC and non-OPEC supply shocks.

[47] As outlined above, the model does not feature investment and capital. The fall in manufactured output relative to services is, however, likely to have been related to lower investment demand from oil producers in response to deteriorating oil prices. This narrative is captured implicitly in the structural model with the assumption that oil producers use manufactured goods as an input in oil production.

Starting in 2014, manufacturing-specific shocks also contributed negatively to oil prices, with gaining importance in the years after.[48] After 2016, the global wedge between manufacturing output and services activity moves still in line with global oil prices, as does the corresponding measure in the US. Interestingly, OPEC supply is also negatively affected by subdued oil demand. After 2016, negative oil supply shocks originating in the OPEC region lead to a contraction in global oil supply, which supports oil price recovery during that episode and later on. This pattern rationalizes production cuts agreed by OPEC and some other countries (for instance, the Russian Federation) during that episode. At the end of the sample, in 2018/19 manufacturing-specific shocks widen the negative manufacturing/services wedge, and thereby contribute to a decline in oil prices.

There are other interesting episodes in the sample. For instance, the historical decomposition reveals, that, the observed dynamics during the oil price decline in 1986 share similarities with the low-oil price episode of 2014-2016. The period before and during the double dip recessions in the early 1980s has interesting similarities with 2003-07. A detailed discussion of these episodes through the lense of the estimated DSGE model can be found in the appendix. There, also the time around the Asian financial crisis and findings for the most recent periods including the massive oil price decline related to the Covid-19 pandemics are discussed in more detail.

6 Conclusion

Understanding the causes and consequences of upswings and downswings in global oil prices is important for the conduct of monetary and fiscal policy. While the classical explanation of oil price movements dating from the 1980s and 1990s is disruptions in global oil production, the more recent literature from the 2000s stresses the role of demand-driven changes in global oil prices and their implication for macroeconomic outcomes in an open economy (see, e.g., Kilian 2008). The trade channel plays a key role consistent with evidence in Kilian and Lewis (2011) and Bodenstein et al. (2012). In this paper, I argue that, for studying the oil/macroeconomy relationship, and, in particular, the relevance of the trade channel, a careful distinction should be made between the manufacturing sector, which exports a lot and uses oil heavily, and the typically large services sector, which exports very little and does not use oil intensively.

I study a model of three regions (US, OPEC, and rest of world) in which the US and rest of world have a trading and oil-intensive manufacturing sector that is related differently to underlying sources of global oil price changes (such as Asian growth) than a relatively large but non-trading services sector. The model features an input-output structure and cross-border manufacturing supply chains as well as global oil inventories and endogenous oil supply. I find that the global oil price is driven, to a large extent, by shocks specific to the manufacturing sector (in the US and abroad) and is thus positively related to the global cyclical gap between manufacturing production and services provision. Given manufacturing supply shocks, – because of the complementarity of oil and non-oil intermediate

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[48] This is in line with evidence in the empirical literature that oil-supply, oil storage demand and activity shocks contributed to the low level of oil prices after 2014 (cf. Baumeister and Kilian (2016b), Kilian (2017), and Baumeister and Hamilton (2019)).

inputs – oil demand and demand for manufactured intermediate inputs as well as global trade and global oil-intensity move in tandem. Of similar importance, in the case of shocks that raise final manufactured goods demand, manufacturing output increases relative to services provision and oil demand of the oil-intensive sector rises, which is amplified by input-output linkages and international trade. From the US perspective, all shocks that originate abroad and fuel global oil prices – including adverse oil supply shocks – cause an increase in manufacturing relative to services and lead to higher inflation stemming from non-oil cost pressure (particularly also nominal wages and intermediate goods prices) and raising nominal interest rates. Such dynamics rationalize, to a large extent, the observed pattern during major episodes, including the 2003-08 surge in oil prices, or (with different signs) the episodes of low oil price around 2015-16.

The results provide evidence for a crucial role played by the trade channel in the transmission of oil-related shocks to the economy. Focusing on this channel and distinguishing between manufacturing and services allows a novel view on historical events. While a common view is that large changes in oil prices are bad for an economy because they especially affect production in oil-intensive sectors like manufacturing negatively, the findings indicate – on the contrary – that in times of rising oil prices the manufacturing sector actually expands relative to the less oil intensive services sector. Notably, I find that, even in the case of oil supply shocks and oil storage demand shocks which fuel oil prices, the global manufacturing sector does better relative to the large service sector, because when such events occur, the former benefits from rising OPEC demand for manufactured goods.

The estimation furthermore reveals that the US central bank raises the interest rate in times of a booming domestic manufacturing sector and a rising oil price. As a result, monetary policy does not directly respond to rising oil prices but raises the interest rate because of higher aggregate core inflation and aggregate output growth. The central bank cannot counteract the diverging pattern in the two sectors of the economy since, in such a two-speed economy, there is no natural rate that fits each sector. If the policy goal is to stabilize output, then consideration should be given to a policy mix and the use of fiscal policy in order to counteract the reallocation effects between the tradeable and the nontradeable sector in times of booming cross-border trade and oil prices. The issue of optimal policy choices is, however, beyond the scope of this paper and left for future research.

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A Appendix: further results

A.1 Discussion of further historical episodes

The late 1970s/ early 1980s

Looking at earlier periods in the sample, the historical decomposition in Figure 9 reveals that the episode before and during the double dip recessions in the early 1980s has interesting similarities with 2003-07, as noted in Baumeister and Kilian (2016a). The global wedge between manufacturing and services increases markedly, which can rationalize a large percentage of rising OPEC production and real oil prices. As noted in Kilian (2009), the Iranian Revolution in 1979 does not coincide with scarcity in global oil production. The historical decomposition reveals that oil supply shocks in fact contributed negatively to oil prices. Consistent with evidence in Kilian and Murphy (2014) and Baumeister and Hamilton (2019), the DSGE model identifies increased demand for oil inventories during that period, which is in line with the narrative of shifted expectations about future supply conditions. Nevertheless, such speculation shocks cannot explain the observed contraction of gross output in the US. While the consequences of these shocks differ for manufacturing and services, the historical decomposition reveals a small positive effect on output.

The historical decomposition can also shed some light on the issue of the role of the central bank for the oil-price /macroeconomy relationship. It has been suggested that, in 1979, the Federal Reserve tightened interest rates as a systematic response to rising oil prices which, as a consequence, amplified potential recessionary effects of oil prices. The key assumption underlying this view is that oil prices are driven by oil supply shocks that are exogenous to economic activity and not by shocks that are related to the US economy. I find as a result that this assumption should be challenged – reinforcing arguments in the recent literature – because oil production was at a high level during this episode before 1980 – to large extent owing to the positive impact on manufacturing-specific shocks on the oil price – and did not contribute to aggregate inflation in the US. The observed monetary policy response tightening is not related to negative oil supply shocks but to economic shocks affecting global oil demand as well as US output. The historical decomposition shows that a non-negligible part of around 25 basis points of the change in the central bank rate compared to the previous year at that time can be rationalized by a systematic response to aggregate inflation and output growth caused by shocks originating in ROW. Nevertheless, these shocks are to some extent outweighed by negative contributions from US manufacturing-specific shocks. In line with the findings of Baumeister and Peersman (2013), high US inflation around 1979 is mainly explained by factors that are not related to global oil price movements. Short-run interest rates are raised because of identified US-activity shocks that do not affect oil price movements to a relevant extent.[49,50]

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[49] It should be noted that the episode occurred early in the sample that starts in 1974 where estimated initial values still shape the dynamics of the variables, since – prior to 1974 – the data appears not to be close to steady state. For this reason, in this particular episode some parts of the plotted dynamics remain unexplained.

[50] It can also be noted that the central bank response to ROW manufacturing-specific shocks fits the manufacturing sector better than the services sector which contracts in response to such shocks. In that sense, a systematic response to aggregate inflation and output has converse effects, because it cannot counteract the sectoral output divergence in such a two-speed economy.

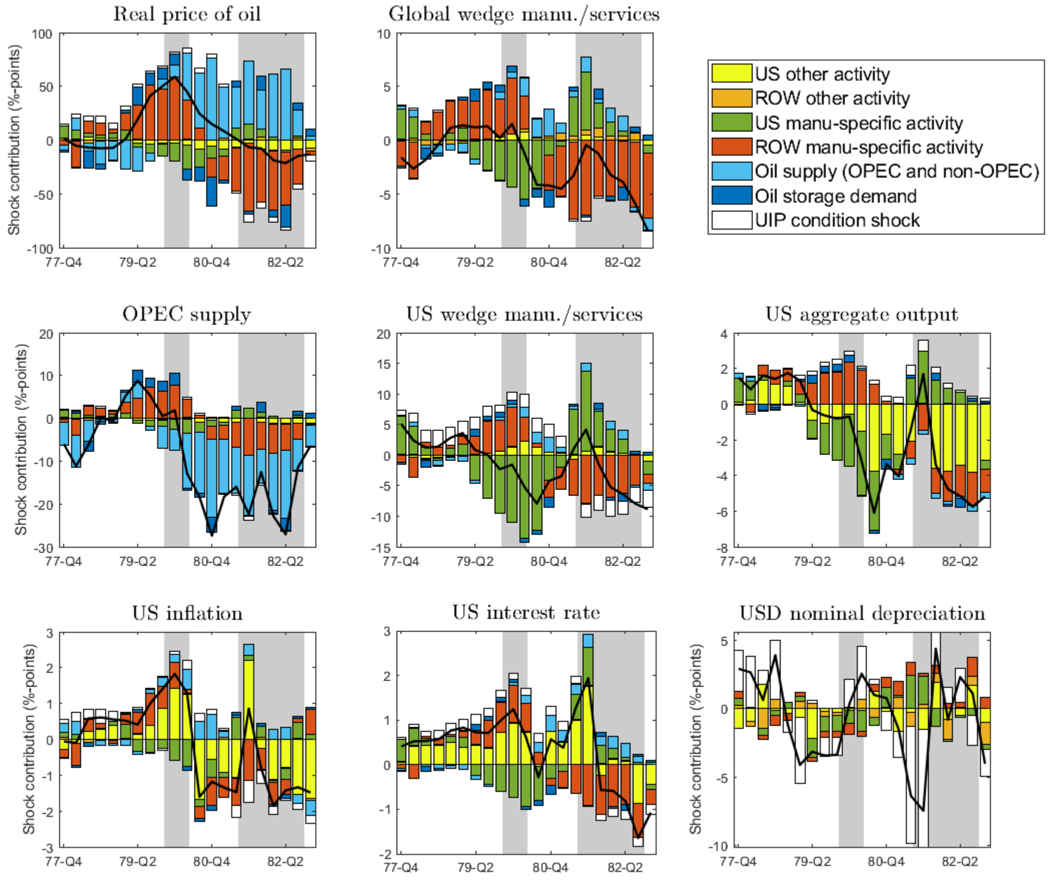

Figure 9: Dynamics around end of 1970s/ early 1980s; for variables with a trend the values can be interpreted as percentage deviations from the trend. (**)

The 1986 fall in oil prices

The fall in oil prices in 1986 is also worth discussing (cf. Figure 10). The period from 1985 to 1987 was characterized by a persistent fall in manufacturing output relative to services. The central bank lowered interest rates in this period of falling (sectoral and aggregate) inflation. The estimation identifies manufacturing-specific shocks as a relevant driver of these dynamics.[51] More importantly, in 1986 OPEC production increases abruptly due to positive oil supply shocks, which relates to the narrative of a breakdown of the OPEC cartel. In the four quarters of 1986, these shocks are the main drivers of the y-o-y change in oil prices.[52] In that year, the global wedge between manufacturing and services also contracted mainly because of oil supply shocks, implying dynamics similar to those observed after 2014. Oil storage demand shocks contribute positively to oil prices in late 1985 but then negatively in some episodes of 1986 (the shocks adds a particularly large

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[51] In the second half of 1985, the USD depreciated quite rapidly because of the Plaza Accord. This is captured by shocks to the uncovered interest rate parity condition. Consistent with findings Kilian and Zhou (2019), the intervention did not support oil prices to a significant extent.

[52] The level of real oil prices – as opposed to the y-o-y changes – had been noticeably dampened by activity shocks. Also, the oil price level between 1980 and 1986 is characterized by too low oil production after the Iran/Iraq war (cf. Figure 5).

