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Abstract

The U.S. Energy Information Administration estimates that approximately 52% of total U.S. crude oil was produced from shale oil resources in 2015. We examine whether the recent low crude oil price is attributable to this shale revolution in the U.S., using a SVAR model with structural breaks. Our results reveal that U.S. supply shocks are important drivers of real oil price and, for example, explain approximately a quarter of the 73% decline between June 2014-February 2016. Failure to consider statistically significant structural changes results in underestimating the role played by global supply shocks, while overestimating the role of the demand shocks.

JEL classification: C32, E32, F43.

Keywords: Oil market, structural breaks, U.S. shale revolution.

1 Introduction

The global oil market is experiencing many changes. Because of the new technology used to extract crude oil and natural gas, the shale revolution[1], the production level of oil and natural gas in the U. S. has risen rapidly, with the level of crude oil reaching almost that of Saudi Arabia and Russia in 2015, as shown in Figure 1. As a result, the U.S. resumed exporting crude oil and natural gas from 2016, after a 40-year ban. At the same time, the global crude oil price fell substantially, and the U.S. real import price fell more than 73% June 2014-February 2016, making it the most rapid decline within this time frame since 1973[2]. Observing these new phenomena (the shale revolution in the U.S. and low oil price), many analysts in the oil industry have predicted that a new normal era for the global oil market has begun, and that the oil price will remain somewhere between U.S.$35 and U.S.$50 per barrel in future[3].

In this study, we conduct a series of structural break tests using an empirical model, like that of Kilian (2009), to check whether recent changes in the oil market are significant to be considered a break, and whether these phenomena are interrelated. More specifically, we conduct the structural break test proposed by Bataa, Osborn, Sensier, and Van Dijk (2014) to individual series in a structural VAR model (SVAR) to decompose the series into a level component, seasonality component, outliers, and a dynamic component. Once the level and seasonality components and outliers are removed from individual series, based on the first-stage structural break test, we apply the test approach of Bataa, Osborn, Sensier, and Van Dijk (2013) to our SVAR model to determine if the dynamic coefficients of the SVAR and the volatilities of structural shocks have undergone structural breaks. We also conduct historical decomposition exercises based on the results of the break test for the SVAR, and examine if the shale revolution and the low oil price are related.

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[1] The shale revolution is a new combination of horizontal drilling and hydraulic fracturing to produce oil and natural gas.

[2] The Western Texas Intermediate (WTI) crude oil price reached U.S.$26.21 per barrel in February 2016, which is a record low since July 2002.

[3] See Hartmann and Sam (2016) and Katy Barnato (2016) 'Oil's new normal may be lower than you think,' CNBC May 31, 2016.

Kilian (2017) examines the impact of the U.S. fracking boom and demonstrates that the U.S. shale oil production had played a role in the low crude oil price in 2016 based on Kilian and Murphy (2014). Using a variant of the Kilian (2009) model, however, we also address whether the low crude oil price is attributable to the U.S. shale production but allow structural breaks in the model. The Kilian (2009) model is popular and widely examined and extended by studies such as Kilian and Park (2009), Kang, Ratti and Vespignani (2017), among others. The difference between these studies and this paper is that we allow structural breaks in the Kilian model because changes in the oil production technology such as shale production in the U.S. and changes on the demand side due to changes in environmental regulation may cause changes in the dynamics of the oil market.

In terms of the dynamics of the oil market, our findings can be summarized as follows. First, U.S. oil production growth has experienced a structural change from a decline of approximately 1.56% a year before the shale revolution to an increase of 4.92% after the revolution. Interestingly, its dynamic coefficients have remained stable. Second, the volatilities of all structural shocks have been subject to structural breaks, and we do find a U.S. supply shock break related to the shale revolution. The shock volatility to the global aggregate demand influencing all commodity prices, has jumped to historic heights since the Global Financial Crisis (GFC). Third, the historical decomposition exercise reveals a substantial contribution from the U.S. supply to the recent low price of crude oil. Fourth, we also find that the failure to account for structural changes in dynamic coefficients overestimates the role of demand shocks and underestimates the role of supply shocks in the oil market. This evidence suggests that the U.S. oil production increase due to the shale revolution has increased the significance of the U.S. supply shock to movement in the real oil price.

Our study is organized as follows. Section 2 briefly presents the econometric methodology employed in this paper and describes data used in the analysis. Empirical evidence is provided in Section 3, and concluding remarks are offered in Section 4.

2 Econometric Methodology and Data

The econometric methodology used in this study builds on that of Bataa, Izzeldin, and Osborn (2016). A critical difference is that we have put the growth rate of U.S. oil production in the first place of the SVAR. Hence, the SVAR in this study consists of four variables; the growth rate of the U.S. oil supply, the growth rate of the global oil supply, changes in the measure of global real economic activity, and the growth rate of the real price of oil. We maintain the recursive identification assumption for the contemporaneous relation between these variables, that, for the first two variables, implies that the U.S. oil supply is unaffected by within-month global oil supply shocks, but that the global oil supply depends on its own within-month shocks and U.S. oil supply shocks as well. This assumption means that the global oil supply includes the U.S. oil supply and the U.S. is one of the main oil producers. According to the recursive identification assumption for the contemporaneous relation between the variables in the SVAR, $\mathbf{A}_0$ will be a lower-triangular matrix in the following baseline-constant parameter equation:

$$\mathbf{A}_0 \mathbf{y}_t = \sum_{i=1}^{p} \mathbf{A}_i \mathbf{y}_{t-i} + \boldsymbol{\varepsilon_t}, \tag{1}$$

where $\boldsymbol{\varepsilon}_t = (\varepsilon_{uoils,t}, \varepsilon_{goils,t}, \varepsilon_{aggd,t}, \varepsilon_{oild,t})'$ denotes a vector of structural shocks with variances of U.S. oil supply, global oil supply, aggregate demand, and oil specific demand shocks σ^2_{uoils}, σ^2_{goils}, σ^2_{aggd}, σ^2_{oild}, respectively. The shock vector $\boldsymbol{\varepsilon}_t$ is both serially and mutually uncorrelated and, hence, $E(\boldsymbol{\varepsilon}_t \boldsymbol{\varepsilon}'_t) = \boldsymbol{\Sigma}$ is diagonal, and constant in the baseline case.

