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Exogenous oil supply shocks in OPEC and non-OPEC countries*

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Abstract

This note expands Kilian's (2008) original time series of exogenous oil supply shocks along two dimensions. First, we extend the sample period and include production shortfalls in OPEC member states during 2004:10–2018:12. Second, we also consider production shortfalls in non-OPEC countries. Our extended series of exogenous oil supply shocks displays statistically significant correlation with alternative estimates of oil supply shocks based on vector-autoregressive models. At the same time, it requires a limited number of assumptions about the counterfactual evolution of production in the countries under consideration rather than the hotly debated identifying restrictions inherent in multivariate structural models.

Keywords: Counterfactual analysis, Crude oil production, Exogenous events, Oil supply shocks

JEL classification: N50, Q31, Q35

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1 Introduction

Recent geopolitical events, such as the 2019 drone strikes on Saudi oil-processing facilities and growing tensions between the U.S. and Iran, have refueled concerns about oil supply disruptions. At the same time, there is an ongoing debate about how to identify oil supply shocks in structural vector-autoregressive (VAR) models of the global oil market (see, e.g., Baumeister and Hamilton, 2019a,b; Caldara et al., 2019; Kilian and Zhou, 2019), calling for external instruments in order to identify the dynamic causal effects of oil supply disruptions.[1] Kilian (2008) proposes a measure of global oil supply shocks based on arguably exogenous production shortfalls due to geopolitical events in major oil-producing countries relative to some country-specific counterfactual. The timing, magnitude, and sign of this measure differs from previous state-of-the-art estimates.

In this note, we expand Kilian's (2008) original time series along two dimensions. First, we extend the sample period and include production shortfalls in OPEC member countries during 2004:10–2018:12. Second, we also consider production shortfalls in major oil-producing countries outside of OPEC such as the U.S., Canada, and Norway, for example. While this adds only three exogenous events to the original sample period, i.e. 1973:1–2004:9, a number of nontrivial production shortfalls occurred during 2004:10–2018:12 in both OPEC and non-OPEC countries. Our time series displays statistically significant, albeit modest contemporaneous correlation with current state-of-the-art estimates of exogenous oil supply shocks based on structural (Bayesian) VAR models. At the same time, it requires a limited number of unambiguous assumptions about the counterfactual evolution of production in the countries under consideration and provides thus an alternative to or instrument for estimates based on multivariate structural models.

Following Kilian (2008), we use monthly data on country-level crude oil production provided by the U.S. Energy Information Administration (EIA) to detect oil supply disruptions and construct counterfactual production series during exogenous historical events. Each counterfactual is derived from the production behavior of a benchmark group of countries that adhered to the same global macroeconomic conditions — in particular the same oil price — and thus similar economic incentives, without being subject to the exogenous event in question or any other exogenous event affecting their oil production at the time. Accordingly, the composition of the benchmark group varies both by country and episode, and the counterfactual is constructed by extrapolating the country's production level in the month prior to an event by the growth rate of production in the respective benchmark group.

In his construction of exogenous oil supply shocks, Kilian (2008) focuses on OPEC countries,

[1] Using external instruments has recently become popular in many areas of macroeconometrics (see Stock and Watson, 2018).

while non-OPEC production levels are merely used for constructing a counterfactual during the Arab Oil Embargo of 1973/74. Bastianin and Manera (2018) extend this series of OPEC supply shocks until December 2013 and include thus the First Libyan Civil War.[2] Similar to Caldara et al. (2019), we also consider exogenous events in major oil-producing countries outside of OPEC such as the Norwegian Oil Strike of 1986 and the Ecuador Earthquakes of 1987, for example.[3]

The rest of this note is structured as follows. Section 2 describes the crude oil production data. Sections 3 and 4 discuss the construction of counterfactuals during exogenous historical events in OPEC and non-OPEC countries, respectively. Section 5 presents our extended time series of exogenous oil supply shocks. Section 6 compares our series with alternative estimates of oil supply shocks based on structural (Bayesian) VAR models. Section 7 concludes.

2 Data

All crude oil production data are from Tables 11.1a and 11.1b in the EIA's *Monthly Energy Review* (MER), where *Total OPEC* production corresponds to the sum of production in all countries that were an OPEC member state in the most recent month featured in the MER. As a consequence, *Total OPEC* production and *Total non-OPEC* production *as of today* are not identical with the time series used in Kilian (2008). We use the March 2019 versions of Tables 11.1a and 11.1b, where the most recent production data and thus the composition of OPEC and non-OPEC countries dates from December 2018. At this point in time, *Total OPEC* included the production levels of Algeria, Angola, Ecuador, Equatorial Guinea, Gabon, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Republic of Congo, Saudi Arabia, United Arab Emirates (UAE), and Venezuela.[4] Due to changes in the composition of OPEC member states over time and the corresponding crude oil production data provided by the EIA, the country-specific counterfactuals in this note and the resulting extended series of exogenous oil supply shocks may differ from the original time series in Kilian (2008) (see Bastianin and Manera, 2018).

3 OPEC Counterfactuals

In this section, we replicate the counterfactuals for exogenous oil production shortfalls in OPEC countries from Kilian (2008) for our extended sample period, 1973:1–2018:12, and consider two additional OPEC countries, i.e. Ecuador and Libya. The counterfactual for an exogenous event

[2] Bastianin et al. (2017) extend this series until December 2015 without including further exogenous events.

[3] Our baseline time series featuring OPEC and non-OPEC events as well as a version restricted to exogenous oil production shortfalls in OPEC countries can be downloaded from the corresponding author's webpage.

[4] Qatar suspended its OPEC membership as of January 2019, while Ecuador has announced to suspend its membership in January 2020.

occurring in country i and period t extrapolates the level of production in $t-1$ by the growth rate of production in all other OPEC countries that were *not* affected by the same or any other exogenous event at the time, i.e.

$$Counterfactual_{i,T} = \prod_{s=t}^{T} \left(\frac{Benchmark_{i,s}}{Benchmark_{i,s-1}} \right) \cdot Production_{i,t-1}, \quad T \geq t. \tag{1}$$

These counterfactuals form the basis for our series of exogenous oil supply shocks in Section 5. The detailed composition of benchmark groups for OPEC countries is summarized in Table A.1 in the online appendix.

3.1 Arab Oil Embargo

The bottom panel of Figure 1 in Kilian (2008) plots the sum of exogenous production shortfalls in Algeria, Iraq, Kuwait, Libya, Qatar, Saudi Arabia, and the UAE during the Arab Oil Embargo in 1973:11–1974:2. The corresponding counterfactual extrapolates the total production of these countries in October 1973 by the growth rate of total non-OPEC production.

Panel (a) of Figure 1 plots the total production shortfall in Algeria, Iraq, Kuwait, Libya, Qatar, Saudi Arabia, and UAE associated with the Arab-Israeli War and the Arab Oil Embargo in 1973–1974. As in the original paper, the effect is expressed in thousand barrels per day (tbpd).

3.2 Counterfactual for Iran

Kilian (2008) identifies the Iranian Revolution as an exogenous event and dates the beginning of adverse effects on the country's crude oil production to October 1978, when striking oil workers brought production to a near-halt. He further argues that, while the Shah abdicated and the Khomeini regime took over in January 1979, the effects on crude oil production continued at least until the end of his sample period in September 2004.

