QUEEN'S MANAGEMENT SCHOOL
RESEARCH PAPER SERIES

Reviewing the Oil Price–GDP Growth Relationship: A Replication Study

Lanouar Charfeddine – Qatar University
Tony Klein – Queen's University Belfast
Thomas Walther – University of St. Gallen

7 August 2019

https://ssrn.com/abstract=3432407

Queen's University Belfast
Queen's Management School
https://www.qub.ac.uk/mgt/

Queen's Management School Research Paper Series
http://ssrn.com/link/Queens-Management-BSR.html

Reviewing the Oil Price–GDP Growth Relationship: A Replication Study[☆]

Lanouar Charfeddine[a], Tony Klein[b,*], Thomas Walther[c,d]

[a]*College of Business and Economics, Qatar University, Qatar*
[b]*Queen's Management School, Queen's University Belfast, UK*
[c]*Institute for Operations Research and Computational Finance, University of St. Gallen, Switzerland*
[d]*Faculty of Business and Economics, Technische Universität Dresden, Germany*

Abstract

This paper presents a thorough replication of Hamilton (2003) which in turn replicates and extends the findings of four seminal papers regarding the oil price–GDP growth relationship. Firstly, we replicate the empirical results obtained with the oil price measures of Hamilton (1983), Mork (1989), Lee et al. (1995), Hamilton (1996), and Hamilton (2003) by using an identical data set of real and nominal oil prices. Secondly, we extend the data sets to 2016Q4 and apply the same methodology. We find that for more recent data, the explanatory power of the proposed oil price measures on GDP growth rates is dwindling. This is an indication that linear autoregressive models do not capture the link sufficiently anymore and more encompassing models are needed.

Keywords: Oil prices, GDP growth, Asymmetry, Nonlinearity

JEL classification: C24; E32; F43; Q43

1. Introduction

Since the publication of the influential paper of Hamilton (1983), the oil shock–macroeconomy relationship has received a particular attention from researchers, policymakers, and international institutions alike. (Hamilton, 1983, 1989, 1996, 2003, 2011b, 2017, Jimenez-Rodriguez & Sanchez, 2005, Kilian, 2009, Kilian & Vigfusson, 2011a,b, Baumeister & Kilian, 2012, 2016a,b). This increase of interest in this particular topic is

motivated by the importance of this commodity as strategic intermediary input during the production process of almost all goods, and as a final good for all economic sectors (transport, agriculture, and service). However, despite the large number of studies examining the impact of oil price changes on the macroeconomy, this nexus continues to spark intense debate. For instance, while Hamilton's studies (Hamilton, 2003, 2011b) show that oil price shocks still have a significant impact on the U.S. real GDP growth, other research suggests that with recent data the negative relationship between oil prices changes and the U.S. economy is still unclear or not present at all (Kilian & Vigfusson, 2011a).

This paper replicates and extends the findings of Hamilton (2003) who, in turn, reviews and replicates the findings of seminal studies focusing on the oil price–GDP relationship (Hamilton, 1983, Mork, 1989, Lee et al., 1995, Hamilton, 1996, 2003). We replicate these empirical results on their respective data range. Then, we update the data to 2016Q4 and re-estimate all models for nominal and real oil prices. The results suggest that all implemented measures explain the relationship insufficiently with recent data.

The five papers replicated in this study are among the most cited in the academic energy economics literature (cited more 10 000 times in total) and are widely used in public policy papers (Lanouar add references here). These five selected papers investigate the oil price–GDP link and each of them proposes a new measure of oil price changes to understand their impact on the macroeconomy. Table 1 gives an overview of recession and factors related to crude oil as a contributing factor. Fig. 1 visualizes recessions and the preceeding oil price movements.

The first paper we focus on is Hamilton (1983) who examines the oil–GDP link motivated by the observation that seven of the eight postwar recessions in the United States have been preceded by a dramatic increase in oil prices. The results of Hamilton (1983) demonstrate that oil prices have a negative and significant impact on gross national product (GNP) for the periods of 1949Q2 to 1972Q4 and 1973Q1 to 1980Q3. Hamilton's results show that the coefficients associated to the first period ($T = 96$ observations) are greater (in absolute terms) than those of the second period ($T = 31$ observations).

The second paper which we take into consideration regarding the derivation of a new

Table 1: Oil price episodes, principal factors, and their corresponding U.S. economic recessions following Hamilton (2011a). A more detailed history can also be found in Barsky & Kilian (2004).

Oil Price Episode	Principal factors	NBER recession
1947–1948	Post-War demand boom for energy and decreases of oil production due to shorter work week create shortages in some U.S. states.	11/1948–10/1949
1952–1953	Disruption of oil supply due to Iranian nationalization of the oil industry in summer '51; decrease of world supply by 19mb/month due to boycott of Iranian oil; disruption in US supply due to oil refinery workers strikes.	07/1953–05/1954
1956–1957	Suez Canal is nationalized by Egyptian leaders in July '56 pulling 10.1% of world's oil production from the markets.	08/1957–04/1958
No oil price increase that corresponds to the U.S. economic recession of 1960–1961.		04/1960–02/1961
1969	Long-lasting decline in U.S. reserves due to strike by east coast fuel oil deliverers in December '68; nationwide strike in the oil, chemical, and atomic workers union January '69; oil price increase by 7%	12/1969–11/1970
1970	Trans-Arabian pipeline rupture in May '70 in Syria leads to 8% increase in nominal oil price.	
1973–1974	The Arab members of the OPEC announce an embargo on oil export to some countries supporting Israel leading to a 7.5% shortfall of total world production.	11/1973–03/1975
1978–1979	Iranian revolution; due to the large public protests in '78 and the strikes in the oil sector in the fall of '78 induce a decrease in world's oil production of 7%.	01/1980–07/1980
1980–1981	The Iran-Iraq decreases the world's oil supply by 6%.	07/1981–11/1982
1990–1991	First Gulf War; Iraq invades Kuwait in August '90; as a consequence, oil production plummets by 6.9% during this period	07/1990–03/1991
1997–1998	The east Asian crisis decreases the oil demand and consequently oil prices diminish to $12 per barrel.	03/2001–11/2001
1999–2000	Asian demand for oil recovers rapidly after the '97 crisis; price increases by 38% between November '99 and November '00.	
2007–2008	Oil demand increases by 5mb/d between '03 and '05; oil price increases from $55 per barrel in 2005 to more than $140.	12/2007–06/2009

oil price measure is Mork (1989) who proposes measures that account for increases and decreases of oil prices separately. Mork (1989) builds his approach on the observation that mostly oil price increases are present in data of previous studies. Mork (1989) examines whether the findings of Hamilton (1983) continue to hold if more recent data are used, including a period of an oil price collapse and other significant decreases. In line with the findings of Hamilton (1983), Mork (1989) finds evidence that oil price increases have a negative and significant impact on the U.S real GNP. However, Mork's results show that oil prices decreases are found to have little, if not zero, correlation to GNP growth. Overall, Mork (1989) provides strong evidence for the asymmetric impact of oil prices on the macroeconomy and finds that accounting for this asymmetric impact might solve problems of parameter instability (Mork, 1989, Tab. 1 and 2, pp. 742-743). Comparing the results of Hamilton (1983) to Mork (1989), we observe that the impact of oil prices

on the U.S. real GNP is decreasing for more recent data and larger sample size.[1]

The third oil price measure which is applied in Hamilton (2003) and replicated in this paper is derived in Lee et al. (1995) who introduce a normalized positive and negative oil price measure. The idea behind these measures is that sudden oil price changes in less volatile times have a greater impact than in times of erratic oil prices. Using similar model frameworks as in Hamilton (1983) and Mork (1989), Lee et al. (1995) find that only normalized positive oil prices are a contributing factor to economic growth in the U.S.