The vector moving average (VMA) representation of the SVAR, which shows the temporal patterns of responses to the shocks, can be derived as

$$\mathbf{y}_t \;\; = \;\; \left(\sum_{i=0}^{p} \mathbf{A}_i^* L^i \right)^{-1} \boldsymbol{\varepsilon}_t = \left(\sum_{k=0}^{\infty} \boldsymbol{\Psi}_k L^k \right) \boldsymbol{\varepsilon}_t = \sum_{k=0}^{\infty} \boldsymbol{\Psi}_k \boldsymbol{\varepsilon}_{t-k}, \tag{2}$$

where $\mathbf{A}_0^* = \mathbf{A}_0$, $\mathbf{A}_i^* = -\mathbf{A}_i$, $\quad i = 1, \ldots p$, and elements of the j^{th} column of $\boldsymbol{\Psi}_k$ give the vector of IRFs for a unit shock to the j^{th} element of $\mathbf{y}_t$ at horizon k.

The historical decomposition of i^{th} element of $\mathbf{y}_t$ is

$$y_{i,t} = \sum_{j} \sum_{k=0}^{\infty} \Psi_{i,j}^{(k)} \varepsilon_{j,t-k} \tag{3}$$

where $\Psi_{i,j}^{(k)}$ is row i and column j of $\mathbf{\Psi}_k$, and $\varepsilon_{j,t}$ is the j^{th} element of $\boldsymbol{\varepsilon}_t$.

Pagan and Robertson (1998) note that in a recursive system, one can always test whether any restrictions placed on $\mathbf{A}_i$ in (1) are valid, such as a necessity to have the same lag structure in every equation. Although we still have a maximum of two years of lag in this study, as in Kilian (2009), who argues for this long lag based on the industry feature, we apply a heterogeneous specification. First, as in Apergis and Miller (2009) we explicitly define a vector in first differences of the relevant variables, that is, $\Delta_1 \mathbf{z}_t = \mathbf{y}_t$. Then, motivated by Bataa *et al.* (2016), the SHVAR is

$$\mathbf{A}_0 \Delta_1 \mathbf{z}_t = \mathbf{\Phi}_1 \Delta_1 \mathbf{z}_{t-1} + \mathbf{\Phi}_2 \Delta_3 \mathbf{z}_{t-1} + + \mathbf{\Phi}_3 \Delta_{12} \mathbf{z}_{t-1} + \mathbf{\Phi}_4 \Delta_{24} \mathbf{z}_{t-1} + \boldsymbol{\varepsilon_t}, \tag{4}$$

where $\Delta_k = (1 - L^k)$. This heterogeneous autoregression specification means that $\Delta_1 \mathbf{z}_t$ depends on previous month, quarter, one-year and two-year changes in $\mathbf{z}_t$. Although this specification is somewhat arbitrary, it can reduce the number of coefficients significantly, and is used widely in the finance literature to capture long lagged effects.

As in Bataa *et al.* (2016) we conduct structural break tests for the above-mentioned SHVAR, equation-wise. Pagan and Robertson (1998) note that the efficient GMM estimator of $\mathbf{A}_0$ in SHVAR model (1) is obtained by applying the ordinary least squares method, equation by equation, with $\boldsymbol{\varepsilon}_j' \boldsymbol{\varepsilon}_j / (T - p)$, $j = uoils, goils, aggd, oild$, used to estimate $\mathbf{\Sigma}$[4]. Bataa *et al.* (2016) emphasize that this equation-wise testing strategy not only reduces the burden of testing for multiple breaks compared with a system approach, but also adds flexibility in allowing different breaks across equations in terms of their

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[4] Sims (1980) and Kilian (2009) and their follow-up studies, compute the estimators of $\mathbf{\Sigma}$ and $\mathbf{A}_0$ by solving $\hat{\mathbf{A}}_0^{-1} \hat{\mathbf{\Sigma}} (\hat{\mathbf{A}}_0')^{-1} = \hat{\mathbf{\Omega}}$, where $\hat{\mathbf{\Omega}}$ is the reduced-form VAR variance-covariance matrix. Numerically, this decomposition is implemented by applying a Choleski decomposition to $\hat{\mathbf{\Omega}}$. Pagan and Robertson (1998) note that this description of the estimator obscures the fact that a simultaneous-equation system has been assumed to be recursive, a point also emphasized by Cooley and LeRoy (1985) in their critique of Sims' work.

numbers and dates.

We obtain data on the oil variables from the U.S. Department of Energy, global activity from Lutz Kilian's website, and CPI is obtained from the FRED database of the Federal Reserve Bank of St. Louis. As in Kilian (2009), the oil price variable is the U.S. refineries' acquisition cost of imported crude oil. The sample period is from January 1973 to August 2016.

3 Empirical Evidence

This section first analyzes each series, without conditioning on the SHVAR model[5]. Here, deterministic components such as means, outliers, and seasonality are estimated and removed, which then allows us to focus on explaining the non-deterministic part of the data using the structural model in (4).

3.1 Individual unconditional analysis

Before applying a break test to the SHVAR, we conduct a univariate analysis to individual series in $\Delta_1\mathbf{z}_t$. That is, the econometric methodology proposed in Bataa *et al.* (2014) is applied to individual series in $\Delta_1 z_t$ to decompose them into a level component, seasonality component, outliers, and dynamic component. Structural breaks are allowed in all components, except outliers. For the dynamic component, breaks are permitted in its AR coefficients and also in its variance. To conserve space, we relegate the details to the original study. Bataa *et al.* (2016) also adopt this methodology for the sub-set of series in our study, and the results are consistent with each other.

The break test results and the estimates conditional on them are shown in Tables 1 and 2. There is a well-known trade-off between size and power when choosing the maximum number of breaks and trimming parameters, that is the minimum fraction of the sample between any two breaks (see Bai and Perron, 1998, 2003, 2006). Based on the previous simulation results, our choice is to allow for a maximum of eight breaks (10%

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[5] Results for unit root analysis and forecast error variance decompositions were consistent with Bataa *et al.* (2016), hence omitted for brevity. They are available upon request.

trimming) when testing for breaks in the mean and variance because there is only one parameter involved. Then, we reduce the maximum of breaks to five (15% trimming) for the AR coefficients, and then further reduce to three breaks (20% trimming) for seasonal dummies because there is only one seasonal observation in a year.