Following this line of argument, we presume that Iranian production has not recovered until the end of our sample period in December 2018, as disputes over the country's nuclear program led the U.S. to impose sanctions on the Central Bank of Iran in December 2011, aggravated by the EU's import ban on Iranian oil and restrictions on transportation insurance starting in July 2012.[5] Due to the lack of progress in nuclear talks, the EU imposed further sanctions, and production dropped from 4,000 tbpd in December 2011 to 2,800 tbpd in October 2012.

After an extended period of heightened political uncertainty and despite first signs of easing

[5]Under the *Related Law Sanctioning Energy Payments*, foreign banks were prohibited from opening an account in the U.S. and existing accounts were sanctioned, if a credit institution processed payments through the Central Bank of Iran. Foreign central banks were subject to the rule only if their transactions with the Central Bank of Iran involved the purchase of Iranian crude oil (Katzman, 2013, pp. 17f.).

tensions in 2014, the *Joint Comprehensive Plan of Action* (JCPOA) was only ratified on July 14 of 2015.[6] The JCPOA subjected Iran's nuclear program to international control in exchange for a substantial easing of economic sanctions, in particular enabling the country to export crude oil without restrictions and accessing nearly $60 billion of foreign exchange reserves (Katzman, 2016, p. 59). On May 8 of 2018, the U.S. government announced to withdraw from the JCPOA and reintroduce sanctions unilaterally, inducing large companies to leave Iran (Katzman, 2019). Panel (b) of Figure 1 illustrates that the installment of sanctions in 2012 as well as in 2016 had substantial negative effects on Iran, reducing crude oil production levels by 1000 tbpd within a few months on both occasions, while the lifting of nuclear-related sanctions after ratification of the JCPOA is characterized by a recovery of production of similar size.

In forming a benchmark group for Iran, Kilian (2008) considers oil-producing countries with similar economic incentives that were not affected by the Iranian Revolution. Accordingly, the Iranian counterfactual is based on the growth rate of oil production in all OPEC countries but Iran, Iraq, and Saudi Arabia. No adjustment of this benchmark group is required at the start of the Iran-Iraq War in September 1980, while we account for the 1987 Ecuador earthquakes, the invasion of Kuwait by Iraq in August 1990, and the Venezuela oil lockout in December 2002 by temporarily excluding these countries from the benchmark. As we extend the sample period to December 2018, we furthermore account for the Libyan civil wars starting in February 2011. Panel (b) of Figure 1 plots the actual and counterfactual production levels for Iran.

3.3 Counterfactual for Iraq

The counterfactual for Iraq starts in October 1978. While the country was not directly affected by the Iranian Revolution, the latter initiated a series of events which led to the Iran-Iraq War in September 1980. Crucially, the abdication of the Shah led to a decline in Iran's military strength and marked the end of political ties with the U.S., making an Iraqi invasion conceivable in the first place. Given its large Shia community, the secular and socialist Ba'athist regime in Iraq felt threatened by Ayatollah Khomeini's seizure of power in neighboring Iran. Hence, the Iranian Revolution provided both opportunity and motive to attack Iran. In order to finance the stockpiling of arms and spare parts in preparation for the coming war, Iraq began accumulating foreign exchange reserves by expanding its crude oil production immediately after the fall of the Shah. The increase in Iraqi production between October 1978 and the September 1980

[6] Under the JCPOA, among other things, Iran agreed to eliminate its stockpile of medium-enriched uranium, cut its stockpile of low-enriched uranium by 98%, and reduce the number of gas centrifuges by about two-thirds for 13 years. To monitor and verify compliance with the agreement, the International Atomic Energy Agency (IAEA) was granted regular access to all of Iran's nuclear facilities. In return for verifiably abiding by its commitments, nuclear-related sanctions will be halted or lifted (Kerr and Katzman, 2018, pp. 9–14 & 20).

therefore represents an exogenous positive oil supply shock rather than a response to a change in market conditions (Kilian, 2008, p. 223).

At the start of the Iran-Iraq War, Iraqi crude oil production came to a near-halt, recovering only slowly afterwards. On the eve of the Gulf War, in July 1990, production had reached levels close to the prior all-time high of 3,728 tbpd, before dropping to virtually zero in March 1991 again, as a U.S.-led coalition liberated Kuwait and advanced into Iraqi territory.[7] Following the defeat in the Gulf War, sanctions and export restrictions imposed by the United Nations (U.N.) kept Iraqi crude oil production at very low levels until November 1996, when production started to recover to pre-war levels, as the effectiveness of sanctions had been largely eroded. The subsequent volatility of Iraqi production during 1997–2002 reflects the uneven enforcement of U.N. sanctions (Kilian, 2008, p. 223). After the invasion by U.S. forces in March 2003, Iraqi crude oil production once again dropped to virtually zero before steadily increasing during the subsequent decade. In September 2014, national production levels reached a new all-time high.

Panel (c) of Figure 1 plots the actual and counterfactual production levels for Iraq. Note that the recovery of Iraqi oil production after 2005 and its overshooting of the counterfactual in 2016 are direct consequences of the politically motivated presence of U.S. troops after the war and represents thus a positive exogenous oil supply shock.

3.4 Counterfactual for Ecuador

On March 5 of 1987, Ecuador was hit by two earthquakes, which severely damaged the country's crude oil production and transportation infrastructure (see also Caldara et al., 2019). Occurring after a month of heavy rainfall, the earthquakes triggered a series of landslides which damaged some 40 km of the Trans-Ecuadorian Pipeline System (SOTE) and caused thus the single largest pipeline failure in history (Crespo et al., 1991, pp. 85f.).[8]

Given that Ecuador suspended its OPEC membership during 1992:12–2007:10, Kilian (2008) did not consider the earthquakes, although the event was clearly exogenous and the country a member of OPEC in 1987.[9] Panel (d) of Figure 1 illustrates that oil production dropped to zero in April 1987, yet recovered swiftly to pre-earthquake levels by October 1987 and continued to increase over the remainder of our sample period.

[7] Aerial and ground combat was confined to Iraq, Kuwait, and areas on the Saudi Arabian border.

[8] Due to the damaging of the SOTE, the *indirect* economic loss was more than four times the *direct* economic loss from the earthquakes. At an average oil price of $19 per barrel, total oil revenues lost between March 5 and August 18 of 1987 amounted to $790 million, while the cost of reconstructing the pipeline was estimated at $50 million (Crespo et al., 1991, p. 98).

[9] Ecuador joined OPEC in 1973 and suspended its membership in 1992. Having resumed its membership in 2007, the country has recently announced to leave OPEC on January 1 of 2020 in search of higher oil revenues.

3.5 Counterfactual for Kuwait

The Iraqi invasion of Kuwait in August 1990 marks the first exogenous political event impairing the country's crude oil production after the Arab Oil Embargo. By the end of the Iran-Iraq War, Iraq was heavily indebted to Saudi Arabia and Kuwait, and tensions within the Iraqi society were growing. Because Kuwait had been part of the Ottoman Empire's province of Basra, the dispute also involved claims to the country as Iraqi territory. Finally, Iraq accused Kuwait of consistently exceeding its OPEC production quota and thus depressing the world oil price as low as $10 per barrel. Despite this mixture of motives, some of them economic in nature, the Iraqi invasion must be considered an exogenous negative oil supply shock.