The last two measures which play an important role in this replication are those of Hamilton (1996) and Hamilton (2003). The former paper introduces the one-year net oil prices increases measure while the latter updates this measure to span three years of oil price changes. Hamilton (1996) bases theses measures on the phenomenon that almost all oil prices decreases after 1986 are followed immediately by oil prices increases indicating the former are corrections of the latter or inversely. Empirically, this one-year net oil price increases measure is negatively and significantly related to the U.S. real GDP growth for the full sample of 1948Q1-1994Q2 and the sub-sample before the first oil prices shock of 1948Q1-1973Q3. For the sub-sample 1973Q4-1994Q2, only the third coefficient associated to the net oil price increases is negative and significant at 5% level. The three-years net oil prices measure of Hamilton (2003) is proposed after the observation that the oil price increase of 1999, which qualifies as a one-year net oil price increase according to Hamilton (1996) measure, is not followed by any decreases in the real economic growth in the year 2000. The economic explanation of Hamilton (2003) is that if the net oil price increases of 1999 does not cause consumers and firms to adjust their spending plans within one year, then the measure should be extended to more quarters which yields the three-years net oil price measure. Hamilton (2003) finds that this measure is more appropriate to capture the effect of oil prices increases on the U.S. real GDP as it now also explains the recession of 2001. Using a sample covering the period from 1949Q2 to 2001Q3, for a

---

[1]As an example, the third and fourth lags coefficients associated to symmetric oil prices, are -0.170 and -0.177 for the period 1949Q2 - 1972Q4 (Table 5, pp. 244 Hamilton (1983)), respectively compared to a lower values of -0.017 and -0.029 for the period 1949Q1 - 1986Q1, respectively.

4

total of $T = 210$ observations, the empirical findings of Hamilton (2003) show that the three-years net oil price has a negative and significant impact on the economic activity proxied by the real economic growth.
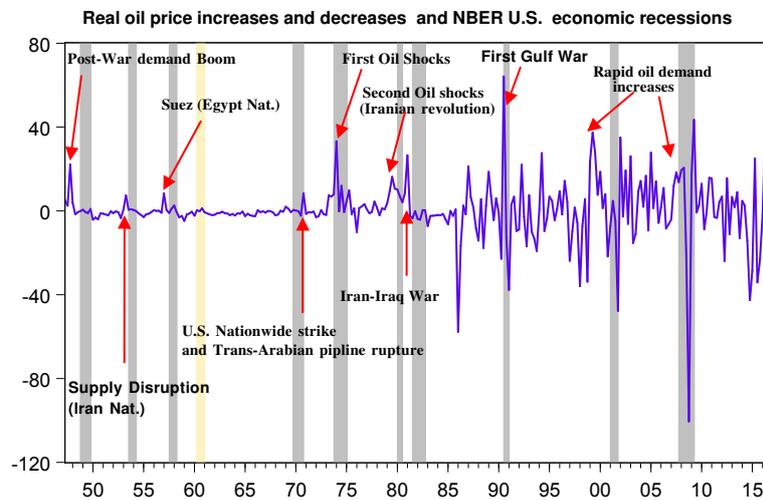

Figure 1: Crude oil price increases and decreases (solid lines) and U.S. recessions (shaded areas). Source: Authors calculations and NBER data.

We review the findings of Hamilton (2003) and replicate the estimations carried out with the oil price measures defined in Hamilton (1983), Mork (1989), Lee et al. (1995), Hamilton (1996), and Hamilton (2003). On an identical observation period, we are able to confirm parameter estimates and obtain values close to those reported in Hamilton (2003). Minor differences might be due different data sets and a more recent deflator. After the successful replication, we extend the data set to 2016Q4 and repeat the estimations. We find that within the proposed model framework of Hamilton (2003), oil price changes— measured with five different transformations—loose predictive power in explaining GDP growth rates. Further analysis shows that parameters are unstable over the whole period and several breakpoints exist. Recent research also suggests that the ARX(p) model might be mispecified or not encompassing enough for this particular economic link. This motivates to introduce mixed data sampling in a regime switching setting to this framework in Charfeddine et al. (2018).

The remainder of this article is structured as follows. The different oil price measures and the ARX(p) framework are introduced in Section 2. Section 3 describes our data sets

5

and gives an overview of preliminary tests thereof. In Section 4, we present the results of the replication study as well as of an extension of these findings with data up to 2016Q4. Section 5 concludes this replication article.

2. Empirical Methodology

2.1. Oil Price Measures

In order to replicate the above mentioned studies, we define the utilized oil price measures in what follows. Let O_t denote oil price changes defined by the following log-difference

$$O_t = 100 * \left(\log p_t - \log p_{t-1} \right),$$

where p_t denotes an oil price at time t in quarterly resolution. This linear, symmetric measure O_t is applied in Hamilton (1983). Based on the assumption that oil price changes have an asymmetric effect on GDP growth rates, nonlinear—or asymmetric—oil price measures are proposed in subsequent research. We are replicating four of these studies and use the oil price measures introduced in Mork (1989), Lee et al. (1995), Hamilton (1996), and Hamilton (2003). We note that Hamilton (1983, 1996, 2003) make use of nominal oil price changes (denoted by O_t^{nom}), whereas Mork (1989) and Lee et al. (1995) utilize real oil price changes (denoted by O_t^{real}).

A final overview of all implemented oil price measures in this replication study is given in Table 2.

2.1.1. Mork's asymmetric approach

Mork (1989) is a direct response to Hamilton (1983). This response applies a refined modelling framework, motivates using refiners acquisition cost (RAC) after 1974Q2 instead of the producer price index (PPI), and tests oil price increases and decreases, whereas no significant effects of the latter are identified. Mork (1989) justifies testing decreases in addition to increases is by highlighting that the data set of Hamilton (2003) is mainly characterized by price increases, leaving decreases untestable. Mork (1989, p. 740) notes that *"[Hamilton's] study pertained to a period in which all the large oil price movements*

were upward, and thus it left unanswered the question whether the correlation persists in periods of price decline. Moreover, the price variable he used was somewhat distorted by price controls in the 1970s." Hence, Mork (1989) updates the data set to 1988Q2 and corrects the oil price measure for several controls. The asymmetric measure proposed by Mork (1989) for price increases is given by

$$O_{\text{Mork},t}^{+} = \max\left(O_t^{\text{real}}, 0\right),$$

and analogously for oil price decreases, defined as

$$O_{\text{Mork},t}^{-} = \min\left(O_t^{\text{real}}, 0\right),$$

where O_t^{real} denotes the real oil price changes of the PPI and RAC[2] and $O_{\text{Mork},t}^{+}$ and $O_{\text{Mork},t}^{-}$ are the positive and negative censored parts of the real oil price changes, respectively.

2.1.2. Volatility-Scaled oil prices of Lee et al.

Lee et al. (1995) revisits Hamilton (1983) from a modeling approach but propose a scaling of oil prices which takes into consideration sudden shocks measured by price volatility. Their motivation stems from the assumption that oil price shocks have a varying impact on GNP growth rates, depending on how *surprising* the timing of the shock is. It is assumed that shocks in stable price periods have larger impact on the macroeconomy than during periods of volatile prices where this specific shock could be considered a reaction to a previous shock. Lee et al. (1995) then argue that adjusting oil price changes by its volatility accounts for these effects as well as the idea of an outbreak of its *prior pattern*. This concept has already been applied in Davies (1987).

Formally, the measure of Lee et al. (1995) builds on the estimation of an AR(p)-GARCH(1,1) model of oil price changes. Then, both oil price increases and decreases are divided by their estimated GARCH volatility to obtain the measures. The AR(p)-

---

[2]Mork (1989) constructs the price set as follows. From 1949Q1 to 1971Q2, the rate of change of PPI is used. From 1971Q3 to 1974Q1, the rate of PPI change is multiplied by the annual log RAC change in order to counter the price control measures in the 70s, and from 1974Q2, the change rate of the RAC is used. See Mork (1989, p. 741) for more detail.