Several interesting points can be noted. First, as panel A shows, the growth rate of the U.S. oil production is the only series that has undergone a structural change in its mean. When the null hypothesis of no break is tested against an unknown number of breaks using $WDMax$, all other cases are statistically insignificant. For the U.S. case, we further follow Bai and Perron's (2003) strategy in identifying the exact number of breaks using sequential tests. The null of one break against an alternative of two breaks is not rejected, as $Seq(2|1)$ is not statistically significant[6].

Table 1 shows that the estimated break point is June 2002, when the mean growth rate had risen from -0.13% (1.56% per annum) to 0.44% (4.92% per annum). Judging from the drastic increase in the growth rate and the estimated break point, this break may be related to the shale revolution[7]. Figure 1 indeed reveals a clear reversal of the growth trend, from being negative to positive at approximately the mid 2000s. The 90% confidence interval is admittedly large, covering a period between 1998 and 2006, but if we ignore that break, the U.S. production growth rate would be estimated at 0.05% and statistically insignificant. Around the same time, its volatility also increased from 1.22% to 2.02%.

There is a seasonality break in July 1998 and an AR coefficient break three months later. The F test for seasonality in Table 1 is statistically significant in both sub-periods and there is some evidence that it has increased in the latter test. Then R^2 of the regression of the U.S. production growth rate on seasonal dummies increased from 0.36 to 0.62 in July 1998, then declined to 0.38 in September 2007, while if we ignore the

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[6] As panel E shows the iteration converges to a two-cycle. The only difference between the two sets of break dates is an extra seasonality break in July 1978. The information criterion suggested in Bataa *el al.* (2016), however, favoured the parsimonious model, so we ignored that break.

[7] Although shale oil extraction was introduced in the early 20th century, the discovery of crude oil in Texas and the Middle East have made the shale oil extraction uneconomical. Due to a new combination of horizontal drilling and hydraulic fracturing, however, shale oil extraction resumed from 2003 in the U.S.

break, it is 0.46. The autoregressive lag over the whole sample is chosen to be 1 by the AIC (maximum is set at eight) and the estimated growth persistence coefficient is statistically insignificant after the break. Indeed the AIC chooses a 0 lag in the latter period. Considering the AR coefficient break is critical, because ignoring it would have led to the conclusion that the persistence (sum of AR coefficients) is still significant.

It is interesting that these late 90s breaks happened when Iraq's crude oil production became extremely volatile, which Kilian (2008) attributed to the uneven enforcement of U.N. sanctions on Iraq after the Persian Gulf War. They are also close to the OPEC and some non-OPEC members' agreement of the synchronized production cut in March 1998 in response to a price collapse. The price fell by 40% from October 1997 to mid-March 1998 and sliced billions of dollars off OPEC revenues, plummeted company share values, and sowed doubts about the viability of new explorations. CNN then reported that the slump was due to weak demand in cash-strapped Asian countries, a 10% rise in OPEC's 1998 production ceiling, a mild northern hemisphere winter, and increased Iraq exports[8]. Despite OPEC members' agreement of the synchronized production cut, the oil price reached an all time low since 1974 of just U.S.$9.39 per barrel in December 1998.

The coincidence of breaks in the U.S. oil production growth persistence, as well as in the seasonality in 1998 support a view of a strong relationship between the business and the seasonal cycles. Based on an observation that co-movements of U.S. macroeconomic variables over the business cycle are mirrored by co-movements over the seasonal cycle, Barsky and Miron (1989) and Beaulieu, MacKie-Mason, and Miron (1992) argued that the similarity suggests similar mechanisms may drive both seasonal and business cycles. Indeed, Cecchetti, Kashyap, and Wilcox (1997) find that for several U.S. manufacturing industries, including that of petroleum, the seasonal variability of production and inventories varies with the state of the business cycle. Then, they provide a model of which firms increase the seasonal variability of their production as the economy weakens. Thus, the increased seasonality and reduced production persistence in 1998 in an environment of overall volatility could have been due to the optimal response by the U.S. producers.

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[8] http://money.cnn.com/1998/03/30/markets/oil/

However, September 2007 is associated with a decline in seasonality.

Next, the seasonality pattern in global oil production experiences a change as soon as the 1990-91 Persian Gulf War started, most likely due to Iraq and Kuwait production interruptions. However, volatility falls by more than 50% after the war (and even further in August 2004). Kilian (2008) notes that the rest of OPEC did not change their production significantly to the higher oil prices triggered by the war since they were already operating at their peak capacity in 1990. The global capacity utilization rate in crude oil production was 98% in 1990. Thus, the origin of the volatility decline may have been the stabilization of oil supply after the first Gulf-war.

Third, Table 1 shows that the global real economic activity, measured by Kilian's shipping tariff index, experienced two breaks in the seasonality and volatility components at approximately the same time. The first was in the early 1980s, after which volatility was reduced by a third. Seasonal volatility also was reduced, as the seasonal R^2 dropped from 0.54 to 0.48. Note that this break precedes the start of the Great Moderation in the U.S. (see Bernanke, 2004 and Nakov and Pescatori, 2010, and references therein)[9]. Then, there is a second break around the onset of the GFC, after which the volatility tripled. This burst in volatility marked the end of the Great Moderation in this series.

Fourth, although the growth rate of the real oil price shows one break in the seasonality component and two volatility breaks as in Bataa *et al.* (2016), the seasonality is statistically significant only after the temporary OPEC collapse in 1985.

3.2 SHVAR analysis

Based on the results in Table 1, we correct for outliers (replacing with a median of six neighboring observations), remove the deterministic seasonality, and then demean the data[10]. With this modified data, we apply the structural break test described in Section 2 to the SHVAR to shed further light on possible changes and implications for the shock transmission mechanism and volatility. The break results for the shock transmission

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[9] This reduced volatility in macroeconomic variables is often dated 1984. Summers (2005) and Coric (2012) argue that this was a global phenomenon.

[10] Corrected outliers are August 2005 and August-September 2008 in the U.S. oil production and September 1975 in the global oil production.

mechanism (i.e., breaks in SHVAR equation coefficients) and for the shock volatility are discussed in section 3.2.1. The break implications for the historical decomposition of real oil price are provided in section 3.2.2. Finally, how shocks are transmitted to the oil market is discussed in section 3.2.3.