After the Iraqi invasion, crude oil production dropped to virtually zero, before recovering to levels close to the counterfactual within four years. Consistent with the EIA's (2011) assessment and in contrast with Kilian (2008), where the counterfactual is modeled until September 2004, we therefore assume that Kuwaiti production returned to normal levels by August 1994. During the remainder of our sample period, production was not affected by further exogenous events. Panel (e) of Figure 1 plots the actual and counterfactual production levels for Kuwait.

3.6 Counterfactual for Saudi Arabia

In contrast to other OPEC or non-OPEC producers, Saudi Arabia could draw on spare capacity and act as a swing producer during our sample period, posing special challenges for the construction of a counterfactual. To offset the production shortfall during the Iranian Revolution, Saudi Arabia temporarily increased its oil production in September 1978, effectively acting as a "producer of last resort". Once the situation in Iran had calmed down, Saudi Arabia curtailed its production in April 1979. Since the spike in production was a direct response to the political event of the Iranian Revolution rather than to the economic incentive of higher oil prices, it must be treated as an exogenous oil supply shock (Kilian, 2008, p. 224).

Following the Iraqi invasion of Kuwait, Saudi Arabia similarly raised its crude oil production temporarily to compensate for shortfalls in Kuwait and Iraq. Between August and December of 1990, Saudi production increased from 5,789 tbpd to 8,481 tbpd, decreased to 7,936 tbpd by March 1991, and stabilized at 7,341 tbpd in April 1991. Based on these data and Figure 5 in Kilian (2008), we model the Saudi counterfactual for this episode during 1990:8–1991:3.

Prior to the Iraq War, the option of a military strike was discussed in public from July 2002. Thus, the war could have been anticipated, inducing Saudi Arabia to expand its production. In contrast to earlier episodes, however, the Iraq War did not have a well-defined end, although the focus of the U.S.-led coalition had shifted from open war to pacification by October 2003

(Kilian, 2008, p. 225).

Panel (f) of Figure 1 plots the actual and counterfactual production levels for Saudi Arabia. All three events discussed above are associated with a sharp increase in Saudi oil production relative to the counterfactual.[10] As in Kilian (2008), we acknowledge the particular incentives of Saudi Arabia as a producer with spare capacity by excluding the country from the benchmark groups of other OPEC members affected by an exogenous event.

3.7 Counterfactual for Venezuela

The Venezuela oil strike (a.k.a. oil lockout) of 2002–2003 succeeded protests against President Chávez and was an attempt of the Venezuelan opposition to force a new presidential election. The strike lasted from December 2002 until February 2003 and impaired the country's crude oil production also afterwards, as some 18,000 employees of the state-owned oil company Petróleos de Venezuela (PDVSA) were fired during the strike. Given the well-defined consequences for the country's production, the Venezuela oil lockout provides a natural candidate for an exogenous oil supply shock.

Panel (g) of Figure 1 plots the actual and counterfactual production levels for 1973:1–2018:12 and illustrates the sharp drop relative to the benchmark group during the Venezuela oil strike, from which the country's production level never fully recovered (see also EIA, 2011). Starting in 2016, Venezuelan production went into decline again, as years of neglect and losses in technical capacity under the Chávez and Maduro governments were aggravated by the country's political and economic crisis (Palacios, 2016, pp. 21f.). As the counterfactual production level remained broadly stable, this represents yet another exogenous oil supply shock.

3.8 Counterfactual for Libya

On February 15 of 2011, protests in the capital Benghazi inspired by the so-called "Arab Spring" in neighboring countries led to clashes with security forces which fired at the crowd. Protests escalated into the First Libyan Civil War (a.k.a. the Libyan Revolution), as forces opposing Muammar al Qadhafi established an interim government — the National Transitional Council. On February 26 of 2011, the U.N. Security Council passed an initial resolution to freeze assets and restrict travel of Qadhafi and his inner circle. As forces loyal to Qadhafi rallied, pushed eastwards, and re-took several coastal cities before reaching Benghazi in early March, a second U.N. resolution authorized member states to establish and enforce a no-fly zone over Libya and

[10] Kilian (2008) further notes that similar war-related peaks may be identified in the production data of other countries. Given that all countries but Saudi Arabia have produced at or close to their capacity constraints during our sample period, the magnitudes of such peaks should be considerably smaller and are therefore ignored.

use "all necessary measures" to prevent attacks on civilians, leading to a bombing campaign by NATO forces against Libyan military installations and civilian infrastructure. In October 2011, anti-Qadhafi forces took the city of Sirte and arrested and killed Qadhafi. Interim authorities then declared that Libya was liberated and elections would be held within eight months.

Panel (h) of Figure 1 illustrates that the civil war triggered a steep contraction of crude oil production in 2011.[11] Escalating protests and strikes in mid-2013 led to a deterioration of overall security, the blockade of major seaports, and the closure of production and transportation infrastructure. As a result, oil production fell by 1000 tbpd within a few months. Production levels slightly recovered in the second half of 2014, following agreements to reopen some of the blocked seaports, but remained well below pre-war levels until the end of our sample period. Panel (h) of Figure 1 plots the counterfactual against the actual production level during 1973:1–2018:12.

4 Non-OPEC Counterfactuals

In contrast to Kilian (2008), we also consider exogenous oil supply disruptions in non-OPEC countries due to strikes and natural disasters, for example. Following the previous logic, our benchmark group for a given event generally consists of all non-OPEC countries that were not affected by the same or any other event for the duration of the counterfactual. In this section, we discuss six events and their effects on country-level crude oil production.[12] The composition of benchmark groups for non-OPEC countries is summarized in Table A.2 in the online appendix.

4.1 Counterfactual for Norway

In April 1986, a strike of the food service workers' union, which demanded a 28% wage increase, automatically spread to production workers under labor negotiation rules and severely impaired Norwegian offshore oil and gas production (see also Caldara et al., 2019). Rather than giving in to caterers' demands, employers evacuated 2,000 oil workers from offshore production facilities, leaving 200 on platforms in the Ekofisk and Statfjord fields for safety reasons. Prior to the strike, Norwegian oil production had amounted to 860 tbpd or 2.25% of total non-OPEC production. When the strike became imminent on April 4, the price of Brent crude oil increased from $11 to $12.20 per barrel within one day. While analysts expected the effect on the spot market to

[11] In response to the 2011 slump of Libyan oil production, the *International Energy Agency* (IEA) coordinated the release of 60 million barrels of crude oil from its emergency reserves — the first release of emergency reserves since Hurricane Katrina in August 2005.

[12] One could argue that Syria and Yemen are never were major oil producers and should thus be ignored in the discussion. A version of the time series *without* Syria and Yemen has a correlation of 0.999 with the exogenous oil supply shock series presented in Section 5.

be modest and temporary, the price of Brent advanced to $14.20 on April 8, its highest level in nearly two months (Lohr, 1986; Daniels, 1986).