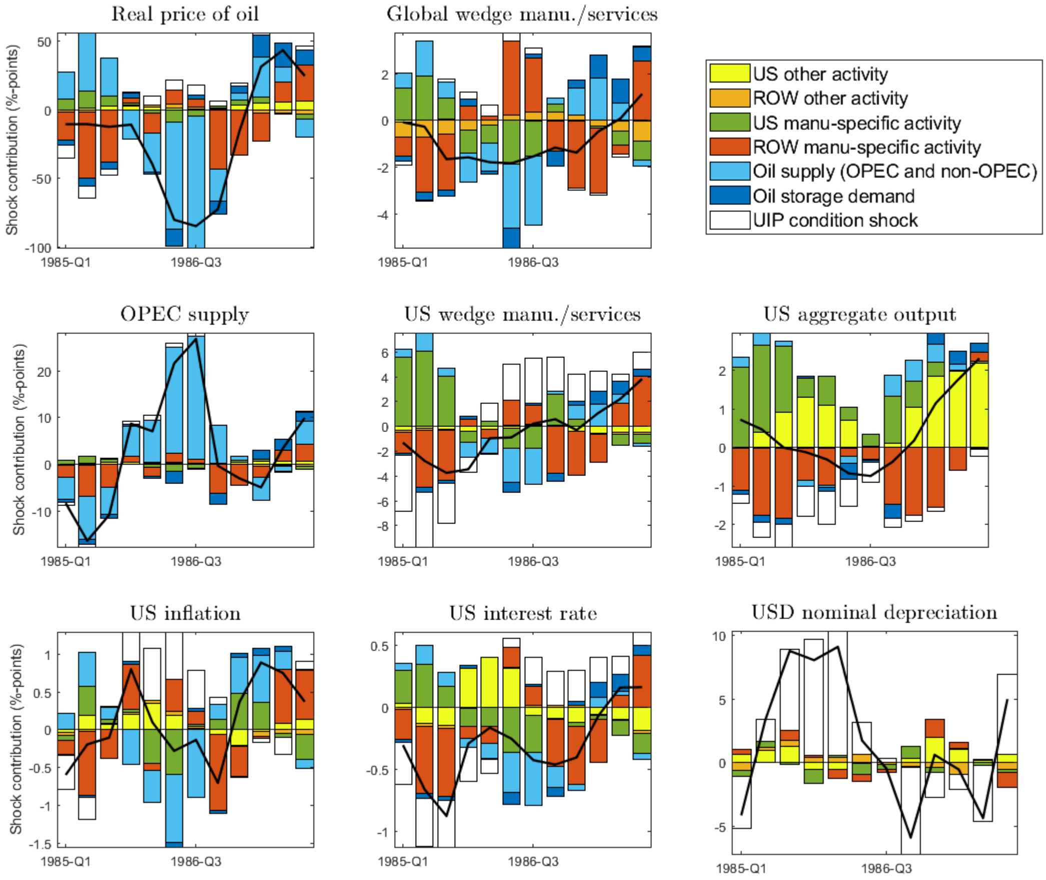

Figure 10: Dynamics around 1986; for variables with a trend the values can be interpreted as percentage deviations from the trend. (**)

amount to the q-o-q change in real oil prices, cf. Figure 20). This finding is consistent with evidence in Kilian and Murphy (2014) who finds speculative pressures in oil market during this period. It can again be interpreted as market participants expecting softer conditions in the future due to higher oil supply, lower oil demand, or both.

Asian financial crisis and dot-com boom and recession

There have been other interesting episodes of mutually interacting oil prices and macroeconomic aggregates. Focusing on the distinction between manufacturing and services can, for example, shed light on the events before and during the 2001 recession. The historical decomposition in Figure 11 reveals that, again, the upswings and downswings in oil prices move in line with the dynamics of the global gap between manufacturing and services activity. During the Asian financial crisis (1997/98) oil supply shocks and oil storage demand shocks, especially, rationalize the downward path of oil prices, while, starting in late 1997, ROW activity shocks also have a dampening effect. Notably, OPEC supply picks up in 2000 as ROW manufacturing-specific demand shocks increase the gap between global manufacturing and services.

According to the estimation, throughout the 1990s, global manufacturing was also supported by US demand. The large cyclical gap between manufacturing and services in the

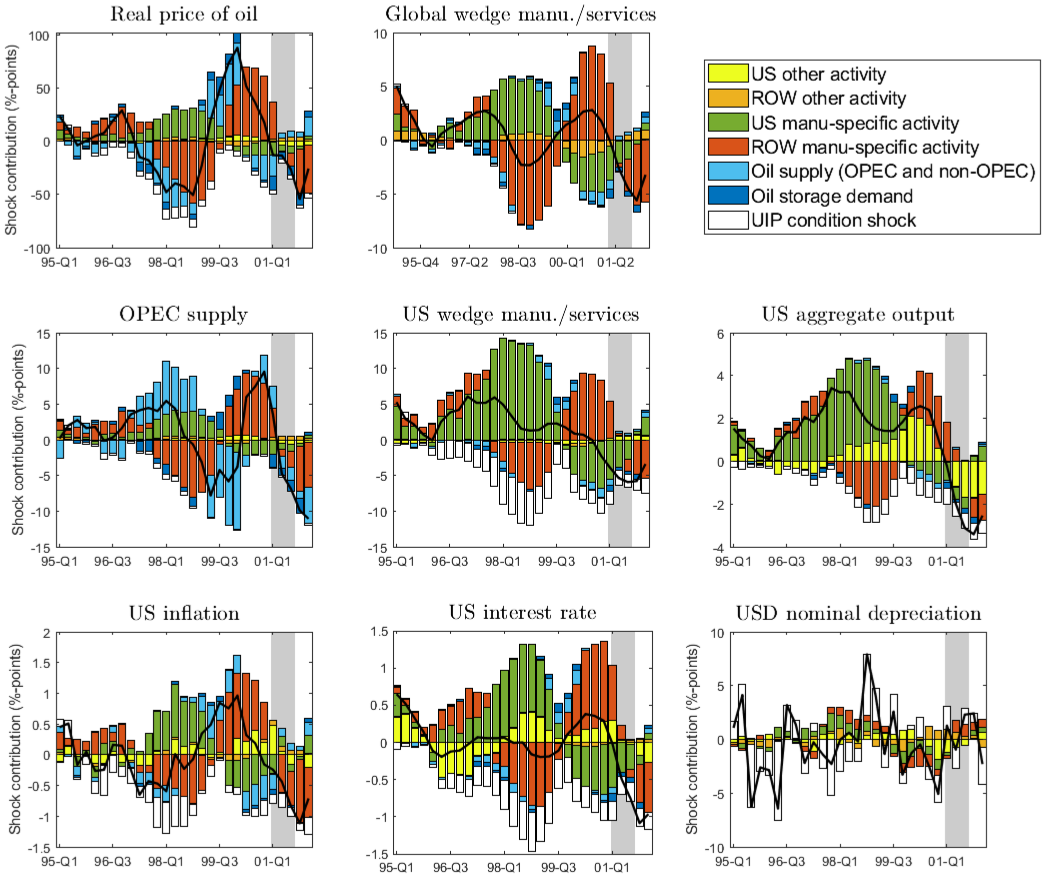

Figure 11: Dynamics after mid-1990s, Asian financial crisis and 2001s US recession; for variables with a trend the values can be interpreted as percentage deviations from the trend. (**)

US is, to a large extent, explained by shocks to US demand for manufactured final goods. This finding is consistent with the evidence reported in Basu, Fernald, and Shapiro (2001) on a large increase in demand for durable manufactured goods – in particular, investment in computers and telecommunications equipment.[53] Interestingly, I find that the recession in 2001 was triggered to a sizeable extent by negative technology shocks in the services sector consistent with anecdotal evidence about the dot com crisis. These shocks did not affect global oil prices importantly.

The Covid-19 pandemics

In the first half of 2020, the global spread of the corona virus Sars-Cov-2 and measures to contain it led to an unprecedented large and sharp decline in global activity. It is left as an issue for future research weather the disruptions related to the Covid-19 pandemics should be considered as outliers or not. For this reason, the sample for benchmark estimation ends in the fourth quarter of 2019. Below, bearing potential caveats, the model is estimated

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[53] They find that technological growth played a major role for US GDP during this episode. In the DSGE model, services sector technology growth lowers inflation and increases gross output, indicating that the narrative is captured in the DSGE model at least to some extent.

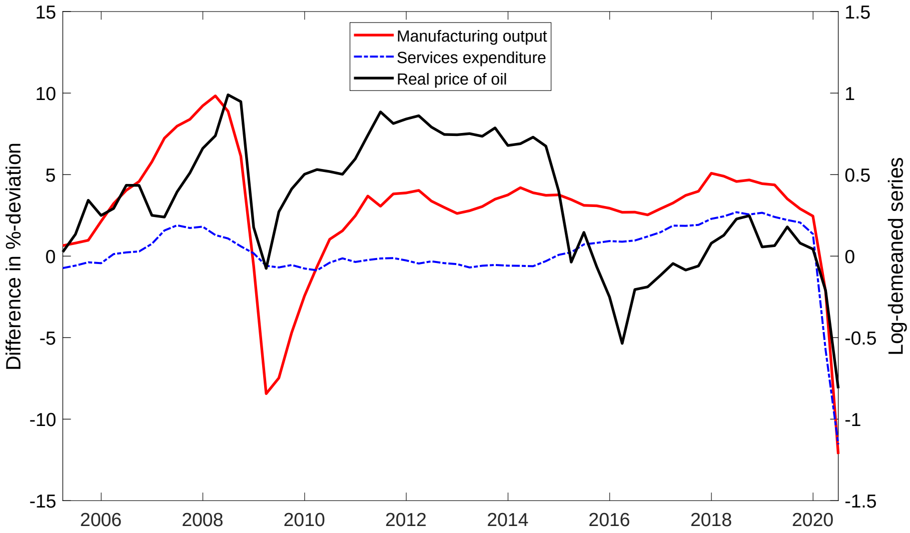

Figure 12: Left-hand axis: Global manufacturing production and global services consumption expenditure (both measured as and index and as a percentage deviation from their respective quadratic trends). Right-hand axis: real oil price. (**)

with all available data including observations up to the second quarter of 2020.[54] This is intended is to shed some light on the dynamics of oil prices during that episode. In the first half of 2020, the oil price comoves closely with manufacturing output (cf. Figure 12). At the same time, activity in the services sector also contracted at a similar pace.

The historical shock decomposition reveals that demand conditions in the global oil market played a dominant role (cf. Figure 13). The fall in oil prices is mainly rationalized by manufacturing-specific shocks, but other business cycle shocks are, to some degree, also important. Although the services sector is less oil-intensive, its oil demand is non-negligible, especially given the sizeable contraction in this sector. Still, despite services being the largest sector of the global economy, and despite a similarly large decline in both sectors, the manufacturing sector is key for understanding oil price dynamics. Also, as in previous episodes that were characterized by large swings in oil prices, the US economy is affected to a major extent through the manufacturing sector's exposure to international trade. Especially intermediate goods trade declined rapidly. Moreover, OPEC's supply contracted as an endogenous response to the disruptions in global economic activity, which feeds back into lower demand for imported manufactured goods in the OPEC region.

A.2 Structural shock comparison with Baumeister and Hamilton's (2019) SVAR

Below, I examine how the imputed shock structure of the estimated DSGE model compares with the shocks of the much more parsimonious SVAR model of Baumeister and

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[54] For the most recent data point (2020 Q4) data on services expenditure is not all available for all countries that are included in the benchmark sample. In particular, data on services expenditure for the United Kingdom, Luxembourg, New Zealand, and Costa Rica is missing. Oil supply and oil inventories in the second quarter are proxied by the mean of monthly values available in April and May 2020.