3.2.1 Structural breaks in the shock transmission mechanism and shock volatility

Because of the large number of variables, the maximum number of possible breaks for the dynamics of SHVAR, that is the shock transmission mechanism, is set to three and the minimum length of a sub-sample is required to be 20% of the sample; the specification for the shock volatility is the same as in section 3.1.

As panel A of Table 2 shows, breaks are detected in the shock transmission mechanism for the global oil supply and oil price only, according to the bootstrapped p-values. Asymptotic critical values suggest more breaks, but turn out to be statistically insignificant when we use a bootstrap check.

The AR coefficient break, which had a substantially wide confidence interval for U.S. production, is being explained away in the structural model. In contrast, for the global production growth equation there is now a break, which was absent in the univariate analysis in section 3.1, and is likely associated with the impact of other variables. The break date is estimated to be in June 1981, with a tight confidence interval. The oil price growth equation experiences a break at essentially the same time, and again it is likely to have its origins in the influence of the other forces in the market, as its own autoregressive dynamics had no significant break.

Table 3 provides information on the implication of these breaks for the instantaneous impact[11]. Global production elasticity with respect to the U.S. production was strong and significant before 1981. An unanticipated 1 percent U.S. production fall used to reduce global production by 0.64 percentage points. However, after the break, the elasticity is negligible and almost insignificant. If we ignore the break, then it would be estimated to

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[11] Note that this is the $\mathbf{A}_0$ matrix, hence the coefficient signs should change once the respective contemporaneous terms are taken to the right hand side of their respective equations.

be much larger.

Evidence for the instantaneous impact of U.S. and global productions on real activity are statistically insignificant as well as economically small, consistent with Kilian (2008, 2009).

Only after 1981 did the real oil price respond to the oil production, relatively more strongly to the global change than to the change in U.S. production. However at the 5% significance level, price elasticity with respect to production is insignificantly different from zero.

The price elasticity with respect to demand increases in 1981. Up until 1981, the global economic activity is not a strong driving force of the oil price. After the break, the price elasticity with respect to demand is much higher and statistically significant.

Panel B of Table 2 shows multiple breaks are also detected for the volatilities of all structural shocks. U.S. supply shock volatility increases after the shale revolution, but reverts to a previous level by December 2011. Global supply shock volatility experiences two breaks in October 1990 and December 2004, during the First/Second Iraq wars. Interestingly, these two breaks are associated with volatility decreases and the current shock volatility is less than a third of what it was before 1990. The supply shock volatility breaks are essentially the same as those found for their unconditional volatilities in Section 3.1.

Both demand shocks experience three volatility breaks, but their dates differ. The aggregate demand shock volatility breaks are in November 1982, December 2012, and September 2008. The latest is associated with the GFC, after which volatility is at a historic height. Oil specific demand shock volatility substantially increases from 2.06% to 7.83% in February 1986, which is close to the near OPEC collapse. This break is also close to Sadorsky (1999) which assumes a change occurs at the end of 1985. Then, there are breaks in March 1991 and November 1995, which first decreases, then increases volatility.

3.2.2 Cumulative effect of oil demand and supply shocks on real price of oil

Panels in Figure 2 show the respective cumulative contribution of each oil demand and oil supply shock to the real price of oil (in the first panel), obtained using equation (3). Red lines (continuous and dot-dash) allow for the breaks in SHVAR coefficients, while blue (dashes and dots) lines do not. For each, we consider two cases: one that recognizes the U.S. production growth rate change due to the shale revolution, and one that does not.

When we assume a constant parameter SHVAR and no level shift in the U.S. production growth (blue dotted lines), then the cumulative effects of the global oil supply shock, aggregate demand shock, and oil-specific demand shock are similar to that reported in Kilian (2009) before December 2007 (the end of his sample). Any difference must reflect a data revision, the heterogeneous specification assumption in equation (4) we are using, and the addition of the U.S. supply equation.

Our preferred model (continuous red lines) acknowledges the formal test result that the U.S. oil production growth has changed from being negative at 1.56% per annum before the shale revolution to positive 4.9% (univariate structural break tests in Table 1), as well as further changes in the shock transmission mechanism. Here, the supply shocks are much more important drivers of real prices than in the constant parameter case. There is a substantial negative contribution, especially from the U.S. supply, explaining the current low oil price. The U.S. supply shocks explain approximately a quarter of the 73% price drop between June 2014 and February 2016.

We also consider two counter-factual scenarios: a) allowing for the shale revolution, but assuming no change in the shock transmission mechanism; b) allowing for the changes in the transmission mechanism, but assuming no shale revolution. Ignoring the SHVAR equation coefficient breaks in Table 2 results in an overestimation of the importance of the demand shocks in explaining the real oil price, especially in the earlier part of the sample.

If we ignore all parameter changes, the U.S. supply shock contribution to the real price of oil is always positive and much larger than that of the global supply. However, once the structural break due to the shale revolution is taken into account, this large positive contribution is present only since the early 2000s. Acknowledging the shale revolution makes an important difference in a model that allows for structural changes in the shock transmission mechanism: ignoring it would lead to the conclusion of a large and positive U.S. supply shock contribution since the 1970s.

3.2.3 Impulse response

The results from the impulse response analysis are presented in Figure 3. Each panel in the figure shows cumulated impulse responses to a shock of a common magnitude, equal to one standard deviation, estimated over the whole sample (their sizes are provided in Table 2 in the text in square brackets). Each of the three columns represents a subsample, as defined by the coefficient break dates of Table 2. Figures also include one (blue dashed line) and two (blue dashed-dotted line) standard deviation confidence bands. The background shaded areas provide corresponding confidence intervals around the responses (dotted line) for a constant parameter model estimated over the whole sample period.

Our benchmark model with constant parameters produce impulse responses that are consistent with that of Kilian (2009) sample in the sense that demand-side shocks, particularly oil market-specific shocks, have persistent and significant impact on the real oil price, in contrast to supply-side shocks. Furthermore, they indicate that our longer sample period has relatively little effect on these responses.

Panel A illustrates responses to a U.S. supply shock. The most significant change that occurred is that the global production's response to the U.S. supply disruption fell sharply after July 1981.