Panel (a) of Figure 2 plots the counterfactual and actual production levels and illustrates that the latter decreased by about 540 tbpd or two thirds between March and April of 1986, yet recovered swiftly and continued to grow along the previous trend in subsequent years. Hence, we assume that the effects of the Norwegian oil worker strike did not persist beyond June 1986.

4.2 Counterfactual for Mexico

Offshore oil and gas production in the Gulf of Mexico is notoriously sensitive to extreme weather such as hurricanes, for example. On October 9 of 1995, Hurricane Roxanne disrupted Mexican crude oil production, as it forced the state-owned Petróleos Mexicanos (PEMEX) to shut down most of its offshore facilities in the Gulf and evacuate some 3,500 workers from rigs in the Bay of Campeche, which accounts for the bulk of Mexican production (Snow, 1995). Following Caldara et al. (2019), we include Hurricane Roxanne in our list of exogenous oil supply disruptions.

Panel (b) of Figure 2 illustrates that the shortfall was only temporary, as Mexican production recovered within two months. The counterfactual is plotted against actual production during 1995:10–1995:11, when output fell short of the benchmark by 884 and 199 tbpd, respectively.

4.3 Counterfactual for the U.S.

In 2005 and 2008, offshore production facilities in the Gulf of Mexico, one of the largest sites for U.S. oil and gas extraction, were impaired by extreme weather again. In August and September 2005, category-5 hurricanes Katrina and Rita caused significant damage to production and transportation infrastructure, bringing U.S. crude oil production in the area to a near-halt.[13] Due to timely preparations for evacuation and the shutdown of production, neither hurricane caused fatalities or major oil spills, and production approached previous levels by January 2006.

In September 2008, Hurricanes Gustav and Ike destroyed 60 offshore platforms, 31 of which were classified as severely damaged. Kaiser and Yu (2010) estimate that the destroyed platforms alone accounted for 1.6% of daily crude oil production in the Gulf of Mexico. At the same time, production losses were confined to outages from shutting down platforms during the hurricanes and repairing destroyed and damaged platforms afterwards.

Panel (c) of Figure 2 plots our counterfactuals for hurricanes Katrina and Ike against actual U.S. production during 1973:1–2018:12. On either occasion, production fell short of the

[13] According to estimates of the U.S. *Bureau of Safety and Environmental Enforcement* (BSEE), 3,050 of the 4,000 platforms and 22,000 of the 33,000 miles of pipelines in the Mexican Gulf were on route of either Katrina or Rita, leaving 115 platforms destroyed and another 52 damaged as well as 535 pipeline segments damaged (see `https://www.bsee.gov/research-record/category/hurricane-katrina-and-rita`).

counterfactual by about 1000 tbpd, yet recovered quickly in the aftermath of the shock.

4.4 Counterfactual for Syria

The shooting of demonstrators demanding the release of political detainees by regular security forces in March 2011 led to violent protests that spread across the country in subsequent months and initiated the Syrian Civil War. After seemingly turning in and releasing political prisoners, President Bashar al-Assad sent tanks into Deraa, Banyas, Homs, and the outskirts of Damaskus to suppress anti-government protests. As a consequence, the U.S. and EU tightened sanctions on the Syrian government. Due to these sanctions, Syria is unable to export crude oil, while the exploration and development of new oil and gas fields are deferred for an indefinite period.[14]

During the civil war, Syrian crude oil production dropped from 394 tbpd in June 2011 to 94 tbpd in January 2013 and 14 tbpd in January 2017. Panel (d) of Figure 2 plots the actual and counterfactual production levels during 1994:1–2018:12 and illustrates that, due to the ongoing war, Syrian production does not display any sign of recovery by the end of our sample period.[15]

4.5 Counterfactual for Yemen

In January 2015, Shia Houthi insurgents captured the presidential palace and further strategic sites in Yemen's capital Sana'a, forcing President Hadi to resign and dissolve parliament. As a coalition of primarily Gulf Arab states led by Saudi Arabia launched air strikes and imposed a naval blockade to hinder the advance of Houthi rebels on Aden and restore the prior government, March 2015 marks the start of the Yemeni Civil War.

From its peak of 466 tbpd in 2001, crude oil production had been falling continuously even prior to 2015 due to aging oil fields in natural decline and reduced exploratory efforts. Repeated attacks on oil pipelines and seaports as well as the closure of the Aden refinery in April 2015 have brought the country's oil and gas production to a near-halt since the start of the civil war. The clear downward trend in production complicates the construction of a valid counterfactual. First, the benchmark group should also display a downward trend in production due to aging oil fields, as it would otherwise overstate the effect of the civil war. Second, the benchmark group must *not* be subject to production quotas. Third, no country in the benchmark group must be affected by an exogenous oil supply shock during 2015:3–2018:12. Among non-OPEC producers, Norway displays a similar trend prior to 2015 and was not affected by exogenous events during the period of interest. For this reason, we extrapolate Yemen's production level

[14] Syrian crude oil is of a heavy and sour type (i.e. has a high sulfur content), which can be processed by specialized refineries only. Before sanctions, 95% of total Syrian oil exports went to Europe, accounting for about 25% of public revenues.

[15] Note that monthly data on Syrian crude oil production is only available from the EIA since January 1994.

in February 2015 by the growth rate of Norwegian production. Panel (e) of Figure 2 plots the actual and counterfactual production levels during 1994:1–2018:12 and illustrates that, due to the ongoing civil war, Yemeni production did not recover until the end of 2018.[16]

4.6 Counterfactual for Canada

On May 1 of 2016, a wildfire was spotted near Fort McMurray, causing the largest evacuation in Alberta's history. Sweeping through the community, the fire destroyed approximately 2,400 homes with another 2,000 declared unsafe due to contamination. 590,000 hectares were burnt, before the fire was under control in July 2016. With an estimated loss of CAD 10 billion, the wildfire represents the most costly natural disaster in Canadian history. As the fire threatened to spread to production facilities north of Fort McMurray, oil sands production in the area dropped by 40% due to preventive shutdowns and the evacuation of personal.

Canadian crude oil production already decreased by 9% in the month prior to the wildfire, from 3,767 tbpd in March to 3,429 tbpd in April, possibly as a concession to the annual wildfire season. When the fire started, production dropped by another 18% to 2,811 tbpd in May. After the fire, production swiftly recovered to 3,657 tbpd in June and 3,855 tbpd in August, thus exceeding pre-fire levels. Panel (f) of Figure 2 plots the counterfactual against the actual production level during our sample period.

5 Exogenous Oil Supply Shocks

To extend the monthly series of exogenous oil supply shocks in Kilian (2008), we compute the effect of each event discussed in Sections 3 and 4 as the difference between actual and counterfactual production for a given country and episode. Accordingly, it can be negative, if actual production falls short of, or positive, if actual production exceeds the counterfactual. We then cumulate the effects across countries and divide the resulting series by *world* crude oil production at each point in time. Given that all EIA production data are in thousand barrels per day, adding up individual effects is straightforward, while expressing the series as a fraction of world production helps accounting for trends in the data.

Figure A.1 in the online appendix plots the resulting monthly series of exogenous oil supply shortfalls and illustrates that the majority of events had a negative impact on production. Figure 3 plots first differences of this series and extends thus Figure 7 in Kilian (2008) both in the time and cross-sectional dimension, as we consider exogenous events affecting oil production in OPEC and non-OPEC countries.