GARCH(1,1) reads

$$O_t^{\text{real}} = \mu + \sum_{i=1}^{p} \alpha_i O_{t-i}^{\text{real}} + e_t,$$

where μ is an unconditional mean, the AR order lag is set to $p = 4$ following Mork (1989), and α_i are the parameters of the autoregressive part. The disturbance term e_t is modeled as GARCH(1,1) process with variance h_t which is defined as

$$e_t = \sqrt{h_t}\zeta_t,$$

$$h_t = \gamma_0 + \gamma_1 e_{t-1}^2 + \gamma_2 h_{t-1},$$

where γ_0, γ_1, and γ_2 refer to GARCH parameters and $\zeta_t \sim \mathcal{N}(0,1)$ i.i.d. for all $t = 1,\ldots,n$. The standardized residual $e_t^* = e_t/\sqrt{h_t}$ is then censored and we obtain the positive and negative oil price measures of Lee et al. (1995) by

$$O_{\text{LNR},t}^+ = \max(0, e_t^*), \quad \text{and}$$

$$O_{\text{LNR},t}^- = \min(0, e_t^*).$$

2.1.3. Hamilton's adjusted measures

Hamilton (1996) proposes a new measure that contrasts oil price increases to decreases in the following four quarters. Hamilton (1996, p. 216) notes "*if one wants a measure of how unsettling an increase in the price of oil is likely to be for the spending decisions of consumers and firms, it seems more appropriate to compare the current price of oil with where it has been over the previous year.*" As a consequence, Hamilton (1996) defines the new measure as difference of the current increase of *nominal* oil prices and the maximum of increases during the previous four quarters. This measure is formally defined as

$$O_{\text{Ham1},t}^+ = \max\left\{0, O_t - \max\left\{O_{t-1}, O_{t-2}, O_{t-3}, O_{t-4}\right\}\right\}. \tag{1}$$

In this study, we additionally define a measure for price decreases which has not been

applied in the original article. The decrease measure reads

$$O_{\text{Ham1},t}^- = \min\left\{0, O_t - \min\left\{O_{t-1}, O_{t-2}, O_{t-3}, O_{t-4}\right\}\right\}.$$

This negative measure is motivated from later studies such as Kilian & Vigfusson (2011b).

While the measure outlined in Hamilton (1996) spans four quarters and hence, assumes that price corrections are happening within a year, the Asian Crisis 1997-1998 had only little immediate impact on economic growth in the U.S. although oil prices drop to roughly $12 per barrel. The recession, identified by NBER (see also Table 1), caused by the wake of this crisis hit the U.S. in 2001, around three years later. Hamilton (2003) suggests to extend the look-back period of the Hamilton (1996) measure, $O_{\text{Ham1},t}^+$, to three years or 12 quarters to account for longer reaction times within a three year window. This adjusted measure is denoted $O_{\text{Ham3},t}^+$ and defined analogously as

$$O_{\text{Ham3},t}^+ = \max\{0, O_t - \max\{O_{t-1}, O_{t-2}, \ldots, O_{t-12}\}\},$$

which now spans twelve quarters. We calculate the net decrease as

$$O_{\text{Ham3},t}^- = \min\{0, O_t - \min\{O_{t-1}, O_{t-2}, \ldots, O_{t-12}\}\},$$

which is—again—not tested in the original article.

Table 2 summarizes the oil price measures implemented in Hamilton (2003) and replicated in this study.

Table 2: Proposed oil price measures in their original definition.

Hamilton (1983)	$O_t = 100 * (\log p_t - \log p_{t-1})$
Mork (1989)	$O_{\text{Mork},t} = \max\left(O_t^{\text{real}}, 0\right)$
Lee et al. (1995)	$O_{\text{LNR},t} = \max(0, e_t^*)$
Hamilton (1996)	$O_{\text{Ham1},t} = \max\left\{0, O_t - \max\left\{O_{t-1}, O_{t-2}, O_{t-3}, O_{t-4}\right\}\right\}$
Hamilton (2003)	$O_{\text{Ham3},t} = \max\{0, O_t - \max\{O_{t-1}, O_{t-2}, \ldots, O_{t-12}\}\}$

2.2. ARX(4) models and an extended version

As this article is motivating Charfeddine et al. (2018), we use an identical base model and follow Hamilton (2003) for the replication exercise in this paper. Hence, we formulate

9

a univariate autoregressive model structure that seeks to explain the impact of oil price shocks as exogenous factor on U.S. GDP growth. Let p denote the autoregressive lags of GDP growth rates and q denotes the lags of quarterly oil price measures defined in Section 2.1. The ARX(p) model reads

$$y_t = \mu_0 + \sum_{i=1}^{p} \phi_i y_{t-i} + \sum_{i=1}^{q} \delta_i O^+_{\{M\},t-i} + u_t, \tag{2}$$

where y_t refers to the rate of real GDP growth and $O^+_{\{M\},t}$ proxies the positively censored oil price changes with $\{M\}$ as a placeholder for the measures defined in the previous subsections, namely $O^+_{\text{Mork},t}$, $O^+_{\text{LNR},t}$, $O^+_{\text{Ham1},t}$, and $O^+_{\text{Ham3},t}$. The parameters ϕ_i are restricted to contain no unit root while $\delta_i \in \mathbb{R}$. Loosening these restrictions has negligible impact on parameter estimates as demonstrated in Charfeddine et al. (2018). The error term u_t is Gaussian i.i.d.

In addition to the replication of Hamilton (2003), we extend Eq. (2) to account for both positive and negative oil price changes. Kilian & Vigfusson (2011a) find that utilizing only positively censored data to explain GDP growth rates leads to an overestimation of their impact on real GDP growth in VAR models. Hence, we extend Eq. (2) with negative measures and obtain a joint model:

$$y_t = \mu_0 + \sum_{i=1}^{p} \phi_i y_{t-i} + \sum_{i=1}^{q} \delta_i O^+_{\{M\},t-i} + \sum_{i=1}^{q} \gamma_i O^-_{\{M\},t-i} + u_t, \tag{3}$$

where p, q, and $O^{+/-}_{\{M\}}$ are defined as above with $\gamma_i \in \mathbb{R}$.

3. Data

The data sets used in this replication article are identical to Charfeddine et al. (2018). For reason of comparison, we use both nominal oil price changes as in Hamilton (1996, 2003), and the real oil price changes as in Mork (1989), Lee et al. (1995), and Kilian & Vigfusson (2011b) for example. However, for the replication of results in Hamilton (2003) we follow the data notation therein. Overall, the data sample covers a period of 70 years of quarterly observations ranging from 1947Q2 to 2016Q4 and provides a total number of

$T = 279$ quarters.

As mentioned in Section 2, we use quarterly data for the ARX(p) model. Quarterly growth rates of chain-weighted real GDP (log changes multiplied with 100) are collected from the U.S. Bureau of Economic Analysis (BEA) and the nominal crude oil producer price index (PPI) is collected from U.S. Bureau of Labor Statistics (BLS). For the ARX(p) models the PPI is seasonally unadjusted and obtained by converting the monthly data to quarterly data by using end-of-period values. Similar to Hamilton (2003), we use changes of the GDP deflator in percentages to convert nominal quarterly changes in oil prices to real price change rates.[3]

3.1. Data sets of the original papers

As each of the five articles proposes a new measure of oil price changes applied on more recent data, end dates of the observation periods differ. Across these papers, oil prices are either obtained from the producer price index (PPI) or refiners acquisition costs (RAC). An overview on the original data sets of Hamilton (1983), Mork (1989), Lee et al. (1995), Hamilton (1996), and Hamilton (2003) is given in Table 3.