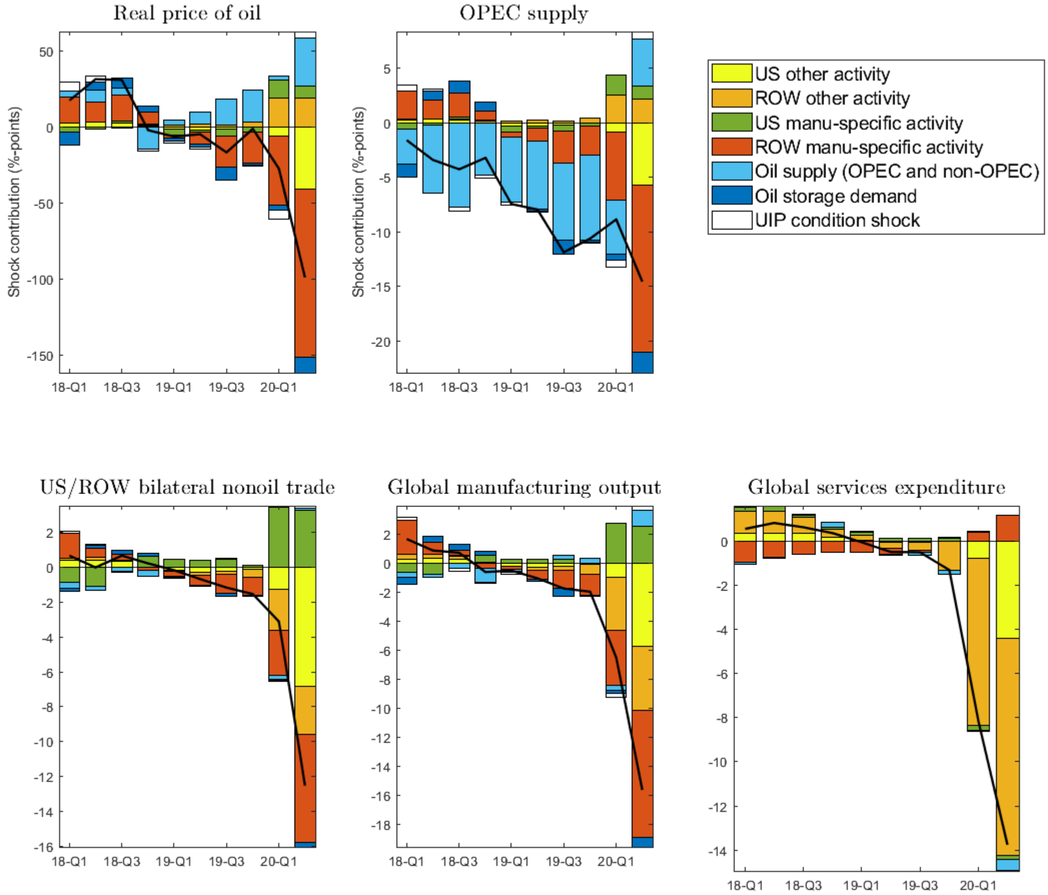

Figure 13: Oil price decline related to the Covid-19 pandemics. (**)

Hamilton (2019). While the SVAR and the DSGE are in general hard to compare with respect to the transmission mechanisms, both structural models employ the identity that unobserved global oil absorption is global oil production minus changes in global oil inventories. Moreover, at least the oil production shocks (i.e. the market share weighted average of OPEC and non-OPEC shocks) as well as the oil inventory demand shocks of the DSGE model have relatively close counterparts in the SVAR. Also, both model share similar data sources.[55] It is therefore interesting to see how the identified shocks of the two different methods correspond to one another.

In Figure 14 it can be observed that the imputed shock series from the two models do indeed accord well with each other. The annualized oil production shocks from the SVAR are positively correlated with their annualized counterparts in the DSGE model (with a correlation coefficient above 0.60). Similarly, the estimated oil storage demand shocks from the model fit well to shocks identified by the SVAR (with a correlation coefficient close to 0.8). Comparing shocks to global oil demand driven by factors other than speculative demand is less straightforward. The SVAR differentiates between global

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[55] In particular, the DSGE model uses similar data on global oil production and global oil inventories. Also, the measure of global manufacturing output used in the DSGE estimation is based on Baumeister and Hamilton's measure of global industrial activity. The DSGE model uses, however, a larger number of twelve time series, compared to four series in the parsimonious SVAR.

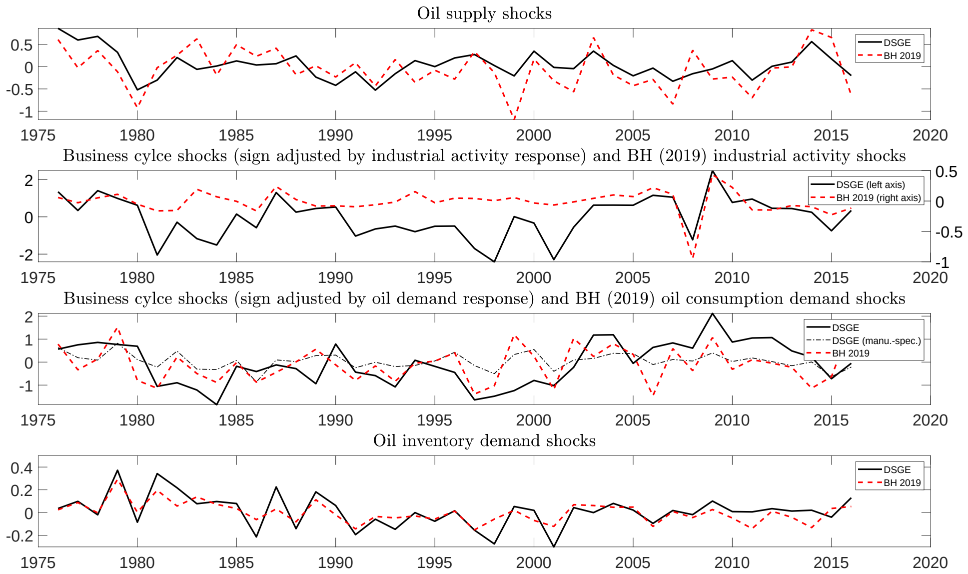

Figure 14: Comparison of the structural shock series from Baumeister and Hamilton's (2019) SVAR (BH2019, red dashed line) with the DSGE model (black line). The figures document the annualized average of the quarterly shock series. In the first panel, the DSGE shocks correspond to a weighted average of OPEC and non-OPEC supply shocks. The second panel reports the sum of all business cycle shocks, i.e. all shocks in the model of section 2 except oil supply and oil storage demand shocks, which are scaled by the sign of the response of production (for instance, a contractionary monetary policy shock is scaled by -1, a positive technology shock is scaled by +1). Correspondingly, in the third panel all business cycle shocks are scaled by the response of oil demand on impact. For oil supply shocks (first panel) the annualized shock series of the SVAR model and the shock series of the DSGE model have a correlation coefficient of 0.60. The correlation coefficient in the second panel is 0.40, in the third panel 0.37 (0.65 when only manufacturing-specific shocks are considered) and in the last panel 0.79.

shocks to industrial activity and oil-consumption shocks, while the DSGE model allows for nine business cycle shocks, including all other shocks than oil supply and oil storage demand shocks. The second and third panels of Figure 14 both plot the annualized shock series of business cycle shocks of the DSGE model by computing an annualized country-size weighted average of US and ROW business cycle shocks – which are assumed to be all shocks of the model except the oil supply and oil storage demand shocks. In the second panel each shock series entering the computation of the average is adjusted by the sign of the response of global manufacturing output in the first period. The third panel performs a similar adjustment for the sign of the response of oil demand (to be consistent with the identifying assumption in the SVAR). Despite the difficulties in comparing the two models with respect to the demand side of the oil the market, the constructed business cycle shock series of the DSGE model still accord relatively well with both the identified industrial activity shocks in the SVAR (Figure 14, panel 2; correlation coefficient is around 0.4) and the identified oil-consumption demand shocks (Figure 14, panel 3; correlation coefficient is around 0.37).

Interestingly, in the third panel of Figure 14, when only manufacturing-specific shocks (manufacturing technology shocks and shocks to final manufactured goods demand) are considered, the correlation coefficient between the annual shocks in the DSGE model and the oil-consumption demand shocks is around 0.66. In the DSGE model, global oil demand is, by definition, the difference between observed global production (especially oil demand from the manufacturing sector) and the observed change in oil inventories (see equation 5); a relation that also underlies the identification approach of Baumeister and Hamilton's (2019) SVAR.[56] For this reason, the oil-consumption demand shocks identified in the SVAR are likely to correspond best to economic activity shocks driving global oil demand in the DSGE model which are by definition related to standard business cycle shocks. This results, nevertheless, indicates that shocks to global activity – in particular, shocks affecting global manufacturing production – are the main demand-type drivers of oil prices. This differs from the interpretation of oil-specific "consumption" demand shocks in Baumeister and Hamilton (2019) where such shocks are, by virtue of their construction, fundamentally unrelated to industrial activity shocks.

Moreover, there are notable differences for some episodes. The DSGE model predicts, for example, an uninterrupted series of positive shocks to global oil demand between 2003 and 2007 that is longer compared to the SVAR, consistent with evidence in Kilian and Hicks (2013) on professional forecast errors. Also, oil speculation shocks are more pronounced during some episodes, for instance in 1986 and around 2001.

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[56] In the SVAR, oil-consumption shocks are identified implicitly by the oil market clearing condition. Notably, in the SVAR, the response of global activity to oil prices is on impact constrained to be negative. This assumption is rather restrictive given the insights of the model presented in section 3.

B Appendix: additional tables

Table 2: Data sources; observed variables

Observable variable	**Data Source**	**Model variable**
Real manufacturing output (US)	Index of manufacturing output (US); (OECD Main Economic Indicators. Source: Haver Analytics.)	$\hat{y}_{T,t}$
Real services output (US)	Services consumption expenditure (US); (US Bureau of Economic Analysis, BEA. Source: Haver Analytics.)	$\hat{y}_{N,t}$
Quarterly inflation in manufacturing (US)	Quarterly growth rate of US Producer Price Index for Manufacturing (Source: OECD MEI, Haver Analytics)	$\pi_{TH,t}$
Quarterly inflation in services (US)	Quarterly growth rate of US Consumer Price Index for Services (US Bureau of Labor Statistics, BLS; FRED database)	$\pi_{N,t}$
Global oil supply	World crude oil production (Source: US Energy Information Administration.)	$\hat{o}_{supply,t}$
OPEC oil supply	OPEC crude oil production (Source: US Energy Information Administration.)	$\hat{o}_{dom,supply,t}$
Global crude oil inventories	US crude oil inventories weighted by the ratio of OECD petroleum inventories to US petroleum inventories as in Kilian and Murphy (2014); data source: US Energy Information Administration.	$\hat{inv}_t$
Real price of oil	Refiner import price of crude oil (Source: US Energy Information Administration) divided by US Consumer Price Index (Source: CPI US All Urban Consumers, BLS; FRED)	$\hat{p}_{oil,t}$
Nominal interest rate (US)	US Treasury Bill Rate (transformed to quarterly frequency); Source:FRED. For the time period 2009:Q3 to 2015:Q4, the US nominal short rate is proxied by the shadow interest rate computed by Wu and Xia (2016).	r_t
Change in nominal effective USD exchange rate	Source: FRED database.	Δs_t
Global level of industrial activity (level of global tradeable production)	Index of global manufacturing production of OECD+6 major emerging economies (source Haver Analytics); own calculations, see (1).	$n\hat{y}_{T,t}+$ $+(1-n)\hat{y}^*_{T,t}$
Global level of services output	Author's calculation based on OECD household consumption expenditure data (data source: Haver Analytics); own calculations, see (2).	$n\hat{y}_{N,t}+$ $+(1-n)\hat{y}^*_{N,t}$

(1) The global level of manufacturing output is computed based on manufacturing output in the OECD plus 6 major emerging markets (equivalent to the measure of global industrial production computed in Baumeister and Hamilton (2019)). For the OECD plus 6 aggregate there is no index of manufacturing output readily available but such an index can be constructed based on weights provided by the OECD composite leading indicator web page. For the case of China, I use the index of industrial production of the Central Plan Bureau as a proxy of Chinese manufacturing output. Moreover, because of data limitations for China before 2001, I use the Baumeister and Hamilton (2019) index of total industrial production as a proxy for global manufacturing output up until 2000. The Baumeister and Hamilton (2019) is available from 1958Q1.

(2) The global level of services consumption expenditure is calculated based on all countries for which data is available in Haver Analytics. The data series is constructed by computing quarterly growth rates of services consumption expenditure for each country and constructing an index based on total growth rates (weighting country-specific rates). Relative weights are based on average weights of a country's GDP (based on purchasing power parity valuation) in global GDP from the IMF WEO in the periods 1980 to 2019 (in five year averages). Data on services consumption expenditure are available for the following countries (starting date of the inclusion in the index for each country in brackets; for China, the data source is not consumption expenditure but nominal services gross value added divided by the overall consumer price index). United States (1974Q1), France (1974Q1), Canada (1974Q1), Korea (1974Q1), Norway (1978Q1), Japan (1980Q1), Italy (1981Q1), United Kingdom (1985Q1), New Zealand (1987Q2), Finland (1990Q1), Germany (1991Q1), Costa Rica (1991Q1), China (1992Q1), Sweden (1993Q1), Chile (1995Q1), Denmark (1995Q1), Iceland (1995Q1), Ireland (1995Q1), Luxembourg (1995Q1), Netherlands (1996Q1), Latvia (1996Q4), Estonia (1997Q4), Czech Republic (1999Q4), Colombia (2000Q1).