[16] Note that monthly data on Yemeni crude oil production is only available from the EIA since January 1994.

6 Comparison with VAR-Based Oil Supply Shocks

Our shock series in Figure 3 is based on crude oil production data and extraneous information about the timing and duration of arguably exogenous events. While this requires the construction of country- and time-specific benchmark groups, we do not impose the kind of identifying assumptions inherent in multivariate time series models. Therefore the methodology in Kilian (2008) is fundamentally different from recent VAR-based estimates of oil supply shocks such as Kilian (2009), Kilian and Murphy (2014), Baumeister and Hamilton (2019a), for example, and more similar in spirit to Caldara et al. (2019). In this section, we compare our extended time series with two VAR-based estimates of oil supply shocks.

Figure 4 plots our exogenous oil supply shocks against the time series of oil supply shocks from Kilian and Murphy (2014) and Baumeister and Hamilton (2019a), which are identified by a combination of sign restrictions and elasticity bounds and a combination of sign restrictions and Bayesian prior information about oil supply and demand elasticities, respectively.[17] Due to the volatility of the VAR-based estimates at the monthly frequency in Panel A, we also compare quarterly and annual averages of all three shock series in Panels B and C, respectively.

While the timing and direction of alternative oil supply shocks coincides for major exogenous production shortfalls, notably during the Iranian Revolution, the Iran-Iraq War, the Gulf War, and the Iraq War, there seems to be less "action" in our series on average over the sample period. When aggregating the monthly shock series to quarterly or annual frequency, the comovement between them is far from obvious.

This is also reflected by the contemporaneous correlations of the three shock series over the common sample period in Table 1.[18] Panel A illustrates that the correlation of our exogenous oil supply shocks with the VAR-based estimates is modest, albeit highly statistically significant, and somewhat more pronounced for the Baumeister and Hamilton (2019a) shocks. For quarterly averages of the monthly time series, the correlation with both VAR-based estimates decreases to about 0.15 while it remains statistically significant at the 5% level. Considering the annual averages in Panel C, the correlation of our exogenous oil supply shock with the Baumeister and Hamilton (2019a) shocks increases to 0.38, while that with the Kilian and Murphy (2014) shocks falls to 0.10 and becomes statistically insignificant at conventional levels.

[17] The Kilian and Murphy (2014) shocks are based on the admissible model with an oil demand elasticity *in use* closest to the sample median using the authors' original code, while extending the sample period to 1973:2–2018:12. The Baumeister and Hamilton (2019a) shocks for 1975:2–2018:7 are made available by the authors here: `https://sites.google.com/site/cjsbaumeister/BH2_supply_shocks.xlsx?attredirects=0&d=1`.

[18] The use of 24 lags in Kilian and Murphy (2014) and 12 lags in Baumeister and Hamilton (2019a) implies that VAR-based estimates of oil supply shocks are only available starting in 1975:2.

7 Conclusion

In this note, we adopt the methodology in Kilian (2008) to construct an extended time series of exogenous oil supply shocks. This is based on publicly available crude oil production data, the identification of arguably exogenous events in oil-producing countries, and the selection of a country- and time-specific benchmark group, which facilitates the construction of counterfactual production levels. The purpose of this exercise is to provide an alternative measure of oil supply shocks that does not rely on the kind of identifying assumptions inherent in structural VAR models of the global oil market, which are hotly debated in the current literature.

Despite a fundamentally different approach, our extended time series of exogenous oil supply shocks displays statistically significant, albeit moderate contemporaneous correlations with the VAR-based shock series in Kilian and Murphy (2014) and Baumeister and Hamilton (2019a) at the monthly frequency as well as for quarterly and annual averages, and may therefore be used as an external instrument in structural VAR models. Both our baseline series featuring OPEC and non-OPEC events as well as a version with only OPEC events can be downloaded from the corresponding author's webpage.

We deliberately refrain from considering the effects of the U.S. shale oil boom and the Canada tar sands boom. While both are at least partly due to technological advances in unconventional crude oil production, their recent expansion must be considered in the context of the run-up of oil prices prior to the financial crisis. In fact, some unconventional oil producers may fail to operate profitably at current spot-market prices (Kilian, 2016, 2017). Note also that positive oil supply shocks do not feature prominently in the VAR-based estimates in Figure 4 either, except during 2014 and 2015. For this reasons, the task of constructing a valid counterfactual for the U.S. shale oil boom and the Canada tar sands boom is left for future research.

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Table 1: Comparison of Exogenous Oil Supply Shocks with VAR-Based Estimates

	A. Monthly shocks		B. Quarterly averages		C. Annual averages	
	KM shocks	BH shocks	KM shocks	BH shocks	KM shocks	BH shocks
EOS shocks	0.173***	0.223***	0.151**	0.148**	0.102	0.381**
KM shocks		0.664***		0.630***		0.484***

Note: Contemporaneous correlation of exogenous oil supply (EOS) shocks with VAR-based estimates of oil supply shocks from Kilian and Murphy (2014) (KM) and Baumeister and Hamilton (2019a) (BH) for 1975:2–2018:12. ***/**/* indicates statistical significance at the 1/5/10% level.

Figure 1: Actual and Counterfactual Crude Oil Production Levels for OPEC Countries