Table 3: Overview of the different observation periods, oil price proxies, and macroeconomic measure for Hamilton (2003) and the replicated papers therein.

Publication	Start Date	End Date	Oil Price	Measure
Hamilton (1983)	1948Q2	1980Q3	PPI	GNP
Mork (1989)	1949Q1	1988Q2	PPI & RAC	GNP
Lee et al. (1995)	1949Q1	1992Q2	RAC	GNP
Hamilton (1996)	1948Q1	1994Q2	PPI	GDP
Hamilton (2003)	1949Q2	2001Q3	PPI	GDP

Our data set diverges from the data used in these papers in the following ways.

Firstly, for the replication results presented in Table 4, we use identical end points as in the replications of Hamilton (2003), 2001Q3, whereas the original papers use data up to 1980Q3, 1988Q2, 1992Q2, and 1994Q2, respectively. Secondly, while Hamilton (1983), Mork (1989), and Lee et al. (1995) use the Gross National Product, Hamilton (1996, 2003) and this paper use the Gross Domestic Product. Additionally, since the data provided

---

[3]Data accessed via `bea.gov/national/index.htm#gdp` (GDP) on 02/16/2017 and `fred.stlouisfed. org/series/CPIAUCSL` (CPI) on 07/20/2017, respectively. We selected the seasonally unadjusted oil price time series WPU0561 via `data.bls.gov/cgi-bin/dsrv?wp` on 02/16/2017. The original data, the constructed data, the code, and outputs are are available upon request.

11

by the Bureau of Economic Analysis is seasonally adjusted, our real GDP time series is somewhat different to the one employed by Hamilton (2003). Our sampling of GDP rates is based on the 2012 dollar value, whereas the dollar value of 1996 is used for the data set in Hamilton (2003). Thirdly, these five articles also use different starting dates, i.e. 1948Q2, 1949Q1, 1949Q1, 1948Q1, and 1949Q2. In this replication, we decide to use the longest possible period, i.e. to use 1948Q2 as Hamilton (1983). Thus, we have four lags, starting 1947Q2 for the first period of the ARX(4) model. Lastly, the oil prices used in the five papers are the Producer Price Index (PPI, Hamilton, 1983, 1996, 2003) and the Refiners' Acquisitions Costs (Mork, 1989, Lee et al., 1995). Here, we use the PPI. Following Hamilton (2003), we calculate the real oil price changes by subtracting the GDP deflator. Thus, again the different real GDP dollar basis leads to slightly different oil price measures. In addition, we also extend the data set to 2016Q4 and re-estimate all models on more recent data to compare findings and implications with the original papers.

Given these data sets, the calculation of the oil price measures is straightforward. The difference between these measures, in particular in scaling and filtering, becomes apparent from Fig. 2, which plots the oil price measures from 1947Q2 to 2016Q4. Comparing Hamilton's measures (Hamilton, 1996, 2003) to those of Mork (1989) and Lee et al. (1995) reveals the filtering character of Hamilton's measures which are becoming zero for price movements that are corrections to previous movements as intended.

4. Results

4.1. Replication of previous studies with identical data

Fistly, we repeat the estimations and replicate the results reported in Hamilton (2003).[4] Secondly, for reasons of comparability with earlier studies and replication of their findings, we later repeat all estimations on the full sample from 1947 to 2016. Results are reported in 4.2. Lastly, we assess the impact of omitting the negative parts in the linear ARX(4) model. *In this subsection only, all references to equations refer to the original article of*

---

[4]In particular, results obtained with the models defined in Eq. (1.5), Eq. (1.6), Eq. (1.8), Eq. (3.2), and Eq. (3.8) of Hamilton (2003) are replicated.

12
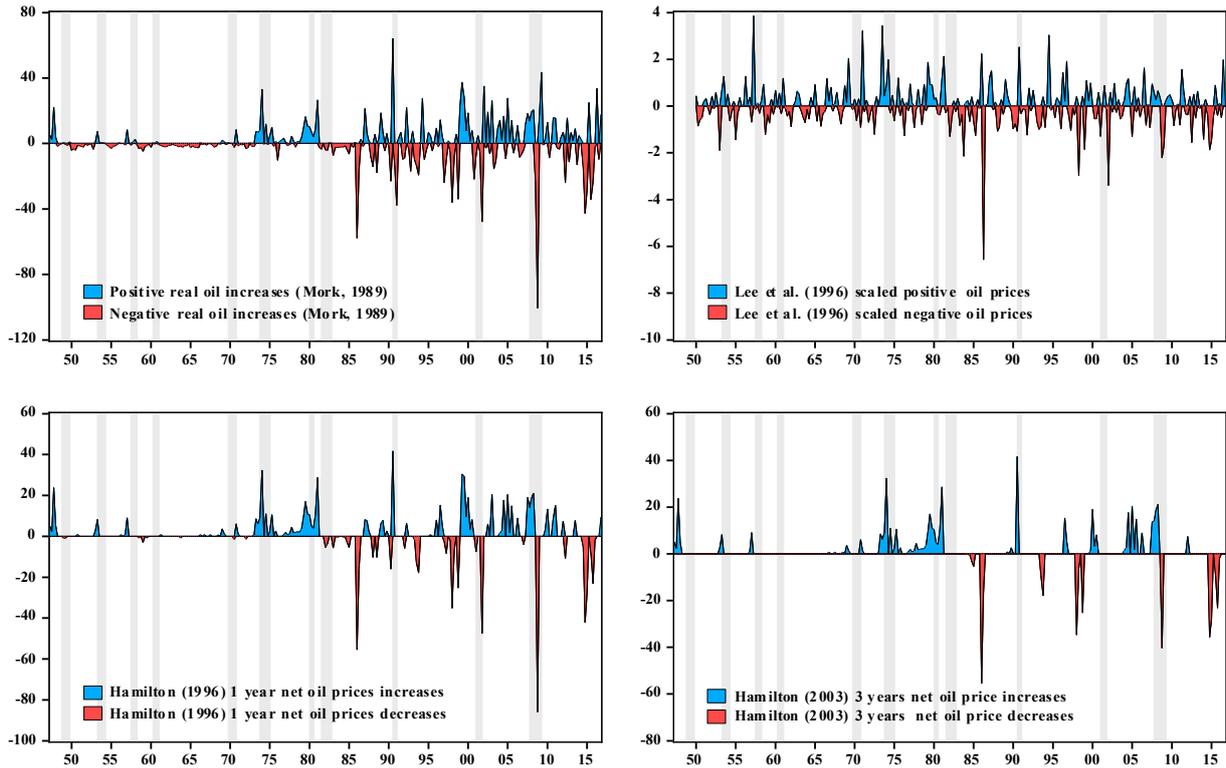
Figure 2: Nonlinear oil price measures from 1947Q2 to 2016Q4 of Mork (1989) *(top left)*, Lee et al. (1995) *(top right)*, Hamilton (1996) *(bottom left)*, and Hamilton (2003) *(bottom right)* applied throughout the paper. Shaded areas indicate the US NBER recession periods.

Hamilton (2003). The model framework is defined in Eq. (2) of this paper. Parameter estimates of the original paper carry an H as superscript while replicated parameters are indicated with r.

4.1.1. Replication: The role of positive oil price changes

The results of the replication with and without negative oil price measures are reported in Table 4. Columns (a) represent the results from Hamilton (2003), while columns labelled with (b) present replication results obtained by applying an identical model framework and data periods as in Hamilton (2003).

The results of estimating Eq. (1.5), the framework of Hamilton (1989) with data from 1949Q2 to 1980Q4, show that only the fourth lag of nominal oil changes has a significant negative impact (coefficients of -0.0647). With the fully estimated model, this means that a 10% increase of nominal oil prices leads to an approx. 1.4% decrease of real GDP growth four quarters later (Hamilton, 2003, p. 369). Comparing columns (a) and (b)

13

shows that we are able to replicate estimates and robust standard errors. For the only significant parameter regarding oil price changes, δ_4, we estimate $\delta_4^{\mathrm{r}} = -0.065$, while Hamilton (2003) reports $\delta_4^{\mathrm{H}} = -0.064$.