Table 4: Exogenous disturbances in the model and shock process; AR (1) autoregressive process of order 1, RW (random walk).

Exogenous disturbance	Shock process
US impatience shock ψ_t	AR (1)
Risk premium shock to US-ROW interest rate differential ς_t	AR (1)
US manufacturing technology shock $Z_{T,t}$	AR (1)
US services technology shock $Z_{N,t}$	AR (1)
ROW manufacturing technology shock $Z^*_{T,t}$	AR (1)
ROW services technology shock $Z^*_{N,t}$	AR (1)
US manufacturing demand shocks $G_{T,t}$	AR (1)
ROW manufacturing demand shock $G^*_{T,t}$	AR (1)
US monetary policy shocks $\xi_{r,t}$	RW
OPEC oil supply shock $Z_{oil,dom,t}$	AR (1)
Non-OPEC oil supply shock $Z_{oil,fringe,t}$	AR (1)
Oil storage demand shocks $INVD_t$	AR (1)

Table 5: Structural Estimation of Parameter Distributions, Prior and Posterior

	Description	***Prior (Mean, SD; uniform: interval)***	***Post. mean***	***Post. conf. interv.***
τ	*Elasticity of substitution between oil and non-oil factors*	*Beta (0.09,0.08)*	0.1122	(0.0979,0.1248)
θ	*Elasticity of substitution between US and ROW goods*	*Normal (1,0.3)*	0.8294	(0.7594,0.8903)
ϕ	*Elasticity of substitution between manufacturing and services*	*Uniform (0,0.44)*	0.4331	(0.4236,0.4400)
φ_T	*Calvo parameter in the manufacturing sector*	*Uniform (0,1)*	0.6498	(0.6266,0.6716)
φ_N	*Calvo parameter in the service sector*	*Uniform (0,1)*	0.7177	(0.6543,0.7748)
φ_W	*Calvo parameter in nominal wage setting*	*Uniform (0,1)*	0.8551	(0.8135,0.8968)
ν_r	*Interest rate smoothing*	*Uniform (0,1)*	0.8421	(0.8200,0.8632)
κ_π	*Taylor rule coefficient for inflation*	*Gamma (1.5, 0.5)*	1.3333	(1.2373,1.4276)
κ_y	*Taylor rule coefficient for output growth*	*Normal (1, 0.5)*	1.5415	(1.2670,1.8342)
ζ^*	*ROW exchange rate pass-through.*	*Uniform (0,1)*	0.0565	(0.0000,0.1308)
$-\kappa$	*Negative of the convenience yield governing oil storage*	*Beta (0.15,0.10)*	0.6017	(0.4879,0.7113)
ρ_{Z_T}	*Autocorrelation productivity shock manufacturing*	*Beta (0.7,0.1)*	0.8740	(0.8550,0.8926)
ξ_{Z_T}	*Stdv:*	*Beta(0.15,0.1)*	0.0386	(0.0358,0.0415)
ρ_{Z_N}	*Autocorrelation productivity shock services*	*Beta (0.7,0.15)*	0.9446	(0.9179,0.9699)
ξ_{Z_N}	*Stdv:*	*Beta(0.15,0.10)*	0.0128	(0.0089,0.0165)
ρ_{GT}	*Autocorrelation manufacturing demand shock (US)*	*Beta (0.7,0.15)*	0.9066	(0.8924,0.9208)
ξ_{GT}	*Stdv:*	*Beta(0.15,0.10)*	0.3572	(0.3201,0.3898)
ρ_{GT}^*	*Autocorrelation manufacturing demand shock (ROW)*	*Beta (0.7,0.15)*	0.9191	(0.9044,0.9349)
ξ_{GT}^*	*Stdv:*	*Beta(0.15,0.1)*	0.3233	(0.2940,0.3512)
$\rho^{os,dom}$	*Autocorrelation oil supply shock (OPEC)*	*Beta (0.7,0.15)*	0.9241	(0.9002,0.9471)
ξ^{os}	*Stdv:*	*Beta(0.10,0.075)*	0.0508	(0.0462,0.0555)
ρ^{os}	*Autocorrelation oil supply shock (non-OPEC)*	*Beta (0.7,0.15)*	0.9630	(0.9442,0.9816)
ξ^{os}	*Stdv:*	*Beta(0.10,0.075)*	0.0114	(0.0104,0.0123)
ρ^{inv}	*Autocorrelation oil storage demand shocks*	*Beta (0.7,0.15)*	0.9105	(0.8912,0.9650)
ξ^{inv}	*Stdv:*	*Beta(0.10,0.075)*	0.0676	(0.0578,0.0777)
ρ^{uip}	*Autocorrelation shock to UIP condition*	*Beta (0.7,0.15)*	0.9947	(0.9907,0.9986)
ξ^{uip}	*Stdv:*	*Gamma(0.004,0.002)*	0.0011	(0.0009,0.0013)
ρ_ψ	*Autocorrelation preference shock (US)*	*Beta (0.7,0.15)*	0.9247	(0.8861,0.9632)
ξ_ψ	*Stdv:*	*Gamma(0.004,0.002)*	0.0093	(0.0072,0.0111)
ξ_r	*Monetary policy shock (US), stdv:*	*Gamma(0.004,0.002)*	0.0024	(0.0022,0.0027)

C Appendix: additional figures

Oil production in selected regions

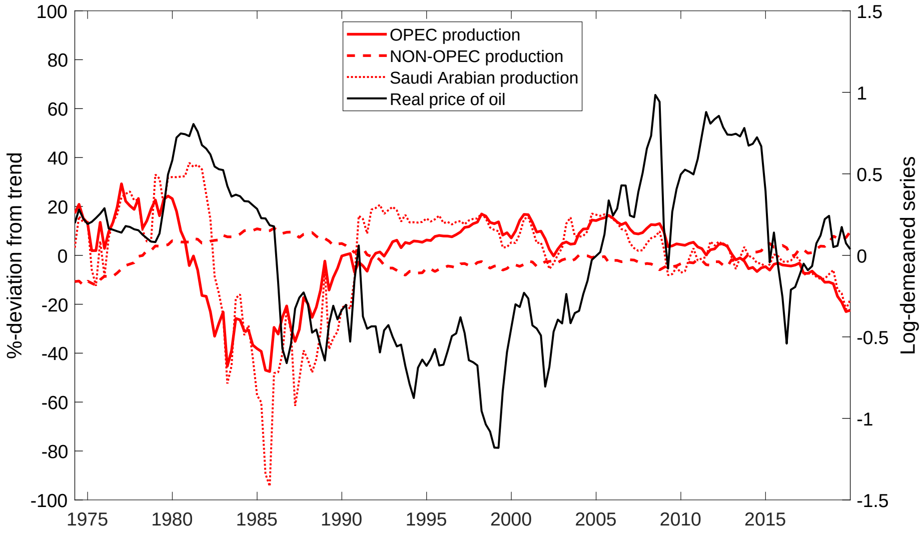

Figure 15: Left-hand axis: Oil production in the OPEC region, in the non-OPEC region and in Saudi Arabia (measured as a percentage deviation from their respective quadratic trend). Right axis: real oil price.

Impulse response function for selected shocks

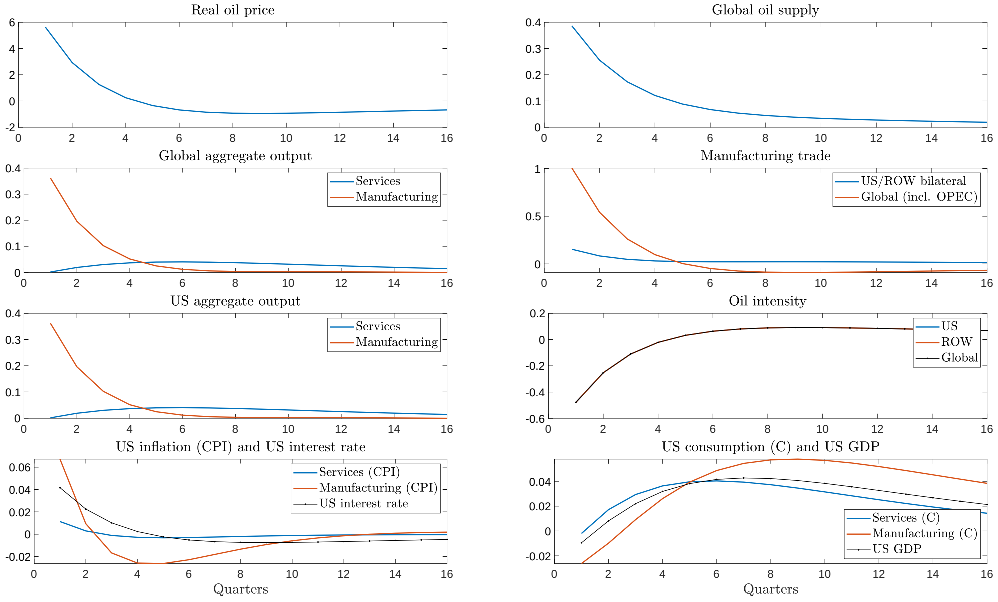

Figure 16: Impulse response function for a shock to the global oil storage demand ξ_{INVD}.

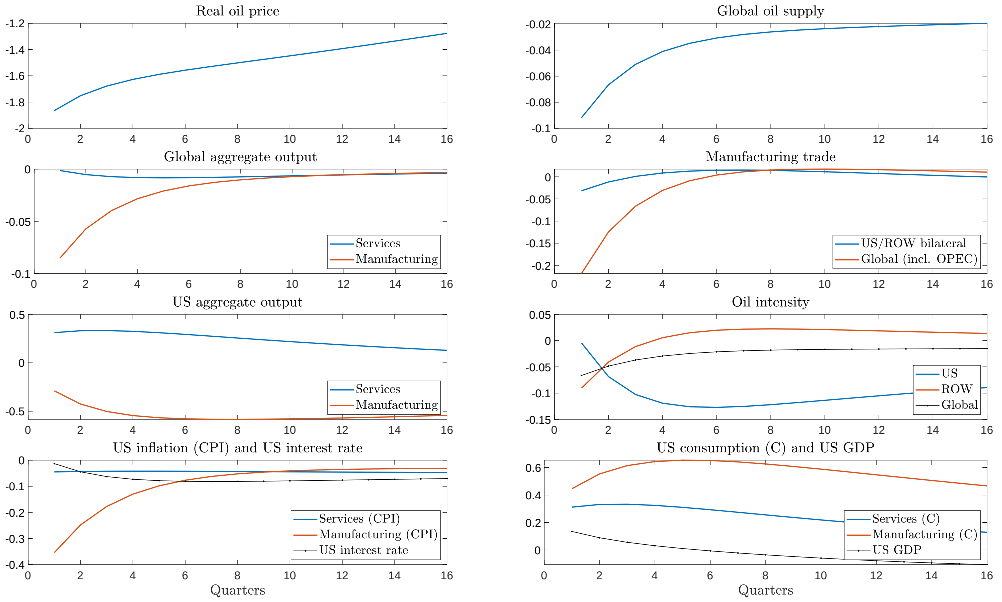

Figure 17: Impulse response function for a shock to the US/ROW uncovered interest rate parity condition ξ_{UIP}.