Whether one allows for breaks or not, both confidence intervals suggest that the U.S. supply disruptions have never impacted the global economic activity. Time-invariant SHVAR suggests wrongly that the one standard deviation U.S. supply shock has the power to trigger approximately 3% oil price inflation in two years. However, that is highly unlikely once we recognize the structural breaks. As red lines with dotted and dashed confidence intervals suggest, such a statistically significant response is possible only since June 1981.

As panel B shows, the global production response to its own disruption is stronger before 1981 than afterwards, when there is a positive shortfall of 0.8 percentage, even after two years. Thus, the supply disruptions seem to be permanent, at least in the two-year horizon. The U.S. production response to a global production loss is positive and there is evidence that the response has become stronger since 1981.

A somewhat counter-intuitive result in panel C is the negative U.S. production response to a global demand shock, although its 95% confidence interval often includes zero. Table 2 shows that this shock has substantially increased in size, post-GFC, from one standard deviation being 6.58% in the benchmark case of the constant parameter model to 12.31%; hence, the response may now be statistically significant. This could be the result that U.S. production has mostly been driven by factors other than global demand. Indeed the U.S. had been a net importer of oil during most of our sample.

Interestingly this was also a prevalent feature of the global production before the early 1980s when the U.S. was the largest producer; only after the USSR. When Saudi Arabia's production surpassed that of the U.S., the global production response to the global demand shock is exactly the opposite to that of the U.S. Here, we see an environment in which producers increase production after positive demand shocks, and decrease when it wanes. Importantly, when we do not acknowledge the break in the global production equation, we see the U.S. response replicated by the global production.

Panel D reveals responses to the oil-specific demand shock and most intriguing changes in the global oil market. Here, the U.S. production responses are almost the opposite to what it was to the aggregate demand shock; it always reacts to offset this oil market-specific or "speculative" demand shock. The global production responded more strongly to this shock prior to 1981.

Finally, we focus on comparing the responses of real oil price to each of those structural shocks when structural breaks and shale revolution are considered and not considered. As shown in Figure 3, although the estimated response of real oil price to U.S. supply shock is not affected much by the consideration of structural breaks and shale revolution, the estimated impulse response of the real oil price to global oil supply shock becomes greater when structural breaks and shale revolution are considered in the impulse response analysis. Moreover, Figure 3 shows that the estimated impulse responses of the real oil price to global demand shock and to oil-specific demand shock are exaggerated without consideration of structural breaks.

4 Conclusion

We apply a series of structural break tests to an extension of Kilian's (2009) model. Implications of detected breaks are analyzed using historical decomposition exercises to determine whether the recent low oil price is attributable to the shale oil production in the U.S.

We find although it is true that the volatility of global supply shocks became less by more than 50% in October 1990, and even further in December 2004, consistent with earlier literature, the volatility of U.S. supply shocks were at an elevated level between September 2002 and December 2011. Furthermore, the global aggregate demand shock that influences all commodity prices jumped to historic heights since the GFC (dated September 2008). More importantly, this jump happens in addition to an already extremely volatile regime of oil-specific demand shock that has been governing the oil market since 1995.

Using the SHVAR dynamics for the oil market we also find the following. First, U.S. oil production growth has experienced a structural change, from a decline about 1.56% per annum before the shale revolution to an increase of 4.9% afterwards. Interestingly, while its SHVAR equation coefficients have remained stable, those of the global oil supply and real oil price experienced a change in mid-1981. This date also marks the end of a large and statistically significant global supply on-impact response with respect to the U.S. supply and emergence of a large- and significant impact price response with respect to global aggregate demand.

Failure to consider statistically significant structural changes results in an underestimation of the role played by the global supply shock, and overestimation of the oil-specific demand shock. Properly accounting for the structural changes in the global oil market is critical, as failure to do so could lead to overlooking large negative contributions from the U.S. supply shocks to the recent low price.

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Table 1. Structural break tests in univariate components

	U.S.A prod.	Global prod.	Real Activity	Oil Price
A. Mean				
$Wdmax$	14.33*	2.91	6.31	4.87
$Seq(2\vert 1)$	9.36			
Break date	**2002.06**			
(90% C.I.)	(98.02-06.10)			
Regime means (s.e.)	-0.13 (0.06)	0.09 (0.06)	-0.15 (0.29)	0.01 (0.27)
	0.41 (0.13)			
	[0.05 (0.06)]	[0.13 (0.05)]	[-0.15 (0.29)]	[0.01 (0.27)]
B. Seasonality				
$Wdmax$	83.84*	70.19*	100.52*	95.22*
$Seq(2\vert 1)$	31.10*	18.10	39.38*	19.31
$Seq(3\vert 2)$	31.10		31.37	
Break dates	**1998.07**	**1990.08**	**1981.09**	**1985.12**
(90% C.I.)	(97.04-99.10)	(86.10-94.06)	(79.08-83.10)	(81.12-89.12)
	2007.09		**2007.10**	
	(06.06-08.12)		(07.01-08.07)	
F test for seasonality	53.38*	19.03*	47.62*	12.23
in regimes	46.46*	76.82*	95.28*	34.16*
	24.36*		25.15*	
	[67.72*]	[38.77*]	[55.53*]	[28.09*]
Seasonal R^2	0.36	0.38	0.54	0.21
in regimes	0.62	0.42	0.48	0.27
	0.38		0.45	
	[0.46]	[0.39]	[0.47]	[0.26]
Outlier dates	05.08,08.08,08.09	75.09		
C. AR coefficients				
$Wdmax$	19.90* (10.67)	4.25 (10.67)	15.83 (18.30)	9.48 (13.38)
$Seq(2\vert 1)$	4.07 (10.97)			
Break dates	**1998.10**			
(90% C.I.)	(94.11-02.09)			
Regime persistence (s.e.)	-0.33 (0.07)	-0.05 (0.07)	0.10 (0.15)	0.42 (0.06)
	0.02 (0.08)			
	[-0.14 (0.06)]	[-0.05 (0.07)]	[0.10 (0.15)]	[0.42 (0.06)]
Regime AR lags	3,0	0	4	1
	[1]	[0]	[4]	[1]
D. Volatility				
$Wdmax$	32.59*	240.54*	227.91*	116.61*
$Seq(2\vert 1)$	12.10*	23.39*	30.74*	46.72*
$Seq(3\vert 2)$	8.71	9.87	10.27	7.86
Break dates	**2002.07**	**1990.08**	**1982.09**	**1981.01**
(90% C.I.)	(01.10-08.04)	(88.08-90.10)	(75.01-83.06)	(78.08-81.08)
	2011.09	**2004.07**	**2008.07**	**1985.10**
	(03.05-13.03)	(00.12-05.08)	(08.06-11.05)	(85.09-87.12)
Regime std. dev.	1.23	2.03	6.02	3.78
	2.02	0.88	3.87	1.93
	1.48	0.59	13.16	7.22
	[1.42]	[1.39]	[6.71]	[6.27]
E. Number of iterations before converging				
Main (sub) loop	19 (3)	3 (2)	3 (2)	3 (2)