This estimation is repeated for data from 1949Q2 to 2001Q3 in Eq. (1.6). Again the only statistically significant lag of oil price changes is δ_4 with an estimated coefficient of $\delta_4^{\mathrm{r}} = -0.0146$ which is close to the reported $\delta_4^{\mathrm{H}} = -0.0160$ in Hamilton (2003). Both coefficients are significant at the 5% level.

Having ruled out the hypothesis of linearity between oil price changes and real GDP growth, we continue our discussion and analysis of the results of the estimation of Eq. (1.8) in column (a) and (b) of Table 4 with the measure of Mork (1989), $O_{\mathrm{Mork},t}^{+}$. Again, the only significant positive oil price change is δ_4 estimated at $\delta_4^{\mathrm{r}} = -0.0213$ which is similar to $\delta_4^{\mathrm{H}} = -0.023$ estimated in Hamilton (2003). Both standard errors are identical at 0.009.

The results of using Hamilton's 1y net oil price increases, $O_{\mathrm{Ham1},t}^{+}$ are presented in column Eq. (3.2), column (a) and (b) in Table 4. Our estimation results in column (b) mirror those reported in Hamilton (2003) in column (a). Yet again, the only significant coefficient is at lag four, estimated at $\delta_4^{\mathrm{r}} = -0.0306$ while $\delta_4^{\mathrm{H}} = -0.031$. Finally, by using the 3y net oil price increases, $O_{\mathrm{Ham3},t}^{+}$, only δ_4 is found to be significant at the 5% level. We estimate the same magnitude ($\delta_4^{\mathrm{r}} = -0.0427$) and level of significance (standard error 0.014) than Hamilton (2003). These results are given in the Eq. (3.8) of Table 4.

In conclusion, we confirm the estimations carried out in Hamilton (2003) with the application of the measures of Hamilton (1983), Mork (1989), Lee et al. (1995), Hamilton (1996), and Hamilton (2003). In the next section, we augment the original framework with negative oil price measures, following an analogous definition as in the five original papers.

4.1.2. Extending the framework: combining positive and negative oil price changes

Kilian & Vigfusson (2011a, p. 427) suggest that if *"both energy price increases and decreases matter for the real GDP but at a different extend, then the censored regressor model is likely to overestimate the effect of an energy price increase."* Following this argument, one may expect that all results reported in side (a) of the columns in Table 5

14

Table 4: Parameter estimates for the replication of the results in Hamilton (2003) using identical periods from 1949Q2 to 1980Q4 for Eq. (1.5), and 1949Q2 to 2001Q3 for the rest of equations. Column (a) refers to the results presented in Hamilton (2003), while column (b) presents our replicated parameter estimations.

	Eq. (1.5)		Eq. (1.6)		Eq. (1.8)		Eq. (3.2)		Eq. (3.6)		Eq. (3.8)	
	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
μ	1.19	1.181	0.72	0.7287	0.88	0.8801	0.89	0.8995	1.05	1.0078	0.98	1.0022
	(0.19)	(0.185)	(0.11)	(0.1143)	(0.13)	(0.1302)	(0.13)	(0.1263)	(0.13)	(0.1291)	(0.13)	(0.1267)
ϕ_1	0.20	0.208	0.28	0.2860	0.26	0.2669	0.25	0.2561	0.20	0.2563	0.22	0.2201
	(0.09)	(0.089)	(0.07)	(0.0688)	(0.07)	(0.0691)	(0.07)	(0.0686)	(0.07)	(0.0662)	(0.07)	(0.0679)
ϕ_2	0.06	0.059	0.13	0.1336	0.12	0.1251	0.11	0.1178	0.12	0.1191	0.10	0.1078
	(0.09)	(0.091)	(0.07)	(0.0717)	(0.07)	(0.0716)	(0.07)	(0.0709)	(0.07)	(0.0674)	(0.07)	(0.0698)
ϕ_3	−0.09	−0.106	−0.06	−0.0784	−0.07	−0.0863	−0.07	−0.0841	−0.09	−0.1483	−0.08	−0.0974
	(0.09)	(0.093)	(0.07)	(0.719)	(0.07)	(0.0716)	(0.07)	(0.0709)	(0.07)	(0.0671)	(0.07)	(0.0696)
ϕ_4	−0.20	−0.181	−0.12	−0.1077	−0.14	−0.1252	−0.14	−0.1230	−0.12	−0.0896	−0.15	−0.1414
	(0.09)	(0.090)	(0.07)	(0.0688)	(0.07)	(0.0686)	(0.07)	(0.0679)	(0.07)	(0.0646)	(0.07)	(0.0667)
δ_1	−0.003	−0.008	−0.003	−0.0042	−0.011	−0.0106	−0.009	−0.0115	−0.18	−0.1394	−0.024	−0.0259
	(0.027)	(0.026)	(0.006)	(0.0063)	(0.009)	(0.0093)	(0.012)	(0.0121)	(0.11)	(0.0974)	(0.014)	(0.0134)
δ_2	−0.030	−0.027	−0.003	−0.0064	−0.005	−0.0079	−0.011	−0.0146	−0.07	0.0204	−0.021	−0.0234
	(0.027)	(0.027)	(0.006)	(0.0063)	(0.009)	(0.0094)	(0.013)	(0.0125)	(0.11)	(0.0963)	(0.014)	(0.0137)
δ_3	−0.036	−0.032	−0.004	−0.0018	−0.007	−0.0047	−0.012	−0.0069	−0.33	−0.2772	−0.018	−0.01404
	(0.027)	(0.027)	(0.006)	(0.0063)	(0.009)	(0.0094)	(0.013)	(0.0125)	(0.11)	(0.0964)	(0.014)	(0.0137)
δ_4	−0.064	−0.065	−0.016	−0.0146	−0.023	−0.0213	−0.031	−0.0306	−0.46	−0.4558	−0.042	−0.0427
	(0.028)	(0.027)	(0.007)	(0.0064)	(0.009)	(0.0094)	(0.012)	(0.0122)	(0.11)	(0.0984)	(0.014)	(0.0137)

Note: For Eq. (3.6), similar to Lee et al. (1995), we estimate a AR(4)-GARCH(1,1) for the period 1949Q2-2001Q3 as in Hamilton (2003), the results show evidence for highly explosive GARCH process. Our results estimation of the AR(4)-GARCH process used by Lee et al. (1995), which is reported in Hamilton (2003) in Eqs. (3), (3.4), and (3.5) reads: (3.3) $O_t = -0.0746 + 0.4069O_{t-1} - 0.0547O_{t-2} + 0.5070O_{t-3} + 0.2861O_{t-4} + e_t$. For Eq. (3.5) we obtain $h_t = 2.0599 + 2.2583e_{t-1}^2 + 0.2156h_{t-1}$.

(which are the results reported in columns (b) in Table 4) are biased by overestimating the impact of price changes on real GDP since all of them are obtained with positively censored price measures only. To assess the impact of omitting the negative (decreases) part, we re-estimate all models of the previous subsection including both positive and negative measures, $O_{\{M\},t}^+$ and $O_{\{M\},t}^-$, as defined in Eq. (3).

The estimation results are reported in side (b) for each column of Table 5. Column (a) are the estimations without negative measures. The estimated coefficients associated with negative (decreasing) oil price measures are all insignificant at the 10% level. Moreover, the results show that the inclusion of the negative oil price measures neither impacts the magnitude of positive oil price measures nor their significance. For example, the estimated coefficient associated to the fourth lag for Eq. (1.8(b)) is −0.0207, whereas for Eq. (1.8(a)), the coefficient is estimated at −0.0213. This holds true for estimates in Eq. (3.2) as well as Eq. (3.8). Moreover, in terms of significance there is no difference between including or omitting the negative measures as all lag coefficients of the oil price proxies keep their level of significance for this data set.