Model-implied oil intensity in the US and ROW (historical shock decomposition)

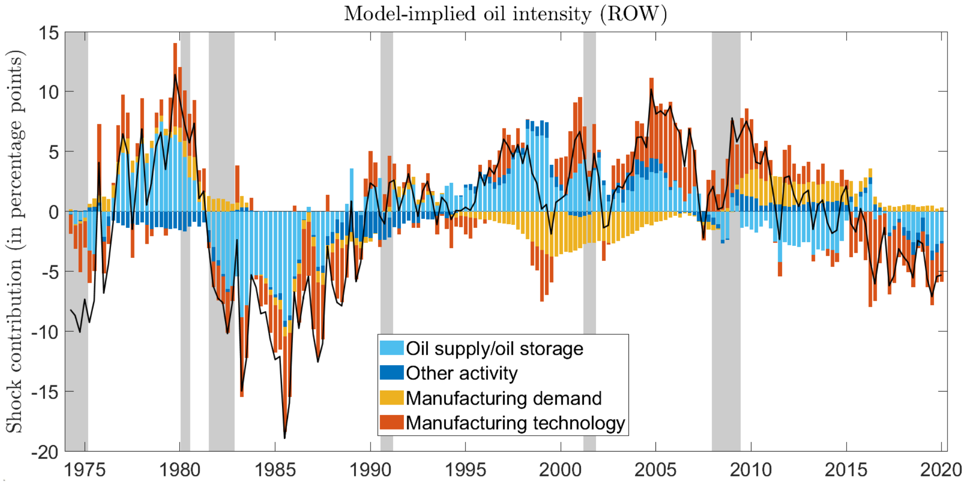

Figure 18: Historical decomposition of the model-implied oil-intensity in the ROW (measured as barrel oil used for one unit of output). (*)

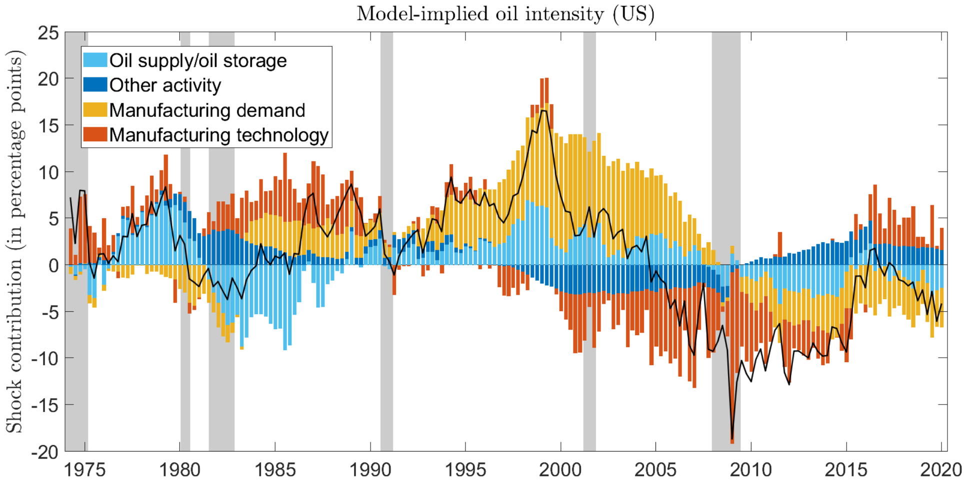

Figure 19: Historical decomposition of the model-implied oil-intensity in the US (measured as barrel oil used for one unit of output). (*)

Quarterly change in real oil price, US inflation and US gross output

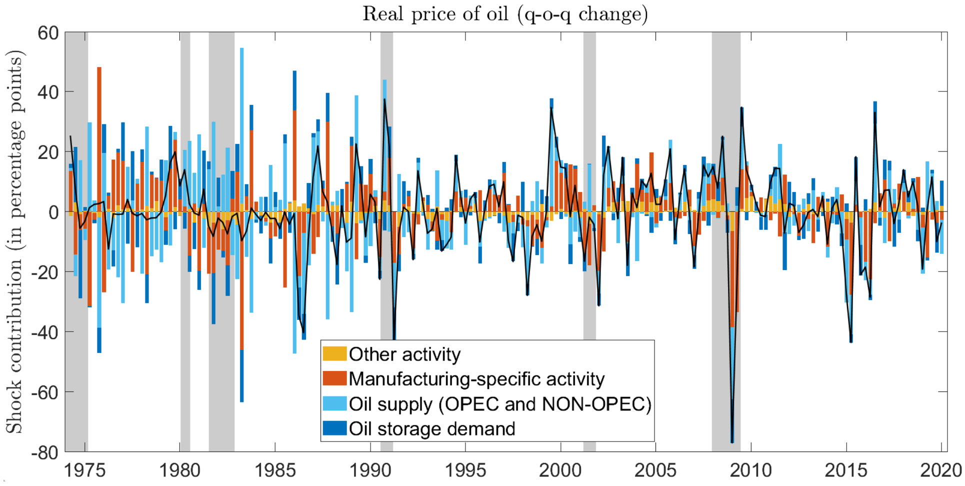

Figure 20: Historical decomposition of the real oil price (q-o-q change). (***)

(***) The demand-type shocks (business cycle shocks) in the oil market are distinguished between shocks specific to the global manufacturing sector, i.e. US and ROW manufacturing technology shocks and manufacturing-specific demand shocks (red bar) as well as other global activity shocks not specific to manufacturing, which include US impatience shocks, US monetary policy shocks, as well as US and ROW service sector technology shocks and shocks to the risk premium for US-denominated bonds (yellow bar). The remaining group includes oil supply and oil storage demand shocks (dark blue).

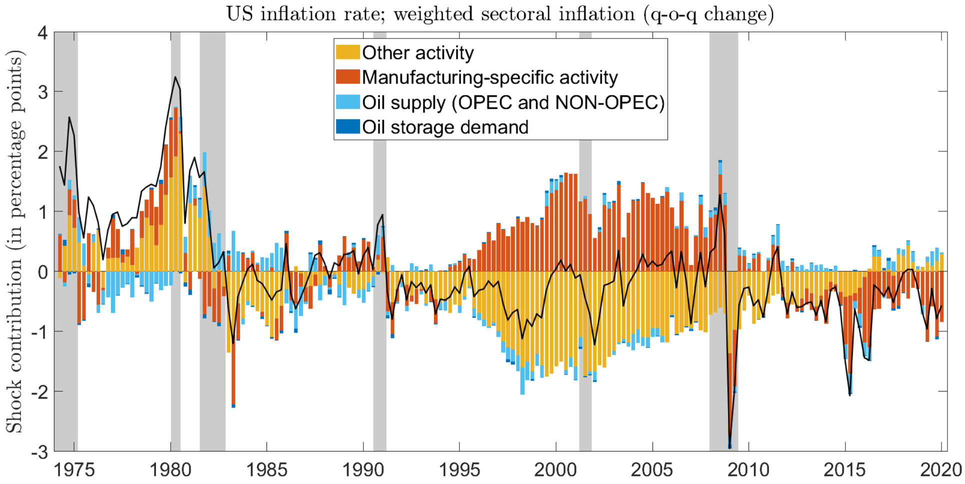

Figure 21: Historical decomposition of US inflation (weighted sectoral activity). (***)

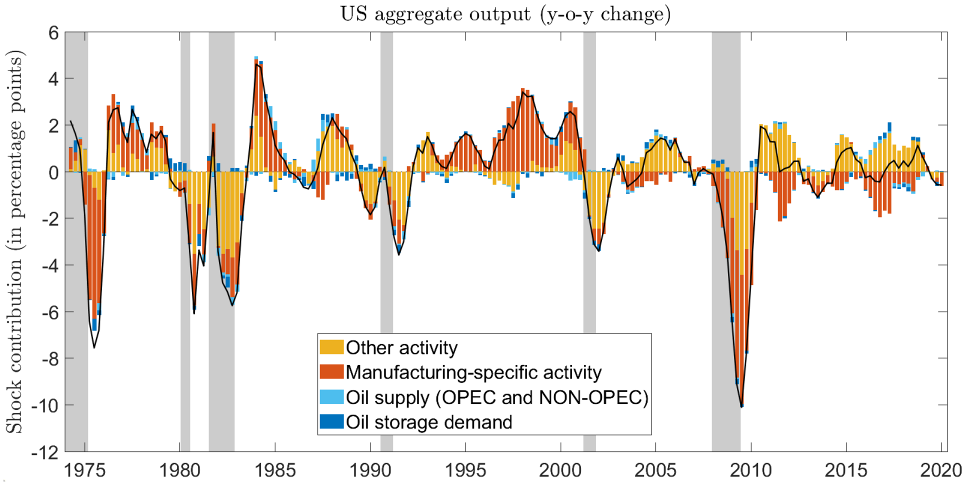

Figure 22: Historical decomposition of US gross output (q-o-q change). (***)

D Appendix to the theoretical model

D.1 Details on the structural model

Household's decision problem

The expected utility function of the representative agent can be separated into consumption C_t and labour N_t,

$$U_0 = E_0 \sum_{t=0}^{\infty} \beta^t \psi_t \left[\frac{C_t^{1-\sigma}}{1-\sigma} - \frac{N_t^{1+\varphi}}{1+\varphi} \right] \tag{D.1}$$

where σ is the relative risk aversion, φ is the inverse elasticity of the labour supply with respect to the real wage, and $\beta \in (0,1)$ denotes the constant discount factor. ψ_t is a preference shock (impatience shock) that follows an AR(1) process in logs.

Financial trade is introduced in a standard way (cf. inter alia Benigno and Thoenissen 2003) by the assumption that Home households can hold Home-issued and ROW-issued bonds, whereas a ROW household can hold only ROW-issued bonds. The intertemporal budget constraint of the representative household is given by

$$\frac{B_{H,t}}{P_t R_t} + \frac{S_t B_{F,t}}{P_t R_t^* \Phi(\frac{S_t \overline{B}_{F,t}}{Y_t P_t}) \exp(\varsigma_t)} = \frac{B_{H,t-1}}{P_t} + \frac{S_t B_{F,t-1}}{P_t} + \frac{W_t}{P_t} N_t - C_t + \Upsilon_{TH,t} + \Upsilon_{N,t} + T_t, \quad \text{(D.2)}$$

where $B_{H,t}$ and $B_{F,t}$ are holdings of Home-issued and ROW-issued bonds, R_t and R_t^* are Home and ROW gross nominal interest rates, the function Φ represents a small financial intermediary cost that depends on the aggregate amount of ROW-issued bonds in real terms scaled by gross output $(\frac{S_t \overline{B}_{F,t}}{Y_t P_t})$[57], ς_t is an exogenous AR(1) shock process that adds a risk-premium to returns of ROW-issued bonds, S_t is the nominal exchange rate (units of domestic currency in units of ROW currency such that an increase represents a depreciation), W_t denote the nominal wage, Υ_{TH} and Υ_N are lump sum profits from firms in the tradeable and the nontradeable sector, and T_t denote remaining lump sum net taxes and profits (from global funds), respectively.[58] The household's decision problem is to maximize (D.1) with respect to (D.2). The ROW agents is assumed to have only access to ROW-issued bonds, so her budget constraint and decision problem differ accordingly.

Optimal oil inventories and oil inventory demand shocks

To allow for a delay between oil production and oil absorption, crude oil is assumed to be storeable above ground. I borrow the specification of oil storage of Unalmis et al. (2012) in which a risk-neutral representative storer in a competitive market buys oil on the spot market and stores it for future selling while facing storage cost. Taking real oil prices P_t^o – expressed in terms of the US CPI – as given, a storer chooses the amount of storage INV_t to maximize expected profits given by

$$\frac{E_t P_{t+1}^o}{R_t} - P_t^o INV_t(1 + \Upsilon(INV_t)) \quad \text{(D.3)}$$

with physical storing cost $\Upsilon(INV_t) = \kappa + (\psi/2) INV_t$ where κ is a convenience yield and ψ a cost that increases with the amount of storage.[59] As in Unalmis et al. (2012), I

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[57] The introduction of this cost ensures model stationarity (cf. Schmitt-Grohe and Uribe 2003). Like in Benigno and Thoenissen (2003), I assume that the cost function Φ takes the value 1 when the net foreign asset position approaches its steady-state value which is assumed to be zero. It is also assumed that the function is differentiable and decreasing in the neighborhood of zero. The profits from financial intermediation are reimbursed to household as lump sum transfers.

[58] The risk premium shock ς_t can rationalize the disconnect between the nominal exchange rates and macro variables (cf. Itskhoki and Mukhin 2019) and is added to include observations of nominal exchange rates in the estimation of the model.

[59] As a simplifying assumption, profits from storing oil are collected in a global fund that belongs to both countries proportionally, such that the same per capita profits from storing are redistributed as a

assume that oil storage is subject to exogenous oil speculation shocks $INVD_t$. It adds an exogenous AR(1) process to the log-linearized optimal storage equation.

Monetary policy

The central bank targets consumer price inflation and the output growth rate such that $R_t = \overline{R}^{(1-\nu_r)} R_{t-1}^{\nu_r} \left(\frac{P_t/P_{t-1}}{\Pi}\right)^{(1-\nu_r)\kappa_\pi} (Y_t/Y_{t-1})^{(1-\nu_r)\kappa_y} \exp(\xi_r)$, where Π is the steady-state gross inflation rate, ν_r characterizes interest rate smoothing, ξ_r is a monetary policy shock, and κ_π and κ_y denote the Taylor rule coefficients for inflation and output growth.