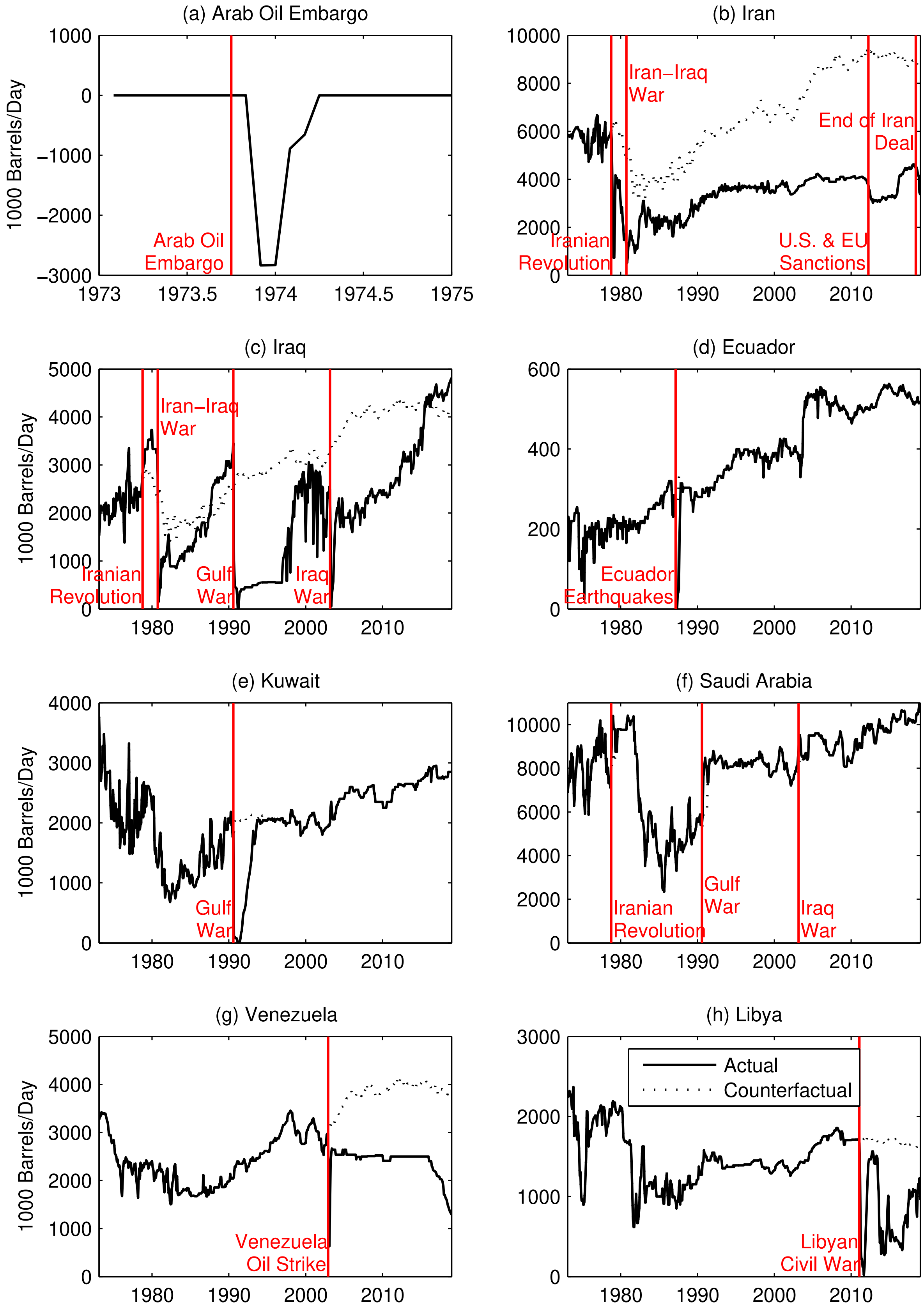


Figure 2: Actual and Counterfactual Crude Oil Production Levels for non-OPEC Countries