In summary, empirical results show that for the data set 1949Q2 to 2001Q3, we obtain identical results to those in Hamilton (2003). Motivated by the theoretical and empirical findings of Kilian & Vigfusson (2011b), we include both positive and negative oil

Table 5: Parameter estimates for the replication of the results in Hamilton (2003) using identical periods from 1949Q2 to 1980Q4 for Eq. (1.5), and 1949Q2 to 2001Q3 for the rest of equations. Where applicable, column (a) refers to positively censored data only (parameters δ_1 to δ_4), while column (b) presents parameters for models including both positive and negative oil price change proxies (with additional parameters γ_1 to γ_4). p-values are given in parentheses. The information criteria applied throughout this study are the Akaike Information Criterion (AIC), the Schwarz Information Criterion (SIC, also known as Bayesian Information Criterion), and the Hannan-Quinn Criterion (HQC), defined as $AIC = (-2LL + 2k)/T$, $SIC = (-2LL + k\log(T))/T$, $HQC = (-2LL + 2k\log(\log(T)))/T$.

	Eq. (1.5)	Eq. (1.6)	Eq. (1.8)		Eq. (3.2)		Eq. (3.8)	
			(a)	(b)	(a)	(b)	(a)	(b)
μ	1.1808	0.7287	0.8801	0.8752	0.8995	0.9126	1.0022	1.0137
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
ϕ_1	0.2078	0.2860	0.2669	0.2692	0.2568	0.2549	0.2201	0.2209
	(0.0222)	(0.0000)	(0.0002)	(0.0002)	(0.0002)	(0.0003)	(0.0014)	(0.0015)
ϕ_2	0.0593	0.1336	0.1251	0.1205	0.1178	0.1167	0.1078	0.1052
	(0.5166)	(0.0640)	(0.0820)	(0.0971)	(0.0984)	(0.1048)	(0.1238)	(0.1376)
ϕ_3	-0.1046	-0.0784	-0.0863	-0.0817	-0.0841	-0.0843	-0.0974	-0.0954
	(0.2633)	(0.2764)	(0.2298)	(0.2601)	(0.2375)	(0.2404)	(0.1635)	(0.1771)
ϕ_4	-0.1813	-0.1077	-0.1252	-0.1306	-0.1230	-0.1225	-0.1414	-0.1417
	(0.0456)	(0.1192)	(0.0697)	(0.0611)	(0.0715)	(0.0754)	(0.0352)	(0.0366)
δ_1	-0.0079	-0.0042	-0.0106	-0.1179	-0.0115	-0.0116	-0.0259	-0.0263
	(0.7635)	(0.5074)	(0.2561)	(0.2317)	(0.3452)	(0.2328)	(0.0551)	(0.0547)
δ_2	-0.0269	-0.0064	-0.0079	-0.0075	-0.0146	-0.0156	-0.0234	-0.0238
	(0.3165)	(0.3064)	(0.4008)	(0.4526)	(0.2440)	(0.2328)	(0.0876)	(0.0854)
δ_3	-0.0317	-0.0018	-0.0047	-0.0058	-0.0069	-0.0076	-0.0140	-0.0144
	(0.2403)	(0.7786)	(0.6197)	(0.5675)	(0.5833)	(0.5491)	(0.3068)	(0.2996)
δ_4	-0.0647	-0.0146	-0.0213	-0.0207	-0.0306	-0.0305	-0.0427	-0.0431
	(0.0188)	(0.039)	(0.0240)	(0.0389)	(0.0134)	(0.0151)	(0.0021)	(0.0021)
γ_1	-	-	-	0.0054	-	0.0043	-	0.0076
	-	-	-	(0.6150)	-	(0.7355)	-	(0.5624)
γ_2	-	-	-	-0.0051	-	0.0039	-	-0.0036
	-	-	-	(0.6285)	-	(0.7572)	-	(0.7853)
γ_3	-	-	-	0.0053	-	0.0029	-	0.0048
	-	-	-	(0.6109)	-	(0.8210)	-	(0.7189)
γ_4	-	-	-	-0.0098	-	-0.0046	-	0.0022
	-	-	-	(0.3595)	-	(0.7201)	-	(0.8666)
	Log-likelihood and information criteria							
LL	-185.284	-285.749	-284.245	-283.597	-282.363	-282.142	-277.170	-276.876
AIC	3.0753	2.8166	2.8023	2.8343	2.7844	2.8204	2.7349	2.7702
SIC	3.2993	2.9760	2.9617	3.0574	2.9438	3.0435	2.8943	2.9934
HQC	3.1663	2.8811	2.8667	2.9244	2.8488	2.9106	2.7994	2.8604

price measures. For this particular data and model set, omitting the negatively censored data has no impact on the results. Factor loads of the negative proxies are statistically insignificant throughout all models and proxies.

4.2. Replication with data up to 2016Q4

This section discusses whether the empirical findings of the five highlighted studies are still valid when newer data up to 2016Q4 are appended.

The results of estimating the oil price - GDP growth relationship with recent data based on the different measures, O_t, $O_{\text{Mork},t}^{-/+}$, $O_{\text{LNR},t}^{-/+}$, $O_{\text{Ham1},t}^{-/+}$, and $O_{\text{Ham3},t}^{-/+}$, are reported in Tab. 6. Columns 2 and 3 refer to results when estimating the ARX(4) model using a linear

16

functional form for the exogenous oil price changes variable O_t without any censoring. The results show that, in line with previous studies, only the fourth lag of oil price changes is significant at the 5% level. Moreover, our results confirm the findings of Hamilton (2003, p. 369) who postulates that the impact of positive oil price changes decreases as the covered time span increases.[5] This can be explained by the fact the recent periods are characterized by higher volatility of oil prices. As mentioned in previous studies, the shortcoming of the linear ARX(4) is the assumption that negative oil price changes have the same impact on GDP growth than positive changes.

The results of applying the oil price measures of Mork (1989), $O_{\text{Mork},t}^{-/+}$, with the extended model defined in Eq. (3) are reported in Tab. 6, columns 4 and 5. Our results show that the measure of Mork (1989) is unable to capture any effect of oil price changes on the GDP growth as all coefficients are insignificant at the 5% level for the period up to 2016Q4. However, at the 10% level we find that both the third and fourth lag, δ_3 and δ_4, of the positive real oil price changes, $O_{\text{Mork},t}^{+}$, are significant. These results indicate that by including recent data, the Mork measure loses its explanatory power on GDP growth.

The results obtained with the measures introduced in Lee et al. (1995) are unambiguous. None of the normalized negative oil price changes, $O_{\text{LNR},t}^{-}$, have a significant impact on real GDP growth as all their associated p-values are substantially higher than 10%. For the positive normalized oil price changes, $O_{\text{LNR},t}^{+}$, the results show that both the second and third lag are highly significant at the 1% level. Compared to Lee et al. (1995, p. 48, Tab. 5), we infer that the cumulative effects, measured by the sum of significant normalized oil price increases, decrease on more recent data.