Non-oil trade balance and real exchange rate

The bilateral trade balance between Home and ROW evolves according to

$$\frac{S_t B_{F,t}}{P_t R_t^* \Phi(\frac{S_t \overline{B}_{F,t}}{P_t})} = \frac{S_t B_{F,t-1}}{P_t} + NX_t, \tag{D.4}$$

$$NX_t = \frac{P_{TH,t}^* S_t \frac{1-n}{n} \left(C_{TH,t}^* + M_{TH,t}^*\right) - P_{TF,t}\left(C_{TF,t} + M_{TF,t}\right)}{P_t} \tag{D.5}$$

where NX_t denotes the real value of net exports. The real exchange rate and the terms of trade is defined as $Q_t \equiv \frac{S_t P_t^*}{P_t}$.

Market clearing and further relations

Markets for ROW-issued bonds clear such that $nB_{F,t} + (1-n)B_{F,t}^* = 0$, for domestically-issued bonds $B_{H,t} = 0$. The model is closed by defining aggregate real domestic output as the sum of the value of the sectoral outputs

$$\frac{P_{Y_t}}{P_t} Y_t = \frac{P_{TH} Y_{T,t} + P_{N,t} Y_{N,t}}{P_t}, \tag{D.6}$$

where P_{Y_t} is the nominal domestic producer price index defined as an output share-weighted sum of the sectoral nominal prices.[60]

Gross domestic product is defined as the sum of consumption, exogenous demand for manufactured goods, and net trade $GDP_t * P_{GDP_t} = C_t P_t + G_{T,t} P_{T,t} + C_{TH,t}^* P_{TH,t}^* S_t + \frac{1-n}{n} M_{TH,t}^* P_{TH,t}^* S_t - C_{TF,t} P_{TF,t} - M_{TF,t} P_{TF,t}$ where P_{GDP_t} is the GDP deflator. Bilateral trade between the US and ROW is defined as $trade_t^{US/ROW} = n * C_{TF,t} + (1-n) * C_{TH,t}^* + n * M_{TF,t} + (1-n) * M_{TH,t}^*$.

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lump sum. For the same purpose, storing firms only take into account US short-run interest rates for discounting future revenue.

[60] This specification follows Ferrero, Gertler, and Svensson 2010. In general, P_{Y_t} is not necessarily equal to the CPI P_t.

Solution approach

The model is log-linearized around a deterministic steady state and the resulting linear model is solved using Dynare. The steady state is characterized by balanced international trade and zero net inflation. All price resetting firms set the same price. All factors of production are subsidized by fiscal transfers such that the distortion from monopolistic competition is offset.

D.2 Market power of the dominant producer

Following Nakov and Nuño (2013), the optimization problem of the dominant producer is to set consumption $C_{dom,t}$ and labour supply $N_{dom,t}$ as well as target the level of global oil prices P_t^o so as to maximize $E_0 \sum_{t=0}^{\infty} \beta^{dom,t} \left[\ln C_{domt} - \frac{N_{dom,t}^{1+\varphi}}{1+\varphi} \right]$ under the constraints (5), (6), and the budget constraint $P_t^{oil} O_{supply,dom,t} = P_{dom,t} C_{dom,t} + P_{dom,t} X_{oil,dom,t}$. The consumption bundle is given by $C_{dom,t} \equiv \left[n^{1/\theta} (C_{dom,TH,t})^{\frac{\theta-1}{\theta}} + (1-n)^{1/\theta} (C_{dom,TF,t})^{\frac{\theta-1}{\theta}} \right]^{\frac{\theta}{\theta-1}}$. The same aggregation defines preferences for imported intermediates $X_{oil,dom,t}$. Note that OPEC is assumed to have the same elasticity of substitution between US and ROW goods as the US. The steady state shares of US and ROW imports in total imports are given by the relative size of the two countries. Defining $\Lambda = -\frac{\chi_t}{\xi_t}$, the optimal decision of the dominant producers gives

$$\Lambda_t + P_t^{oil} = \frac{1}{\alpha_{dom}} \frac{C_{dom,t} N_{dom,t}^{\varphi+1}}{O_{dom,t}} \tag{D.7}$$

$$\Lambda_t + P_t^{oil} = \frac{1}{\beta_{dom}} P_t^x \frac{X_t}{O_{dom,t}} \tag{D.8}$$

$$\Lambda_t = -\frac{P_t^{oil} O_t^{dom}}{\tau O_t + O_{fringe,t} + \frac{1}{\Psi}(INV_t * \Psi + \kappa + 1 + INV_{t-1}\Psi + \kappa + 1)} \tag{D.9}$$

In steady state, $\overline{INV} * \Psi + \kappa + 1 = \beta$ and $\Theta = \frac{\beta}{\overline{INV}\Psi} = \frac{\beta}{\beta - 1 - \kappa} > 0$. Then

$$\Lambda = -\frac{O_{dom}/O_{demand}}{\tau + 2\Theta \frac{INV}{O_{demand}}}.$$

Using the posterior mean estimates as well as observed shares, we have the following parameter values, $\tau = 0.11$, $\Theta = 1.67$, $\frac{INV}{O_{supply}} = 0.33$, $\frac{O_{dom}}{O_{supply}} = 0.41$, therefore $\Lambda \approx -0.1461$. The resulting markup is $\mu = \frac{P^{oil}}{P^{oil} + \Lambda}$(cf. for details Nakov and Nuño 2013), which is, given that prices are normalized at unity in steady state, 17%.

D.3 Log-linearized model

Below, the log-linearized model is reported. The variables are expressed in terms of percentage deviation from their steady state values. Exceptions are the net foreign asset position (*cf.* main body of the manuscript), as well as the trade balance, which are normalized by the steady state output level and expressed as an absolute deviation.

Euler equation (US and ROW)

$$E_t(\hat{c}_{t+1} - \hat{c}_t) = [r_t - E_t\hat{\pi}_{t+1}] - (1-\rho_\psi)\hat{\psi}_t, \tag{D.10}$$

$$E_t(\hat{c}^*_{t+1} - \hat{c}^*_t) = \left[r^*_t - E_t\hat{\pi}^*_{t+1}\right] - (1-\rho^*_\psi)\hat{\psi}_t^{\,*}. \tag{D.11}$$

The preference shock evolves according to

$$\hat{\psi}_t = \rho_\psi \hat{\psi}_{t-1} + \varepsilon_{\psi,t}, \tag{D.12}$$

$$\hat{\psi}^*_t = \rho_\psi \hat{\psi}^*_{t-1} + \varepsilon^*_{\psi,t}. \tag{D.13}$$

US/ROW bilateral cross-border risk sharing

$$E_t(\hat{q}_{t+1} - \hat{q}_t) = E_t(\hat{c}_{t+1} - \hat{c}_t) - E_t(\hat{c}^*_{t+1} - \hat{c}^*_t) + (1-\rho_\psi)\hat{\psi}_t - (1-\rho^*_\psi)\hat{\psi}_t^{\,*} + \chi b_t + \varsigma_t. \tag{D.14}$$

with the shock to the cross-border risk premium given by

$$\varsigma_t = \rho_\varsigma \varsigma_{t-1} + \varepsilon_{\varsigma,t}.$$

Good market clearing (US and ROW)

Final consumption demand

$$\hat{c}_{T,t} = -\phi \hat{t}_{T,t} + \hat{c}_t, \tag{D.15}$$

$$\hat{c}^*_{T,t} = -\phi \hat{t}^*_{T,t} + \hat{c}^*_t, \tag{D.16}$$

$$\hat{c}_{N,t} = -\phi \hat{t}_{N,t} + \hat{c}_t, \tag{D.17}$$

$$\hat{c}^*_{N,t} = -\phi \hat{t}^*_{N,t} + \hat{c}^*_t, \tag{D.18}$$

where $\hat{t}_{T,t} = \hat{p}_{T,t} - \hat{p}_t$,$\hat{t}^*_{T,t} = \hat{p}^*_{T,t} - \hat{p}^*_t$,$\hat{t}_{N,t} = \hat{p}_{N,t} - \hat{p}_t$ and $\hat{t}^*_{N,t} = \hat{p}^*_{N,t} - \hat{p}^*_t$.

Tradeable final goods market clearing

$$\hat{c}_{TH,t} = -\theta \hat{t}_{TH,t} + \hat{c}^{tot}_{T,t}, \tag{D.19}$$

$$\hat{c}^*_{TH,t} = -\theta \hat{t}^*_{TH,t} + \hat{c}^{*tot}_{T,t}, \tag{D.20}$$

$$\hat{c}^*_{TF,t} = -\theta \hat{t}^*_{TF,t} + \hat{c}^{*tot}_{T,t}, \tag{D.21}$$

$$\hat{c}_{TF,t} = -\theta \hat{t}_{TF,t} + \hat{c}^{tot}_{T,t}, \tag{D.22}$$

where $\hat{t}_{TH,t} = \hat{p}_{TH,t} - \hat{p}_{T,t}$, $\hat{t}^*_{TH,t} = \hat{p}^*_{TH,t} - \hat{p}^*_{T,t}$, $\hat{t}_{TF,t} = \hat{p}_{TF,t} - \hat{p}_{T,t}$and $\hat{t}^*_{TF,t} = \hat{p}^*_{TF,t} - \hat{p}^*_{T,t}$. Demand for tradeables in the US and in ROW is given by

$$\hat{c}^{tot}_{T,t} = [(1-\iota_T)\hat{c}_{T,t} + \iota_T \hat{g}_{T,t}], \tag{D.23}$$

$$\hat{c}^{*tot}_{T,t} = [(1-\iota_T)\hat{c}^*_{T,t} + \iota_T \hat{g}^*_{T,t}], \tag{D.24}$$

where ι denotes the share of exogenous demand in total demand.
The manufacturing demand shocks evolves according to

$$\hat{g}_{T,t} = \rho_{G_T} \hat{g}_{T,t-1} + \varepsilon_{g_T,t}, \tag{D.25}$$

$$\hat{g}^*_{T,t} = \rho^*_{G_T} \hat{g}^*_{T,t-1} + \varepsilon_{g^*_T,t}, \tag{D.26}$$

where ε_{G_T},$\varepsilon_{G^*_T}$ are i.i.d.

Bilateral net foreign asset position (US/ROW)

$$\beta^* b_t = b_{t-1} + nx_t \tag{D.27}$$

Bilateral non-oil trade balance (US/ROW)

$$\begin{aligned} nx_t = {} & \frac{C}{Y}(1-\gamma)\delta \left[\hat{t}^*_{TH} + \hat{t}^*_T + \hat{q}_t + \hat{c}^*_{TH,t} - \hat{c}_{TF,t} - (\hat{t}_{TF} + \hat{t}_T)\right] + \\ & + \frac{Y_T}{Y}\tilde{\alpha}_{M,T}\omega \left[\hat{t}^*_{TH} + \hat{t}^*_T + \hat{q}_t + \hat{m}^*_{TH,t} - \hat{m}_{TF,t} - (\hat{t}_{TF} + \hat{t}_T)\right] \end{aligned} \tag{D.28}$$

Production (factor demand)

Oil factor demand is given by

$$\hat{o}_{T,t} = \tau(\hat{w}_t) + (\hat{n}_{T,t}) - \tau(\hat{p}_{Oil,t}), \tag{D.29}$$

$$\hat{o}_{N,t} = \tau(\hat{w}_t) + (\hat{n}_{N,t}) - \tau(\hat{p}_{Oil,t}), \tag{D.30}$$

$$\hat{o}^*_{T,t} = \tau(\hat{w}^*_t) + (\hat{n}^*_{T,t}) - \tau(\hat{p}_{Oil,t} - \hat{q}_t), \tag{D.31}$$

$$\hat{o}^*_{N,t} = \tau(\hat{w}^*_t) + (\hat{n}^*_{N,t}) - \tau(\hat{p}_{Oil,t} - \hat{q}_t). \tag{D.32}$$

Non-oil intermediate goods factor demand is given by

$$\hat{m}_{T,t} = \tau(\hat{w}_t) + (\hat{n}_{T,t}) - \tau(\hat{p}_{M;T,t}), \tag{D.33}$$

$$\hat{m}_{N,t} = \tau(\hat{w}_t) + (\hat{n}_{N,t}) - \tau(\hat{p}_{M,N,t}), \tag{D.34}$$

$$\hat{m}^*_{T,t} = \tau(\hat{w}^*_t) + (\hat{n}^*_{T,t}) - \tau(\hat{p}^*_{M,T,t}), \tag{D.35}$$

$$\hat{m}^*_{N,t} = \tau(\hat{w}^*_t) + (\hat{n}^*_{N,t}) - \tau(\hat{p}^*_{M,N,t}). \tag{D.36}$$