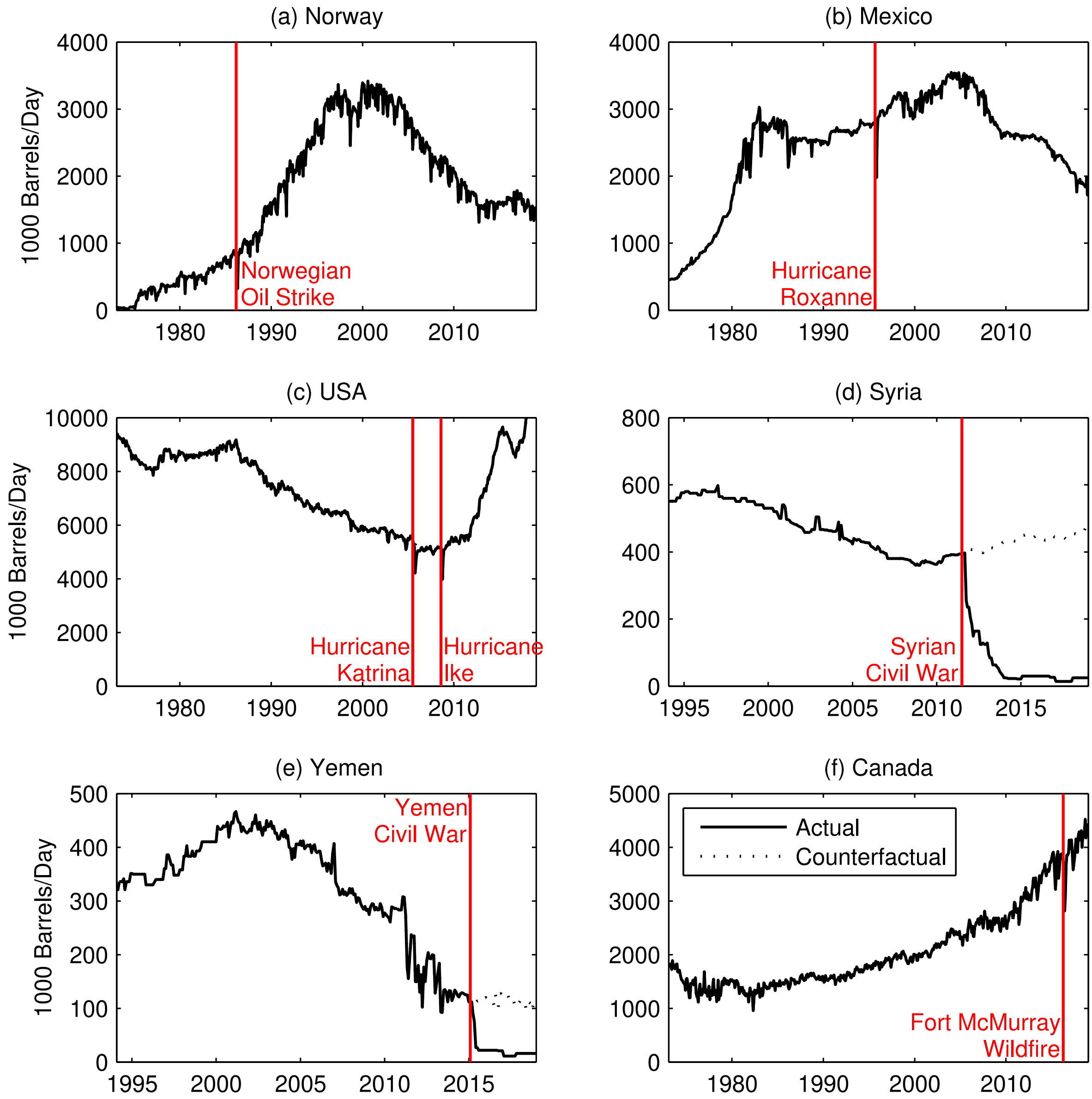
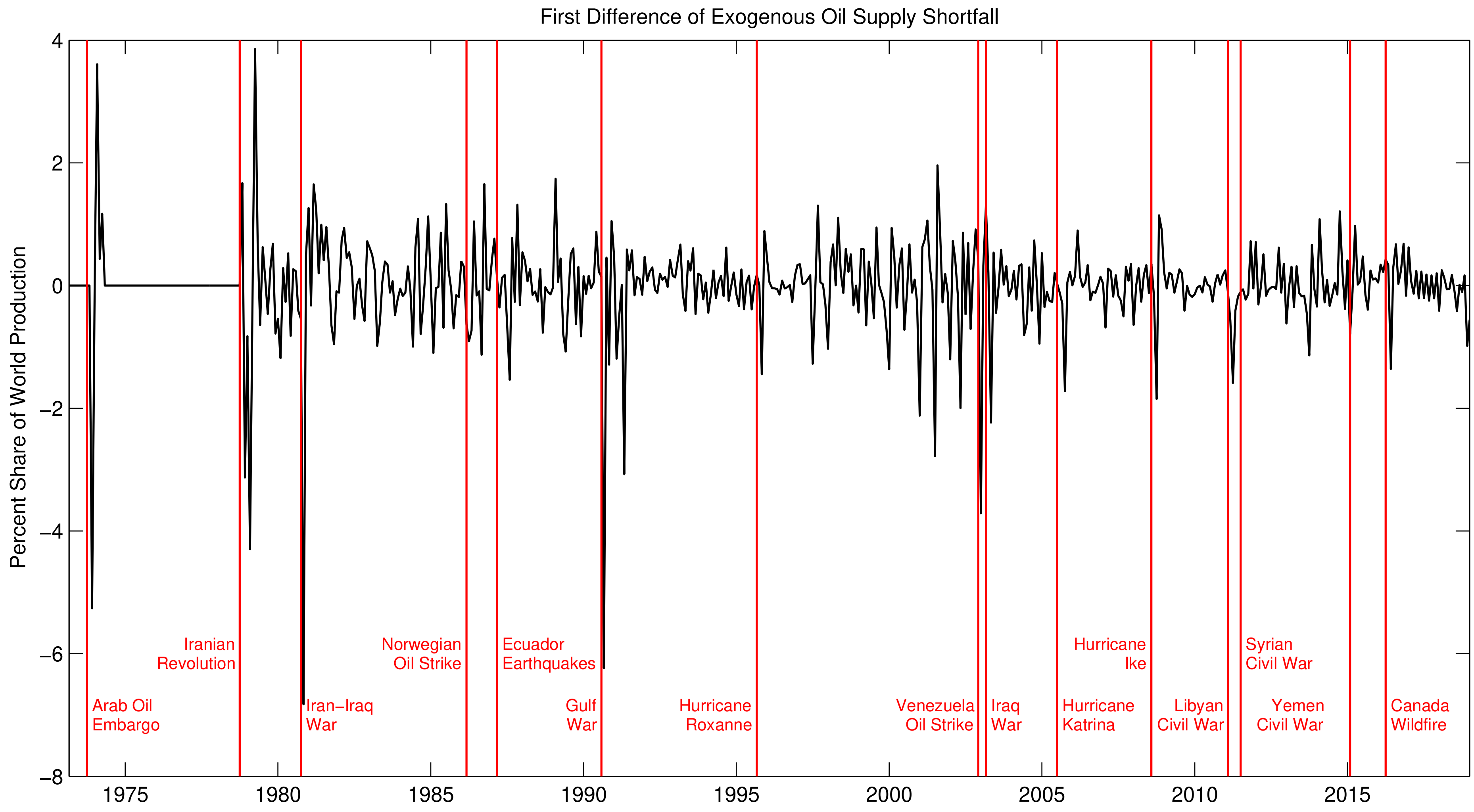
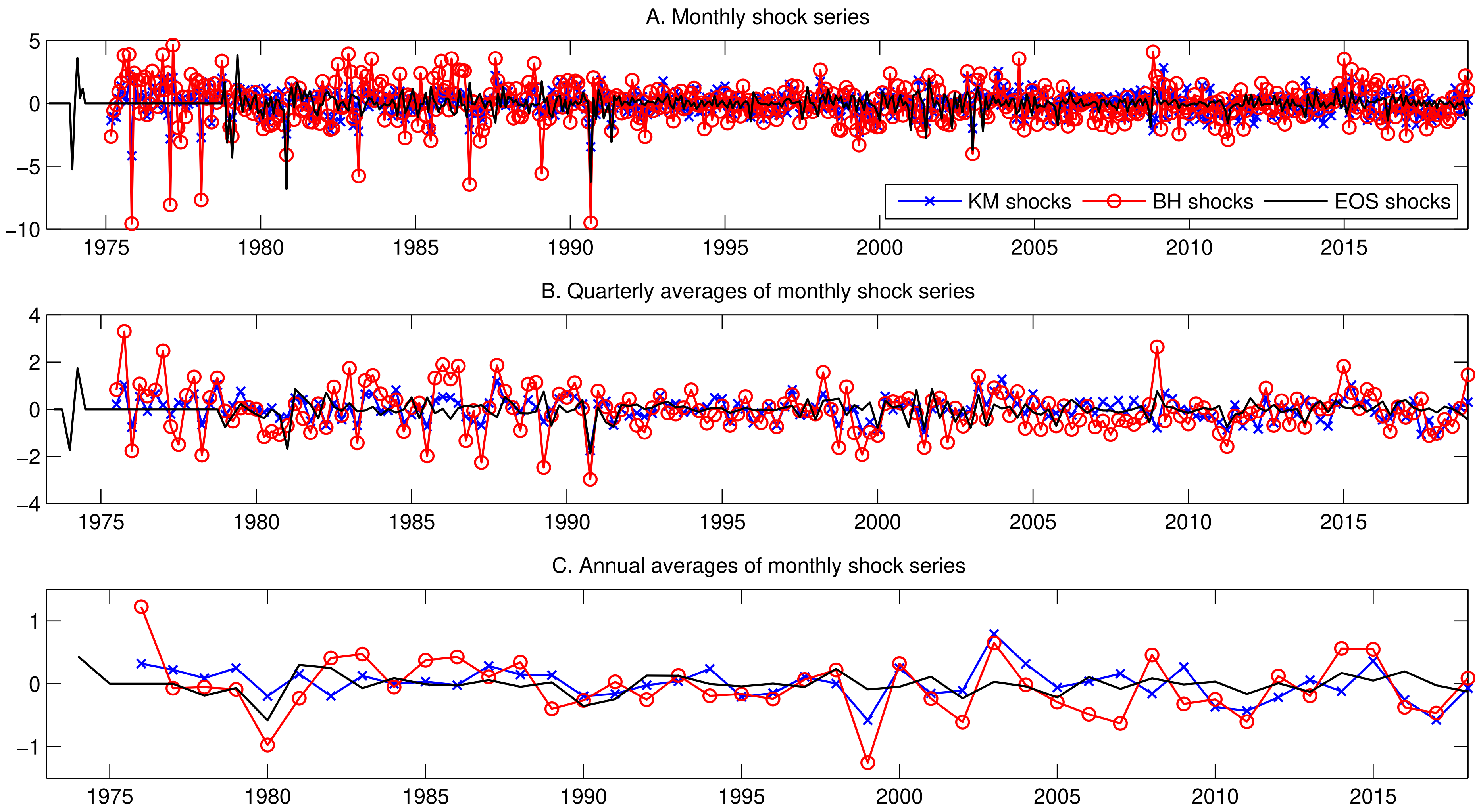


Figure 3: Exogenous Oil Supply Shocks for OPEC and Non-OPEC Countries



Note: First difference of cumulative oil production shortfalls relative to country-specific counterfactuals as a fraction of world crude oil production.

Figure 4: Comparison of Exogenous Oil Supply Shocks with VAR-Based Estimates



Notes: Comparison of exogenous oil supply (EOS) shocks with VAR-based estimates of oil supply shocks from Kilian and Murphy (2014) (KM) and Baumeister and Hamilton (2019a) (BH). EOS shocks as a fraction of world crude oil production. KM and BH shocks normalized by the authors.