Notes: Decomposition using the iterative method of Bataa *et al.* (2014), with breaks detected using Qu and Perron's (2007) test. * indicates a rejection of the null hypothesis with 95% confidence. The null hypothesis of $WDmax$ test is no structural break while the alternative is up to M breaks. If the null is rejected then $Seq(i+1|i)$ test is sequentially applied to determine the exact number of breaks, starting with a null of 1 break against an alternative of 2, until the null is not rejected. Asymptotic 5% critical values of $WDmax$, $Seq(2|1)$ and $Seq(3|2)$ tests for the mean and volatility are 10.67, 10.97 and 11.88, respectively (trimming 10% and $M = 8$). The critical values of $WDmax$, $Seq(2|1)$ and $Seq(3|2)$ for the seasonality are 30.92, 30.63, 31.84 respectively (20% trimming and $M = 3$). Those for the autoregressive parameters (10% trimming and $M = 8$) are reported next to the test statistics in brackets in panel C as the lag orders differ across variables. Finally, the numbers required to achieve convergence are shown. If the iteration converges to a two cycle (when 19) it reports results based on Bataa *et al* (2016)'s information criteria.

Table 2. Structural break tests for oil market SHVAR equations

	U.S.A prod.	Global prod.	Economic activity	Oil price
A. Shock transmission mechanism				
$Wdmax$	208.66*(40.85)	259.61*(42.61)	212.50*(44.05)	342.12*(45.66)
$Seq(2/1)$	33.44 (39.37)	74.67*(41.22)	34.27 (42.40)	27.99 (44.01)
$Seq(3/2)$		82.52*(42.60)		
$Seq(4/3)$		102.15*(43.89)		
$Seq(5/4)$		0.0(44.79)		
Bootstrap p-values	15.14	5.91	28.20	0.48*
		12.62		
		11.30		
		2.66**		
Break dates		**1981.06**		**1981.05**
(90% C.I.)		(81.04-81.08)		(80.01-82.09)
B. Shock volatility				
$Wdmax$	25.72*	197.03*	241.08*	179.64*
$Seq(2/1)$	11.99*	23.50*	14.59*	11.24*
$Seq(3/2)$	7.34	7.63	12.16*	22.30*
$Seq(4/3)$			4.99	11.24
Bootstrap p-values	0.00*	0.00*	0.00*	0.00*
	1.10*	0.01*	0.18*	0.16*
			0.00	0.00*
Volatility break dates	**2002.09**	**1990.10**	**1982.11**	**1986.02**
(90% C.I.)	(01.11-08.05)	(88.06-91.01)	(77.03-83.07)	(86.01-89.06)
	2011.12	**2004.12**	**2002.12**	**1991.03**
	(03.07-13.01)	(00.08-06.02)	(00.08-08.08)	(90.04-91.08)
			2008.09	**1995.11**
			(08.08-12.09)	(95.08-97.07)
Std. dev. of shock	σ_{uoils}	σ_{goils}	σ_{aggd}	σ_{oild}
Regime I	1.23 (0.06)	1.75 (0.13)	5.23 (0.35)	2.06 (0.17)
Regime II	1.88 (0.14)	0.81 (0.05)	3.46 (0.19)	7.83 (1.24)
Regime III	1.29 (0.15)	0.55 (0.04)	4.92 (0.56)	3.77 (0.32)
Regime IV			12.31 (0.90)	7.05 (0.30)
[No break]	[1.41 (0.06)]	[1.31 (0.05)]	[6.58 (0.24)]	[6.00 (0.21)]
C. Number of iterations for convergence				
	2	3	2	3

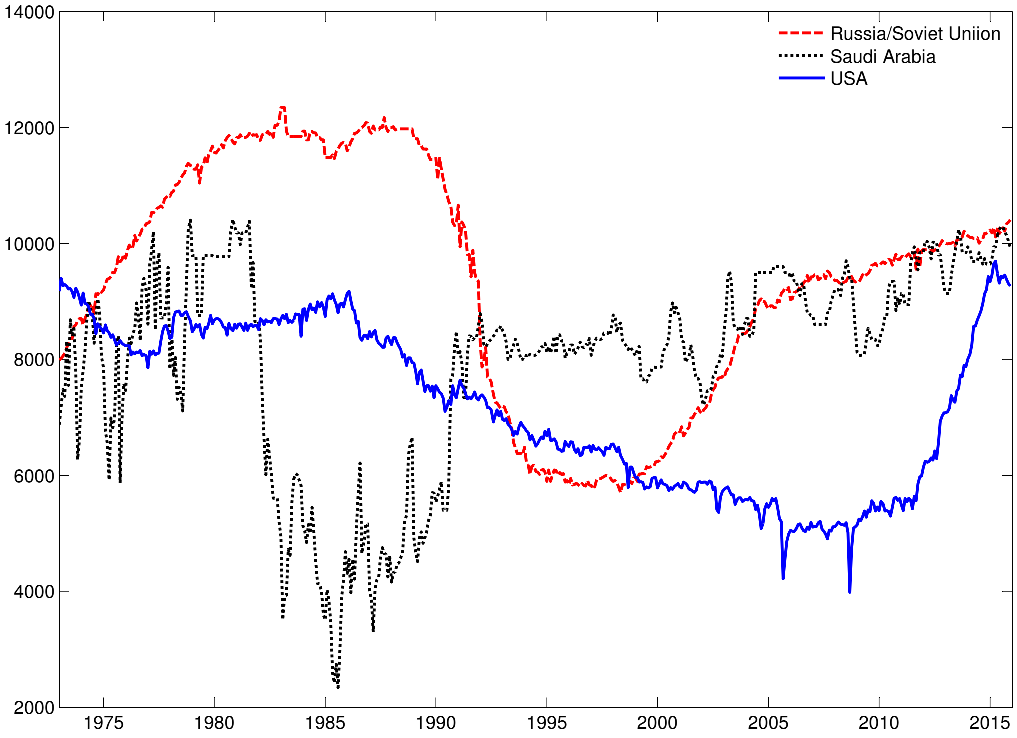
Notes: Values reported are at convergence of the iterative procedure of Bataa *et al.* (2016). $WDmax$ is the overall test that examines the null hypothesis of no break against an unknown number of breaks, to a maximum of 5 breaks for each SHVAR equation and 8 for the variance. If the overall statistic is significant at 5%, sequential tests are applied starting with the null hypothesis of one break and continuing until the relevant statistic is not significant. Asymptotic critical values for the 5% significance level are reported next to respective test statistics in parenthesis in panel A since the number of parameters are different in the SHVAR equations. The critical values for shock volatility break tests applicable to panel B are the same to those for volatility in Table 1. *Indicates the statistic is significant at 5%. The bootstrap p-values correspond to the null hypothesis that an asymptotically detected break does not exist. When bootstrap tests are significant at 5% the break dates are estimated and 90% confidence intervals provided. Shock standard deviations over these breaks are then reported as well as ignoring them (in square brackets). The last panel reports the number of iterations required to converge in coefficient and volatility break dates.