Combining the above equations with the factor demand for labour and the production functions gives

$$\hat{y}_{T,t} = (1 - \tilde{\alpha}_{O,T} - \tilde{\alpha}_{M,T})(\hat{n}_{T,t}) + \tilde{\alpha}_{O,T}\hat{o}_{T,t} + \tilde{\alpha}_{M,T}\hat{m}_{T,t} + \hat{z}_{T,t}, \tag{D.37}$$

$$\hat{y}^*_{T,t} = (1 - \tilde{\alpha}^*_{O,T} - \tilde{\alpha}^*_{M,T})(\hat{n}^*_{T,t}) + \tilde{\alpha}^*_{O,T}\hat{o}^*_{T,t} + \tilde{\alpha}^*_{M,T}\hat{m}^*_{T,t} + \hat{z}^*_{T,t}, \tag{D.38}$$

$$\hat{y}_{N,t} = (1 - \tilde{\alpha}_{O,N} - \tilde{\alpha}_{M,N})(\hat{n}_{N,t}) + \tilde{\alpha}_{O,N}\hat{o}_{N,t} + \tilde{\alpha}_{M,N}\hat{m}_{N,t} + \hat{z}_{N,t}, \tag{D.39}$$

$$\hat{y}^*_{N,t} = (1 - \tilde{\alpha}^*_{O,N} - \tilde{\alpha}^*_{M,N})(\hat{n}^*_{N,t}) + \tilde{\alpha}^*_{O,N}\hat{o}^*_{N,t} + \tilde{\alpha}^*_{M,N}\hat{m}^*_{N,t} + \hat{z}^*_{N,t}. \tag{D.40}$$

Technology evolves according to

$$\hat{z}_{T,t} = \rho_{Z_T}\hat{z}_{T,t-1} + \varepsilon_{Z_T,t}, \tag{D.41}$$

$$\hat{z}_{N,t} = \rho_{Z_N}\hat{z}_{N,t-1} + \varepsilon_{Z_N,t}, \tag{D.42}$$

$$\hat{z}^*_{T,t} = \rho_{Z_T}\hat{z}^*_{T,t-1} + \varepsilon_{Z^*_T,t}, \tag{D.43}$$

$$\hat{z}^*_{N,t} = \rho_{Z_N}\hat{z}^*_{N,t-1} + \varepsilon_{Z^*_N,t}, \tag{D.44}$$

where ε_{Z_T}, etc. are i.i.d.

Tradeable intermediate goods market clearing

$$\hat{m}_{TH,t} = -\theta\hat{t}_{TH,M,t} + \hat{m}_{T,t}, \tag{D.45}$$

$$\hat{m}^*_{TH,t} = -\theta\hat{t}^*_{TH,M,t} + \hat{m}^*_{T,t}, \tag{D.46}$$

$$\hat{m}^*_{TF,t} = -\theta\hat{t}^*_{TF,M,t} + \hat{m}^*_{T,t}, \tag{D.47}$$

$$\hat{m}_{TF,t} = -\theta \hat{t}_{TF,M,t} + \hat{m}_{T,t}, \tag{D.48}$$

where $\hat{t}_{TH,Mt} = \hat{p}_{TH,t} - \hat{p}_{M,T,t}$, $\hat{t}^*_{TH,Mt} = \hat{p}^*_{TH,Mt} - \hat{p}^*_{M,T,t}$, $\hat{t}_{TF,Mt} = \hat{p}_{TF,t} - \hat{p}_{M,T,t}$and $\hat{t}^*_{TF,Mt} = \hat{p}^*_{TF,t} - \hat{p}^*_{M,T,t}$.

Goods market clearing (non-oil), (US and ROW)

Total nontradeable market clearing (at Home and ROW) is given by

$$\hat{y}_{N,t} = (1 - \tilde{\alpha}_{M,N})\hat{c}_{N,t} + \tilde{\alpha}_{M,N}\hat{m}_{N,t} \tag{D.49}$$

$$\hat{y}^*_{N,t} = (1 - \tilde{\alpha}^*_{M,N})\hat{c}^*_{N,t} + \tilde{\alpha}^*_{M,N}\hat{m}^*_{N,t} \tag{D.50}$$

Total tradeable market clearing at Home and ROW is given by

$$\begin{aligned}
\hat{y}_{T,t} = &\left(1 - \frac{C_{dom,TH} + X_{dom,TH}}{Y_T} - \tilde{\alpha}_{M,T}\right)\left[(1-\delta)\hat{c}_{TH,t} + \frac{1-n}{n}\delta^* \hat{c}^*_{TH,t}\right] + \\
&+ \tilde{\alpha}_{M,T}\left[(1-\omega)\hat{m}_{TH,t} + \frac{1-n}{n}\omega^* \hat{m}^*_{TH,t}\right] \\
&+ \frac{C_{dom,TH} + X_{dom,TH}}{Y_T}\left[\beta_{dom}\hat{x}_{TH,dom,t} + (1-\beta_{dom})\hat{c}_{TH,dom,t}\right],
\end{aligned}$$

$$\begin{aligned}
\hat{y}^*_{T,t} = &\left(1 - \frac{C_{dom,TF} + X_{dom,TF}}{Y^*_T} - \tilde{\alpha}^*_{M,T}\right)\left[(1-\delta^*)\hat{c}^*_{TF,t} + \frac{n}{1-n}\delta \hat{c}_{TF,t}\right] + \\
&+ \tilde{\alpha}^*_{M,T}\left[(1-\omega^*)\hat{m}^*_{TF,t} + \frac{n}{1-n}\omega \hat{m}_{TF,t}\right] \\
&+ \frac{C_{dom,TF} + X_{dom,TF}}{Y^*_T}\left[\beta_{dom}\hat{x}_{TF,dom,t} + (1-\beta_{dom})\hat{c}_{TF,dom,t}\right].
\end{aligned}$$

Total labour is

$$\hat{n}_t = \frac{N_T}{N}\hat{n}_{T,t} + \frac{N_N}{N}\hat{n}_{N,t}, \tag{D.51}$$

$$\hat{n}^*_t = \frac{N^*_T}{N^*}\hat{n}^*_{T,t} + \frac{N^*_N}{N^*}\hat{n}^*_{N,t}. \tag{D.52}$$

Gross output evolves as

$$\hat{y}_t = \frac{Y_T}{Y}\hat{y}_{T,t} + \frac{Y_N}{Y}\hat{y}_{N,t}, \tag{D.53}$$

$$\hat{y}^*_t = \frac{Y^*_T}{Y^*}\hat{y}^*_{T,t} + \frac{Y_N}{Y}\hat{y}^*_{N,t}. \tag{D.54}$$

Consumer price inflation and inflation of non-oil tradeable (US and ROW)

$$\hat{\pi}_t = (1-\gamma)\hat{\pi}_{T,t} + \gamma\hat{\pi}_{N,t}, \tag{D.55}$$

$$\hat{\pi}^*_t = (1-\gamma^*)\hat{\pi}^*_{T,t} + \gamma^*\hat{\pi}^*_{N,t}. \tag{D.56}$$

$$\hat{\pi}_{T,t} = (1-\delta)\hat{\pi}_{TH,t} + \delta\hat{\pi}_{TF,t} \tag{D.57}$$

$$\hat{\pi}^*_{T,t} = \delta^*\hat{\pi}^*_{TH,t} + (1-\delta^*)\hat{\pi}^*_{TF,t} \tag{D.58}$$

Price setting in the nontradeable good sector (US and ROW)

Inflation in the domestic nontradeable services sector is

$$\hat{\pi}_{N,t} = \beta E_t\hat{\pi}_{N,t+1} + \frac{(1-\beta\varphi_N)(1-\varphi_N)}{\varphi_N}(\hat{mc}_{N,t} - \hat{t}_{N,t}). \tag{D.59}$$

Real marginal costs follow

$$\hat{mc}_{N,t} = (1-\tilde{\alpha}_{O,N}-\tilde{\alpha}_{M,N})\hat{w}_t + \tilde{\alpha}_{O,N}\hat{p}_{Oil,t} + \tilde{\alpha}_{M,N}\hat{p}_{M,N,t} - (1-\tilde{\alpha}_{O,N}-\tilde{\alpha}_{M,N})\hat{z}_{N,t}, \tag{D.60}$$

where $\hat{w}$ is the real wage and $\hat{p}_{oil,t}$ the real price of oil, both measured in terms of the home consumption good. For sector N, the oil share in the real marginal cost is $\tilde{\alpha}_{O,N}$. Similar in ROW

$$\hat{\pi}^*_{N,t} = \beta^* E_t\hat{\pi}^*_{N,t+1} + \frac{(1-\beta^*\varphi^*_N)(1-\varphi^*_N)}{\varphi^*_N}(\hat{mc}^*_{N,t} - \hat{t}^*_{N,t}), \tag{D.61}$$

$$\hat{mc}^*_{N,t} = (1-\tilde{\alpha}^*_{O,N}-\tilde{\alpha}^*_{M,N})\hat{w}^*_t + \tilde{\alpha}^*_{O,N}\hat{p}^*_{Oil,t} + \tilde{\alpha}^*_{M,N}\hat{p}^*_{M,N,t} - (1-\tilde{\alpha}^*_{O,N}-\tilde{\alpha}^*_{M,N})\hat{z}^*_{N,t}, \tag{D.62}$$

Price setting in the tradeable good sector (US and ROW)

The New Keynesian (NK) Phillips curve for Home-produced Home-consumed manufactured goods is given by

$$\hat{\pi}_{TH,t} = \beta E_t\hat{\pi}_{TH,t+1} + \frac{(1-\beta\varphi_{TH})(1-\varphi_{TH})}{\varphi_{TH}}(\hat{mc}_{T,t} - \hat{t}_{TH} - \hat{t}_T) \tag{D.63}$$

where $\hat{t}_{TH} + \hat{t}_T = \hat{p}_{TH,t} - \hat{p}_t$real marginal costs follow

$$\hat{mc}_{T,t} = (1-\tilde{\alpha}_{O,T}-\tilde{\alpha}_{M,T})\hat{w}_t + \tilde{\alpha}_{O,T}\hat{p}_{Oil,t} + \tilde{\alpha}_{M,T}\hat{p}_{M,T,t} - (1-\tilde{\alpha}_{O,T}-\tilde{\alpha}_{M,T})\hat{z}_{T,t}, \tag{D.64}$$

where, similar to above, the oil share in the real marginal cost is $\tilde{\alpha}_{O,T}$.

Correspondingly, the NK Phillips curve for Home-produced ROW-consumed manufactured goods is given by

$$\hat{\pi}^*_{TH,t} + \zeta^* \Delta s_t = \beta \left(E_t \hat{\pi}_{TH,t+1} + \zeta^* \Delta s_{t+1} \right) + \frac{(1-\beta\varphi_{TH})(1-\varphi_{TH})}{\varphi_{TH}} (\hat{mc}_{T,t} - t^*_{TH} - t^*_T - q_t) \tag{D.65}$$

Correspondingly in ROW

$$\hat{\pi}^*_{TF,t} = \beta E_t \hat{\pi}^*_{TF,t+1} + \frac{(1-\beta\varphi^*_{TH})(1-\varphi^*_{TH})}{\varphi^*_{TH}} (\hat{mc}^*_{T,t} - \hat{t}^*_{TF,t} - \hat{t}^*_T), \tag{D.66}$$

$$\hat{\pi}_{TF,t} - \zeta \Delta s_t = \beta \left(E_t \hat{\pi}_{TF,t+1} - \zeta \Delta s_{t+1} \right) + \frac{(1-\beta\varphi^*_{TH})(1-\varphi^*_{TH})}{\varphi^*_{TH}} (\hat{mc}^*_{T,t} - \hat{t}_{TF,t} - \hat{t}_T + \hat{q}_t), \tag{D.67}$$

$$\hat{mc}^*_{T,t} = (1 - \tilde{\alpha}^*_{O,T} - \tilde{\alpha}^*_{M,T}) \hat{w}^*_t + \tilde{\alpha}^*_{O,T} \hat{p}^*_{Oil,t} + \tilde{\alpha}^*_{M,T} \hat{p}^*_{M,T,t} - (1 - \tilde{\alpha}^*_{O,T} - \tilde{\alpha}^*_{M,T}) \hat{z}^*_{T,t}, \tag{D.68}$$