Online Appendix

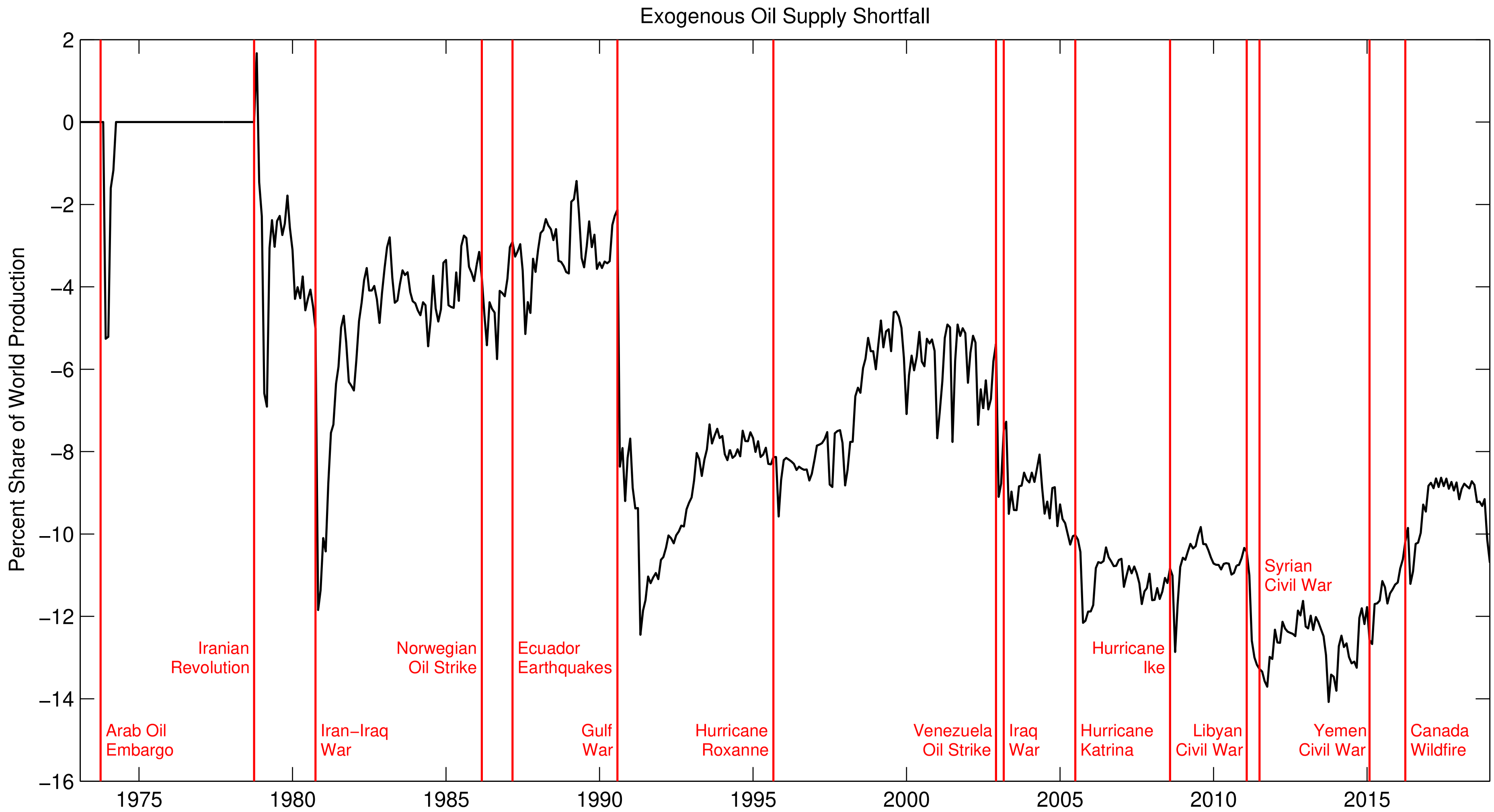
Table A.1: Composition of Country-Specific Benchmark Groups for OPEC Events

Country	Time Period	Composition of Benchmark Group
Iran	1978:10–1987:2	OPEC – Iran – Iraq – Saudi Arabia
	1987:3–1987:9	OPEC – Iran – Iraq – Saudi Arabia – Ecuador
	1987:10–1990:7	OPEC – Iran – Iraq – Saudi Arabia
	1990:8–1994:7	OPEC – Iran – Iraq – Saudi Arabia – Kuwait
	1994:8–2002:11	OPEC – Iran – Iraq – Saudi Arabia
	2002:12–2011:1	OPEC – Iran – Iraq – Saudi Arabia – Venezuela
	2011:2–2018:12	OPEC – Iran – Iraq – Saudi Arabia – Venezuela – Libya
Iraq	1978:10–1987:2	OPEC – Iraq – Iran – Saudi Arabia
	1987:3–1987:9	OPEC – Iraq – Iran – Saudi Arabia – Ecuador
	1987:10–1990:7	OPEC – Iraq – Iran – Saudi Arabia
	1990:8–1994:7	OPEC – Iraq – Iran – Saudi Arabia – Kuwait
	1994:8–2002:11	OPEC – Iraq – Iran – Saudi Arabia
	2002:12–2011:1	OPEC – Iraq – Iran – Saudi Arabia – Venezuela
	2011:2–2018:12	OPEC – Iraq – Iran – Saudi Arabia – Venezuela – Libya
Ecuador	1987:3–1987:9	OPEC – Ecuador – Iran – Iraq – Saudi Arabia
Kuwait	1990:8–1994:7	OPEC – Kuwait – Iran – Iraq – Saudi Arabia
Saudi Arabia	1978:10–1979:4	OPEC – Saudi Arabia – Iran – Iraq
	1990:8–1991:3	OPEC – Saudi Arabia – Iran – Iraq – Kuwait
	2002:7–2002:11	OPEC – Saudi Arabia – Iran – Iraq
	2002:12–2003:10	OPEC – Saudi Arabia – Iran – Iraq – Venezuela
Venezuela	2002:12–2011:1	OPEC – Venezuela – Iran – Iraq – Saudi Arabia
	2011:2–2018:12	OPEC – Venezuela – Iran – Iraq – Saudi Arabia – Libya
Libya	2011:2–2018:12	OPEC – Libya – Iran – Iraq – Saudi Arabia – Venezuela

Table A.2: Composition of Country-Specific Benchmark Groups for Non-OPEC Events

Country	Time Period	Benchmark Composition
Norway	1986:4–1986:6	Non-OPEC – Norway
Mexico	1995:10–1995:11	Non-OPEC – Mexico
USA	2005:8–2006:1	Non-OPEC – USA
	2008:9–2008:11	Non-OPEC – USA
Syria	2011:6–2015:2	Non-OPEC – Syria
	2015:3–2016:3	Non-OPEC – Syria – Yemen
	2016:4–2016:7	Non-OPEC – Syria – Yemen – Canada
	2016:8–2018:12	Non-OPEC – Syria – Yemen
Yemen	2015:3–2018:12	Norway
Canada	2016:4–2016:7	Non-OPEC – Canada – Syria – Yemen

Figure A.1: Exogenous Oil Production Shortfall for OPEC and Non-OPEC Countries



Note: Cumulative exogenous oil production shortfalls relative to country-specific counterfactuals as a fraction of world crude oil production.