Table 3. Impact response matrix estimates

	Regime	U.S.A prod.	Global prod.	Economic activity	Oil price
U.S. prod	75.02-81.05	1			
	81.06	1			
	81.07-16.08	1			
	[no break]	1			
World prod	75.02-81.05	-0.64 (0.12)	1		
	81.06	-0.64 (0.12)	1		
	81.07-16.08	-0.07 (0.04)	1		
	[no break]	[-0.11 (0.06)]	1		
Economic Act	75.02-81.05	0.05 (0.21)	0.12 (0.23)	1	
	81.06	0.05 (0.21)	0.12 (0.23)	1	
	81.07-16.08	0.05 (0.21)	0.12 (0.23)	1	
	[no break]	[0.05 (0.21)]	[0.12 (0.23)]	1	
Real price	75.02-81.05	0.05 (0.62)	-0.13 (0.68)	-0.08 (0.13)	1
	81.06	0.25 (0.21)	0.39 (0.24)	-0.13 (0.05)	1
	81.07-16.08	0.25 (0.21)	0.39 (0.24)	-0.13 (0.05)	1
	[no break]	[0.25 (0.21)]	[0.39 (0.24)]	[-0.13 (0.05)]	1

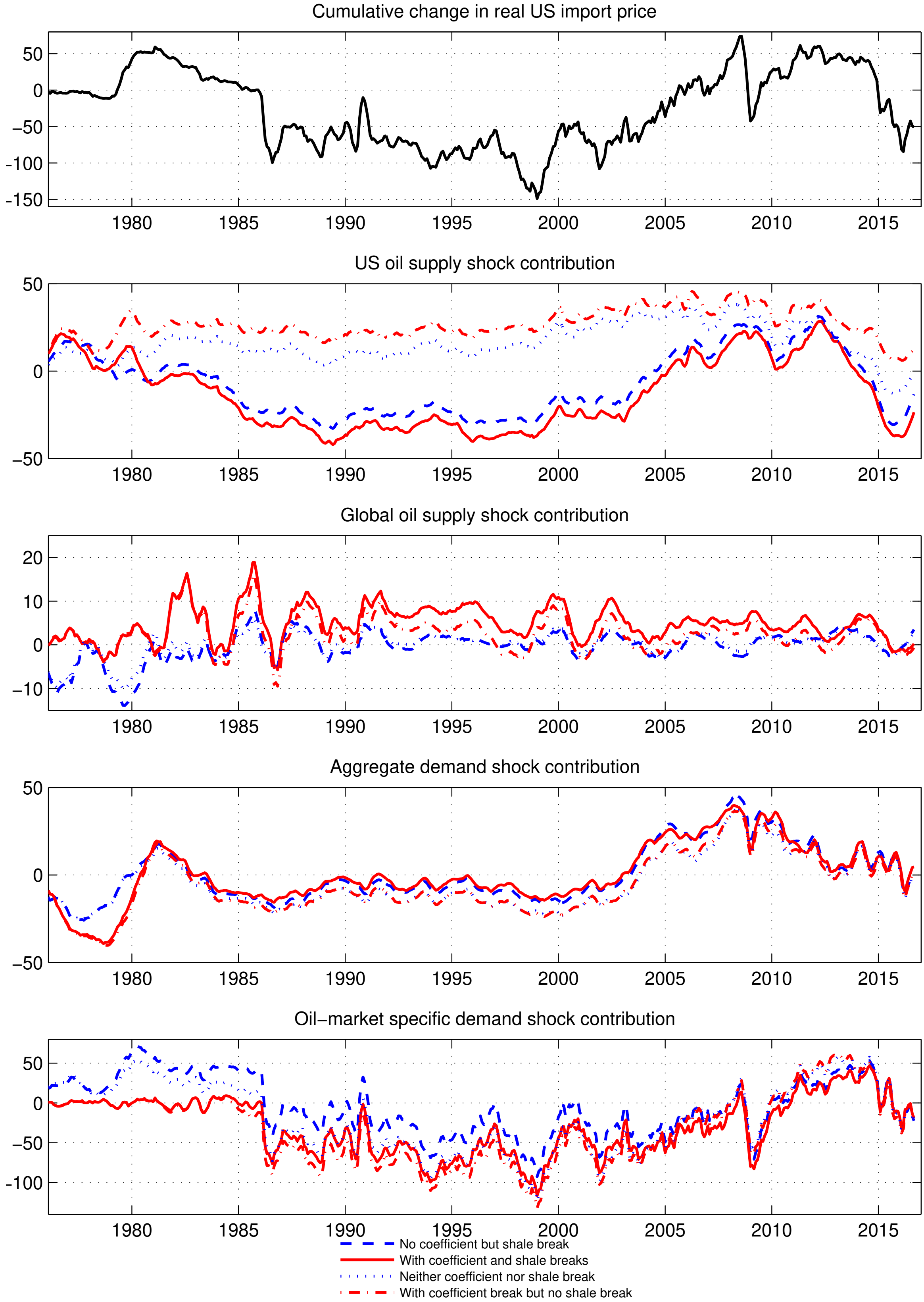
Notes: Table reports point estimates and bootstrap standard deviations of below diagonal elements of $\mathbf{A}_0$ over regimes defined by the breaks in panel A of Table 2. Also provided in [square brackets] are the quantities that ignore the breaks.