Wage setting and labour supply (US and ROW)

$$\hat{\pi}_{W,t} = \beta E_t \hat{\pi}_{W,t+1} - \frac{(1-\beta\varphi_w)(1-\varphi_w)}{\varphi_w(1+\varphi\varepsilon_w)} \left[\hat{w}_t - (\varphi \hat{n}_t + \hat{c}_t) \right]. \tag{D.69}$$

$$\hat{\pi}^*_{W,t} = \beta E_t \hat{\pi}^*_{W,t+1} - \frac{(1-\beta\varphi^*_w)(1-\varphi^*_w)}{\varphi^*_w(1+\varphi^*\varepsilon^*_w)} \left[\hat{w} - (\varphi \hat{n}^*_t + \hat{c}^*_t) \right]. \tag{D.70}$$

Real wages follow

$$\hat{w}_t = \hat{w}_{t-1} + \hat{\pi}_{W,t} - \hat{\pi}_t, \tag{D.71}$$

$$\hat{w}^*_t = \hat{w}^*_{t-1} + \hat{\pi}^*_{W,t} - \hat{\pi}^*_t, \tag{D.72}$$

Real exchange rate and relative prices

In log-linearized terms the real exchange rate is given by

$$\hat{q}_t = \hat{q}_{t-1} + \Delta \hat{s}_t + \hat{\pi}^*_t - \hat{\pi}_t. \tag{D.73}$$

Furthermore following identities hold

$$\begin{aligned} \hat{t}_{T,t} &= \hat{p}_{T,t} - \hat{p}_t, \\ \hat{t}^*_{T,t} &= \hat{p}^*_{T,t} - \hat{p}^*_t, \\ \hat{t}_{N,t} &= \hat{p}_{N,t} - \hat{p}_t, \end{aligned}$$

$$\hat{t}^*_{N,t} = \hat{p}^*_{N,t} - \hat{p}^*_t$$

and

$$\begin{aligned}\hat{t}_{TH,t} &= \hat{p}_{TH,t} - \hat{p}_{T,t},\\ \hat{t}^*_{TH,t} &= \hat{p}^*_{TH,t} - \hat{p}^*_{T,t},\\ \hat{t}_{TF,t} &= \hat{p}_{TF,t} - \hat{p}_{T,t},\\ \hat{t}^*_{TF,t} &= \hat{p}^*_{TF,t} - \hat{p}^*_{T,t}.\end{aligned}$$

The relative prices evolve according to

$$\widehat{relprice}_{HF,t} = \widehat{relprice}_{HF,t-1} + \hat{\pi}_{TH,t} - \hat{\pi}_{TF,t}, \tag{D.74}$$

$$\widehat{relprice}^*_{HF,t} = \widehat{relprice}^*_{HF,t-1} + \hat{\pi}^*_{TH,t} - \hat{\pi}^*_{TF,t}, \tag{D.75}$$

$$\widehat{relprice}_{TN,t} = \widehat{relprice}_{TN,t-1} + \hat{\pi}_{T,t} - \hat{\pi}_{N,t}, \tag{D.76}$$

$$\widehat{relprice}^*_{TN,t} = \widehat{relprice} + \hat{\pi}^*_{T,t} - \hat{\pi}^*_{N,t}, \tag{D.77}$$

Furthermore following identities hold for final goods and services prices

$$\hat{t}_{TH,t} = \delta * \widehat{relprice}_{HF,t}, \tag{D.78}$$

$$\hat{t}_{TF,t} = -(1-\delta) * \widehat{relprice}_{HF,t}, \tag{D.79}$$

$$\hat{t}^*_{TH,t} = (1-\delta^*) * \widehat{relprice}^*_{HF,t}, \tag{D.80}$$

$$\hat{t}^*_{TH,t} = -\delta^* * \widehat{relprice}^*_{HF,t}. \tag{D.81}$$

$$\hat{t}_{T,t} = \gamma * \widehat{relprice}_{TN,t}, \tag{D.82}$$

$$\hat{t}_{N,t} = -(1-\gamma) * \widehat{relprice}_{TN,t}, \tag{D.83}$$

$$\hat{t}^*_{T,t} = \gamma^* * \widehat{relprice}^*_{TN,t}, \tag{D.84}$$

$$\hat{t}^*_{N,t} = -(1-\gamma^*) * \widehat{relprice}^*_{TN,t}, \tag{D.85}$$

for intermediate manufactured goods prices

$$\hat{t}_{TH,m,t} = \omega * \widehat{relprice}_{HF,t}, \tag{D.86}$$

$$\hat{t}_{TF,m,t} = -(1-\omega) * rel\hat{price}_{HF,t}, \tag{D.87}$$

$$\hat{t}^*_{TH,m,t} = (1-\omega^*) * rel\hat{price}^*_{HF,t}, \tag{D.88}$$

$$\hat{t}^*_{TH,n,t} = -\omega^* * rel\hat{price}^*_{HF,t}, \tag{D.89}$$

as well as for non-oil intermediate goods and services prices (in terms of consumer prices)

$$\hat{p}_{M,T,t} = (\delta - \omega) * rel\hat{price}_{HF,t} + \gamma * rel\hat{price}_{TN,t}, \tag{D.90}$$

$$\hat{p}^*_{M,T,t} = (\delta^* - \omega^*) * rel\hat{price}_{HF,t} + \gamma * rel\hat{price}_{TN,t}, \tag{D.91}$$

$$\hat{p}_{M,N,t} = \hat{t}_{N,t},$$

$$\hat{p}^*_{M,N,t} = \hat{t}^*_{N,t}.$$

Monetary policy (US and ROW)

$$\hat{r}_t = \nu_r \hat{r}_{t-1} + (1-\nu_r)\kappa_\pi \hat{\pi}_t + (1-\nu_r)\kappa_y(\hat{y}_t - \hat{y}_{t-1}) + \varepsilon^r_t, \tag{D.92}$$

$$\hat{r}^*_t = \nu^*_r \hat{r}^*_{t-1} + (1-\nu^*_r)\kappa^*_\pi \hat{\pi}^*_t + (1-\nu_r)\kappa^*_y(\hat{y}^*_t - \hat{y}^*_{t-1}) + \varepsilon^r_t. \tag{D.93}$$

Global oil market

Global oil demand is given by

$$\hat{o}_{demand,t} = \frac{O_T}{O_d}\hat{o}_{T,t} + \frac{O^*_T}{O_d}\hat{o}^*_{T,t} + \frac{O_N}{O_d}\hat{o}_{N,t} + \frac{O^*_N}{O_d}\hat{o}^*_{N,t}. \tag{D.94}$$

Global oil storage evolves according to

$$i\hat{n}v_t = \Theta\left(E_t \hat{p}^{oil}_{t+1} - \hat{p}^{oil}_t - (\hat{r}_t - \hat{\pi}_{t+1})\right) + invd_t \tag{D.95}$$

where $\Theta = \frac{\beta}{\Psi\overline{S}} = \frac{\beta}{\beta-1-\kappa} > 0$ and the global storage demand shock is given by

$$i\hat{n}vd_{t+1} = \rho^{invd} i\hat{n}vd_t + \varepsilon^{invd}_{t+1}. \tag{D.96}$$

The optimality conditions of the **“dominant” oil producer** are given by

$$(1-\mu)\hat{\lambda}_t + \mu\hat{p}^{oil}_t = c_{dom,t} + (\varphi+1) * \hat{n}_{dom,t} - \hat{o}_{dom,t} \tag{D.97}$$

$$(1-\mu)\hat{\lambda}_t + \mu\hat{p}^{oil}_t = \hat{p}^x_t + \hat{x}_{dom,t} - \hat{o}_{dom,t} \tag{D.98}$$

$$\hat{\lambda}_t = \hat{p}_t^{oil} + \hat{o}_{dom,t} + \frac{1-\mu}{\mu}\frac{1}{oilshare_{dom}}\left(\tau\hat{o}_{demand,t} + \frac{\overline{INV}}{\overline{O}^s}\left[\widehat{inv}_t + \widehat{inv}_{t-1}\right]\right) \tag{D.99}$$

where the real price of imported manufactured goods (in terms of the US CPI) and the extraction of oil given by a Cobb Douglas production function follow

$$\hat{p}_t^x = n\hat{t}_{TH} + (1-n)\hat{t}_{TF} + \hat{t}_T, \tag{D.100}$$

$$\hat{o}_{dom,t} = \hat{z}_{dom,t} + \alpha_{dom} * \hat{n}_{dom,t} + \beta_{dom} * \hat{x}_{dom,t} \tag{D.101}$$

with

$$\hat{z}_{dom,t+1} = \rho^{dom}\hat{z}_{dom,t} + \varepsilon_{t+1}^{dom}. \tag{D.102}$$

Due to financial autarky we have

$$\hat{p}_t^{oil} + \hat{o}_{dom,t} = (1-\beta_{dom})\left[\hat{c}_{dom,t} + \hat{p}_t^x\right] + \beta_{dom}\left[\hat{x}_{dom,t} + \hat{p}_t^x\right]. \tag{D.103}$$

Relative prices of US/ROW intermediates follow

$$\hat{t}_{XH,dom,t} = (1-n) * \widehat{relprice}_{HF}, \tag{D.104}$$

$$\hat{t}_{XF,dom,t} = -n * \widehat{relprice}_{HF}, \tag{D.105}$$

and demand for manufactured goods is given by

$$\hat{x}_{TH,dom,t} = -\theta\hat{t}_{XH,dom,t} + \hat{x}_{dom,t}, \tag{D.106}$$

$$\hat{x}_{TF,dom,t} = -\theta\hat{t}_{XF,dom,t} + \hat{x}_{dom,t}, \tag{D.107}$$

$$\hat{c}_{TH,dom,t} = -\theta\hat{t}_{XH,dom,t} + \hat{c}_{dom,t}, \tag{D.108}$$

$$\hat{c}_{TF,dom,t} = -\theta\hat{t}_{XF,dom,t} + \hat{c}_{dom,t}. \tag{D.109}$$

Global oil market clearing

$$\hat{o}_{demand,t} = \hat{o}_{s,t} + \frac{INV}{O_{supply}}\widehat{inv}_{t-1} - \frac{INV}{O_{supply}}\widehat{inv}_t, \tag{D.110}$$

$$\hat{o}_{s,t} = \frac{O_{fringe}}{O_{supply}}\hat{o}_{fringe,t} + \frac{O_{dom}}{O_{supply}}\hat{o}_{dom,t}. \tag{D.111}$$

$$\hat{o}_{fringe,t} = \hat{z}_{fringe,t+1} = \rho^{fringe}\hat{z}_{fringe,t} + \varepsilon_{t+1}^{fringe}. \tag{D.112}$$

Further variables

Gross domestic product

$$\hat{gdp}_t = \frac{C}{GDP}\hat{c}_t + \frac{G_T}{GDP}\hat{g}_T + \frac{C_{TF}}{GDP}\left(\hat{c}^*_{TH,t} - \hat{c}_{TF,t}\right) + \frac{M_{TF}}{GDP}\left(\hat{m}^*_{TH,t} - \hat{m}_{TF,t}\right),$$

$$\hat{gdp}^*_t = \frac{C^*}{GDP^*}\hat{c}^*_t + \frac{G^*_T}{GDP^*}\hat{g}^*_T + \frac{C^*_{TH}}{GDP^*}\left(\hat{c}_{TF,t} - \hat{c}^*_{TH,t}\right) + \frac{M^*_{TH}}{GDP^*}\left(\hat{m}_{TF,t} - \hat{m}^*_{TH,t}\right).$$

Bilateral trade between US and ROW

$$\hat{trade}_t^{US/ROW} = \frac{1}{2}\left[\frac{C_{TF}}{C_{TF} + M_{TF}}\left(\hat{c}^*_{TH,t} + \hat{c}_{TF,t}\right) + \frac{M_{TF}}{C_{TF} + M_{TF}}\left(\hat{m}^*_{TH,t} + \hat{m}_{TF,t}\right)\right].$$

Non-oil OPEC trade (with US and ROW)

$$\hat{trade}_t^{OPEC} = (1 - \beta_{dom})\left[\hat{c}_{dom,t}\right] + \beta_{dom}\left[\hat{x}_{dom,t}\right].$$

Global manufacturing production and service activity (real economic activity)

$$\hat{rea}_{T,t} = n * \hat{y}_{T,t} + (1 - n) * \hat{y}^*_{T,t}, \tag{D.113}$$

$$\hat{rea}_{N,t} = n * \hat{c}_{N,t} + (1 - n) * \hat{c}^*_{N,t}. \tag{D.114}$$

Wedge between global manufacturing production and services activity (and US counterpart)

$$\hat{wedge}^*_t = \hat{rea}_{T,t} - \hat{rea}_{N,t}, \tag{D.115}$$

$$\hat{wedge}_t = \hat{y}_{T,t} - \hat{c}_{N,t}. \tag{D.116}$$