The results of applying the net oil price measure of Hamilton (1996), $O_{\text{Ham1},t}^{-/+}$, are reported in columns 8 to 9 of Tab. 6. Regarding the net oil price increases, the results are in line with the findings of other oil price proxies; only the fourth lag is significant with an estimated coefficient of $\delta_4 = -0.0271$. These empirical results show that the 1y

---

[5]For instance, the fourth lag of the oil price changes is estimated at -0.064 in Hamilton (2003, p. 369, Eq. (1.6)) for the period 1949Q2 to 1980Q4. Extending the period to 2001Q4, it decreases to -0.016. For the period 1948Q2 to 2016Q4, we obtain a statistically significant estimate of -0.0089 reported in Tab. 6.

net oil price increases have lower impact for the longer sample. For instance, using data up to 2016Q4, the estimated δ_4 is lower in absolute terms than the reported coefficient of -0.0310 in Hamilton (2003). With a longer time period covered with the models, the behavior of consumers and their reactions to price, demand, and supply changes might have changed. By taking into consideration the volatility of oil price changes, they become less sensitive to fluctuation of oil prices. This could hold true for the last 15 years in particular as these years are characterized by extremely erratic prices compared to earlier subsets. Hamilton (2003) already suggests that the 1y net oil price measure is not consistent with recent oil price fluctuations relative to 2003.

The results obtained with the 3y net measures, $O_{\text{Ham3,t}}^{-/+}$ and $O_{\text{Ham3,t}}^{+}$, are reported in columns 10 and 11 in Tab. 6. The fourth lag of the positively censored measure, δ_4 is highly significant at the 1% level. Allowing for a 10% level of significance, we find the load of the first lag, δ_1, also significant.

Table 6: Regression results from the linear extended Hamilton (1989) model using different oil price measures for the period 1948Q2 to 2016Q4.

	O_t		$O_{\text{Mork,}t}^{+/-}$		$O_{\text{LNR,}t}^{+/-}$		$O_{\text{Ham1,}t}^{+/-}$		$O_{\text{Ham3,}t}^{+/-}$	
	Coef.	p-value	Coef.	p-value	Coef.	p-value	Coef.	p-value	Coef.	p-value
μ_0	0.5671	(0.0000)	0.8002	(0.0000)	0.9753	(0.0000)	0.8224	(0.0000)	0.8299	(0.0000)
ϕ_1	0.3288	(0.0000)	0.2978	(0.0000)	0.2808	(0.0000)	0.2804	(0.0000)	0.2608	(0.0000)
ϕ_2	0.1433	(0.0269)	0.1198	(0.0632)	0.0764	(0.2425)	0.1177	(0.0665)	0.1165	(0.0654)
ϕ_3	-0.0623	(0.3336)	-0.0801	(0.2131)	-0.0495	(0.4507)	-0.0748	(0.2416)	-0.0789	(0.2102)
ϕ_4	-0.0742	(0.2253)	-0.1084	(0.0783)	-0.0512	(0.3980)	-0.1007	(0.0983)	-0.1035	(0.0832)
δ_1	-0.0003	(0.9308)	-0.0086	(0.2434)	-0.0948	(0.3033)	-0.0111	(0.2509)	-0.0199	(0.0725)
δ_2	-0.0036	(0.3559)	-0.0085	(0.2421)	-0.2478	(0.0082)	-0.0119	(0.2181)	-0.0150	(0.1685)
δ_3	-0.0049	(0.2199)	-0.0132	(0.0743)	-0.4011	(0.0000)	-0.0125	(0.1976)	-0.0180	(0.1009)
δ_4	-0.0089	(0.0250)	-0.0127	(0.0818)	-0.1124	(0.2434)	-0.0271	(0.0050)	-0.0341	(0.0002)
γ_1	-	-	0.0071	(0.2369)	-0.0173	(0.8432)	0.0064	(0.3498)	0.0098	(0.2992)
γ_2	-	-	-0.0012	(0.8362)	0.0941	(0.2814)	0.0011	(0.8738)	-0.0053	(0.5837)
γ_3	-	-	0.0007	(0.9148)	0.1127	(0.1963)	0.0021	(0.7604)	0.0003	(0.9759)
γ_4	-	-	-0.0089	(0.1509)	0.0581	(0.5054)	0.0004	(0.9537)	-0.0011	(0.9096)
σ_0	0.9099	(0.0000)	0.9023	(0.0000)	0.8469	(0.0000)	0.8947	(0.0000)	0.88047	(0.0000)
				Log-likelihood and information criteria						
LL	-359.689		-355.282		-324.083		-352.945		-348.541	
AIC	2.6886		2.6857		2.4588		2.6687		2.6366	
SIC	2.8202		2.8698		2.6429		2.8528		2.8208	
HQC	2.7414		2.7596		2.5327		2.7426		2.7106	

Note: The oil price measures refer to the uncensored O_t of Hamilton (1983), the asymmetric measures $O_{\text{Mork,}t}^{-/+}$ of Mork (1989), the volatility scaled measures $O_{\text{LNR,}t}^{-/+}$ of Lee et al. (1995), and Hamilton's measures $O_{\text{Ham1,}t}^{-/+}$ (Hamilton, 1996) as well as $O_{\text{Ham3,}t}^{-/+}$ (Hamilton, 2003).

4.3. Exclusion and stability tests

In order to statistically assess whether the oil price changes have a significant impact on the real GDP growth, we conduct two exclusion tests for each oil price measure. Test (a) has the null hypothesis that all parameters related to the oil measure are zero, i.e. $H_0 : \delta_1 = \delta_2 = \delta_3 = \delta_4 = \gamma_1 = \gamma_2 = \gamma_3 = \gamma_4 = 0$. Test (b) attempts to capture the importance of measures for oil price increases and decreases separately. The results of these two tests for each model (as in Tab. 6) are reported in column 2 and 3 of Tab. 7. For the symmetric linear ARX(4) model with the O_t measure, the null hypothesis, stating that oil price changes do not have a significant impact on the real GDP growth, cannot be rejected at the 10% level. For the four censored oil price measure, we reject the null hypothesis. Test (b) goes into more detail and we find that the rejection of test (a) is mainly attributed due to the measure capturing the increase of oil prices. For all measures we reject the null hypothesis that oil price increases are not relevant, while all hypotheses on oil price decreases cannot be rejected. The results from the ARX(4) model suggest that only oil price increases are important for the oil price-GDP relation.

An important issue that might arise when using long periods of data is the possibility of structural changes. This instability of the relationship between oil prices and GDP growth is tested in literature using the Chow test and the tests of Andrews (1993) and Andrews & Ploberger (1994). The results of the Sup F, Avg F, and Exp F (Andrews & Ploberger, 1994) tests are reported in columns 3-5 of Tab. 7 with their p-values in parentheses.[6] The results show that the null hypotheses of stability of the oil price changes-GDP growth relationship are rejected for all oil price measures at the 1% level for most of the tests.

From this detected instability of parameters over the full data sample, we imply that several breakpoints exist. These breakpoints might not be breaks in the classical sense but rather induced by the behaviour of oil prices as such. Prior to 1973, oil prices behave

---

[6]The F-statistics of the Andrews (1993) and Andrews & Ploberger (1994) test are calculated as log ratios $F_\tau = 2 \left(LL_1 - LL_0 \right)$ where LL_0 and LL_1 are the log-likelihoods from the full model and the model with implemented break point at $t = \tau$. The F_τ-statistics are calculated for each possible break point between $t_1 = \lfloor 0.15T \rfloor$ and $t_2 = \lceil 0.85T \rceil$, where T is the total number of observations. Then, the statistics are Sup $F = \max_{t_1 < \tau < t_2} F_\tau$, Avg $F = \frac{1}{t_2 - t_1 - 1} \sum_{\tau=t_1}^{t_2} F_\tau$, and Exp $F = \ln \left(\frac{1}{t_2 - t_1 - 1} \sum_{\tau=t_1}^{t_2} \exp\left(\frac{1}{2} F_\tau \right) \right)$. The p-values are calculated following the procedure of Hansen (1997).

Table 7: Exclusion tests for linear models with data from 1948Q2 to 2016Q4. Exclusion test (a) restricts oil price increases and decreases. Test (b) restricts increases and decreases separately. The Andrews and Ploberger test has the null hypothesis that the model parameters are stable over the whole sample.

	Exclusion tests		Andrews and Ploberger (1994) tests		
	(a)	(b)	Sup F	Avg F	Exp F
Panel A: Hamilton (1983)					
O_t	1.8123 (0.1267)		3.3181 (0.0018)	2.3673 (0.0009)	1.2733 (0.0106)
Panel B: Mork (1989)					
$O^+_{\mathrm{Mork},t}$	1.9883 (0.0482)	3.3181 (0.0113)	2.7424 (0.0160)	1.8571 (0.0044)	0.9760 (0.0446)
$O^-_{\mathrm{Mork},t}$		0.7954 (0.5291)			
Panel C: Lee et al. (1995)					
$O^+_{\mathrm{LNR},t}$	3.1229 (0.0022)	5.9678 (0.0001)	3.0700 (0.0040)	1.6327 (0.0189)	0.8554 (0.1116)
$O^-_{\mathrm{LNR},t}$		0.7642 (0.5491)			
Panel D: Hamilton (1996)					
$O^+_{\mathrm{Ham1},t}$	2.5837 (0.0099)	4.9776 (0.0007)	3.2016 (0.0022)	1.7776 (0.0074)	0.9638 (0.0492)
$O^-_{\mathrm{Ham1},t}$		0.2645 (0.9006)			
Panel E: Hamilton (2003)					
$O^+_{\mathrm{Ham3},t}$	3.7337 (0.0004)	6.9907 (0.0000)	3.1735 (0.0000)	1.6593 (0.0112)	0.9836 (0.0347)
$O^-_{\mathrm{Ham3},t}$		0.2995 (0.8781)			

like step functions and thereafter, like a price driven by supply and demand as well as policy changes.[7] Other major events and periods, such as the Great Moderation, might also be a contributing factor to the above detected instability.

5. Conclusions

In this replication paper, we review the findings of Hamilton (2003) who estimates the oil price–GDP link with different measures for oil price changes. These measures are defined in the papers of Hamilton (1983), Mork (1989), Lee et al. (1995), Hamilton (1996), and Hamilton (2003), which represent some of the most influential papers with focus on the oil-macroeconomy relationship.

We are able to confirm all estimation results. Minor differences are caused by slightly varying data sets of this paper. After this successful replication of the findings of Hamilton

---

[7]We thank Lutz Kilian for a fruitful discussion on this topic.

(2003), we augment the model framework with negative oil price changes and find that they add no additional explanatory power to this link. We then extend the data sets to 2016Q4. We observe that the the explanatory power is decreasing and all oil price measures insufficiently explain GDP growth rates. Parameter stability tests confirm that the oil price–GDP link is prone to breaks.

The observations and findings of this paper motivate further analyses carried out in Charfeddine et al. (2018) in which we advance this replication study as follows. Firstly, accounting for changes in oil price behavior we limit the data set to begin in 1973. Secondly, regarding the observed parameter instability we introduce a regime switching variant of the ARX(p) model applied in this paper. Lastly, in order to analyse a higher frequency of observations we apply mixed data sampling to review quarterly GDP growth rates with monthly oil price changes.

References

Andrews, D. W. K. (1993). Tests for Parameter Instability and Structural Change With Unknown Change Point. *Econometrica*, *61*, 821. doi:`10.2307/2951764`.

Andrews, D. W. K., & Ploberger, W. (1994). Optimal Tests when a Nuisance Parameter is Present Only Under the Alternative. *Econometrica*, *62*, 1383–1414. doi:`10.2307/2951753`.

Barsky, R. B., & Kilian, L. (2004). Oil and the Macroeconomy Since the 1970s. *Journal of Economic Perspectives*, *18*, 115–134. doi:`10.1257/0895330042632708`. `arXiv:9809069v1`.

Baumeister, C., & Kilian, L. (2012). Real-Time Forecasts of the Real Price of Oil. *Journal of Business & Economic Statistics*, *30*, 326–336. doi:`10.1080/07350015.2011.648859`.

Baumeister, C., & Kilian, L. (2016a). Forty Years of Oil Price Fluctuations: Why the Price of Oil May Still Surprise Us. *Journal of Economic Perspectives*, *30*, 139–160. doi:`10.1257/jep.30.1.139`.

Baumeister, C., & Kilian, L. (2016b). Understanding the Decline in the Price of Oil since June 2014. *Journal of the Association of Environmental and Resource Economists*, *3*, 131–158. doi:`10.1086/684160`.

Charfeddine, L., Klein, T., & Walther, T. (2018). Oil Price Changes and U.S. Real GDP Growth: Is this Time Different? *Working Paper - SSRN Electronic Journal*, (pp. 1–42). URL: `https://www.ssrn.com/abstract=3222572`. doi:`10.2139/ssrn.3222572`.

Davies, R. B. (1987). Hypothesis testing when a nuisance parameter is present only under the alternative. *Biometrika*, *74*, 33–43. doi:`10.1093/biomet/74.1.33`.

Hamilton, J. D. (1983). Oil and the Macroeconomy since World War II. *Journal of Political Economy*, *91*, 228–248. doi:`10.1086/261140`.

Hamilton, J. D. (1989). A New Approach to the Economic Analysis of Nonstationary Time Series and the Business Cycle. *Econometrica: Journal of the Econometric Society*, *57*, 357–384. doi:`10.2307/1912559`.

Hamilton, J. D. (1996). This is what happened to the oil price-macroeconomy relationship. *Journal of Monetary Economics*, *38*, 215–220. doi:`10.1016/S0304-3932(96)01282-2`.

Hamilton, J. D. (2003). What is an oil shock? *Journal of Econometrics*, *113*, 363–398. doi:`10.1016/S0304-4076(02)00207-5`.

Hamilton, J. D. (2011a). Historical Oil Shocks. *NBER Working Paper 16790*, (pp. 1–51).

Hamilton, J. D. (2011b). Nonlinearities and the Macroeconomic Effects of Oil Prices. *Macroeconomic Dynamics*, *15*, 364–378. doi:`10.1017/S1365100511000307`.

Hamilton, J. D. (2017). Why You Should Never Use the Hodrick-Prescott Filter. *The Review of Economics and Statistics*, *Forthc.*, 1–45. doi:`10.1162/REST{\_}a{\_}00706`.

Hansen, B. E. (1997). Approximate Asymptotic P Values for Structural Change Tests. *Journal of Business & Economic Statistics*, *15*, 60–67. doi:`10.1080/07350015.1997.10524687`.

Jimenez-Rodriguez, R., & Sanchez, M. (2005). Oil price shocks and real GDP growth: empirical evidence for some OECD countries. *Applied Economics*, *37*, 201–228. doi:`10.1080/0003684042000281561`.

Kilian, L. (2009). Not All Oil Price Shocks Are Alike: Disentangling Demand and Supply Shocks in the Crude Oil Market. *American Economic Review*, *99*, 1053–1069. doi:`10.1257/aer.99.3.1053`.

Kilian, L., & Vigfusson, R. J. (2011a). Are the responses of the U.S. economy asymmetric in energy price increases and decreases? *Quantitative Economics*, *2*, 419–453. doi:`10.3982/QE99`.

Kilian, L., & Vigfusson, R. J. (2011b). Nonlinearities in the Oil Price-Output Relationship. *Macroeconomic Dynamics*, *15*, 337–363. doi:`10.1017/S1365100511000186`.

Lee, K., Ni, S., & Ratti, R. A. (1995). Oil shocks and the macroeconomy: the role of price variability. *Energy Journal*, *16*, 39–56. doi:`10.5547/ISSN0195-6574-EJ-Vol16-No4-2`.

Mork, K. A. (1989). Oil and the Macroeconomy When Prices Go Up and Down: An Extension of Hamilton's Results. *Journal of Political Economy*, *97*, 740–744.