Figure 1. Oil Production Levels among Main Oil Producers



Note: Thousand barrels per day. Source: International Energy Agency.

Figure 2. Historical decomposition



Cumulative change in real US import price

US oil supply shock contribution

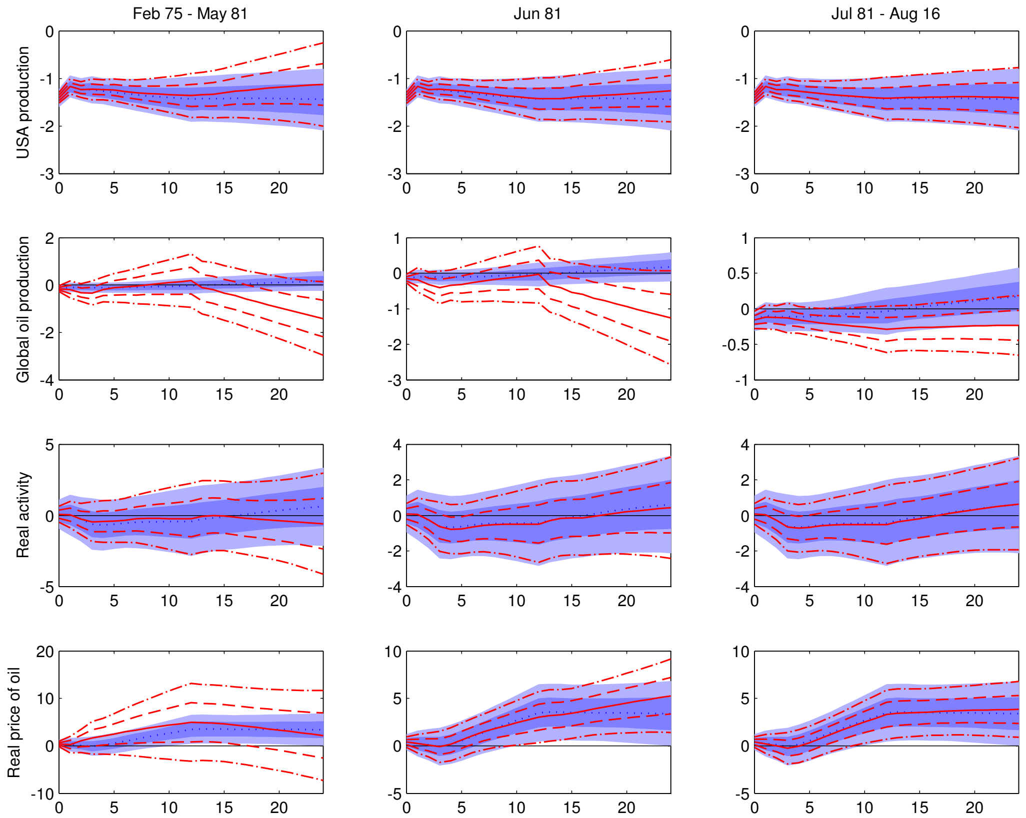
Global oil supply shock contribution

Aggregate demand shock contribution

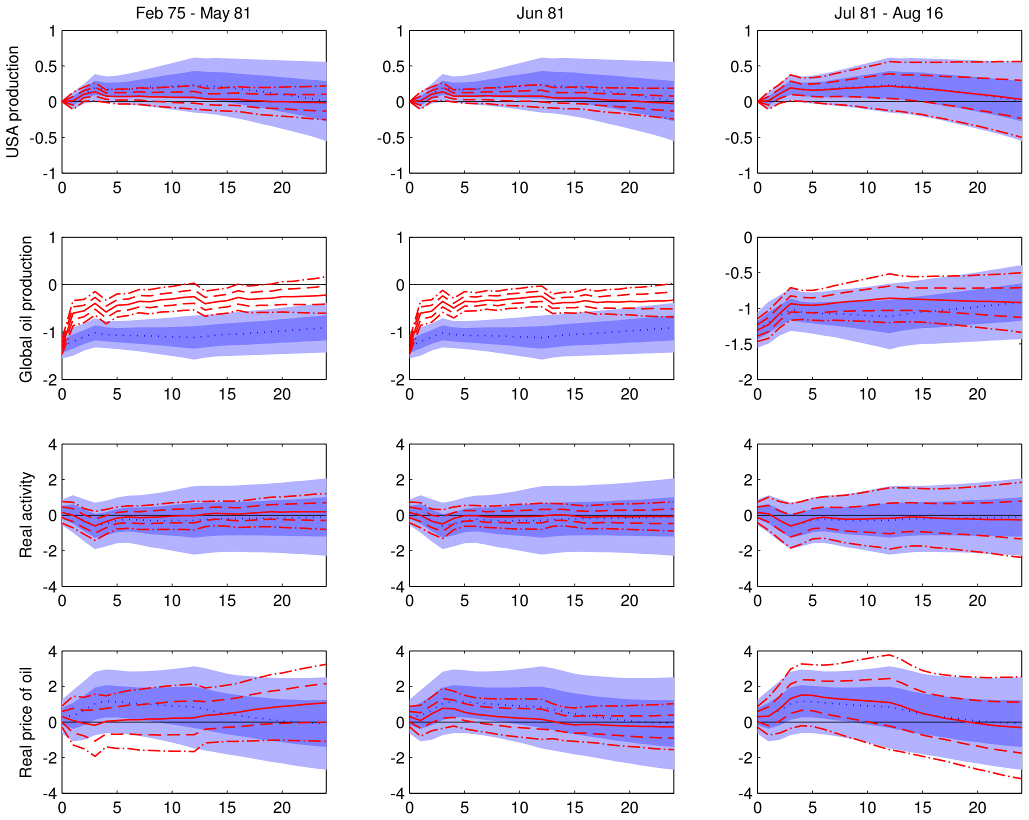
Oil–market specific demand shock contribution

Note: Cumulative effect of structural shocks on the real price of crude oil.

Figure 3. Impulse Responses



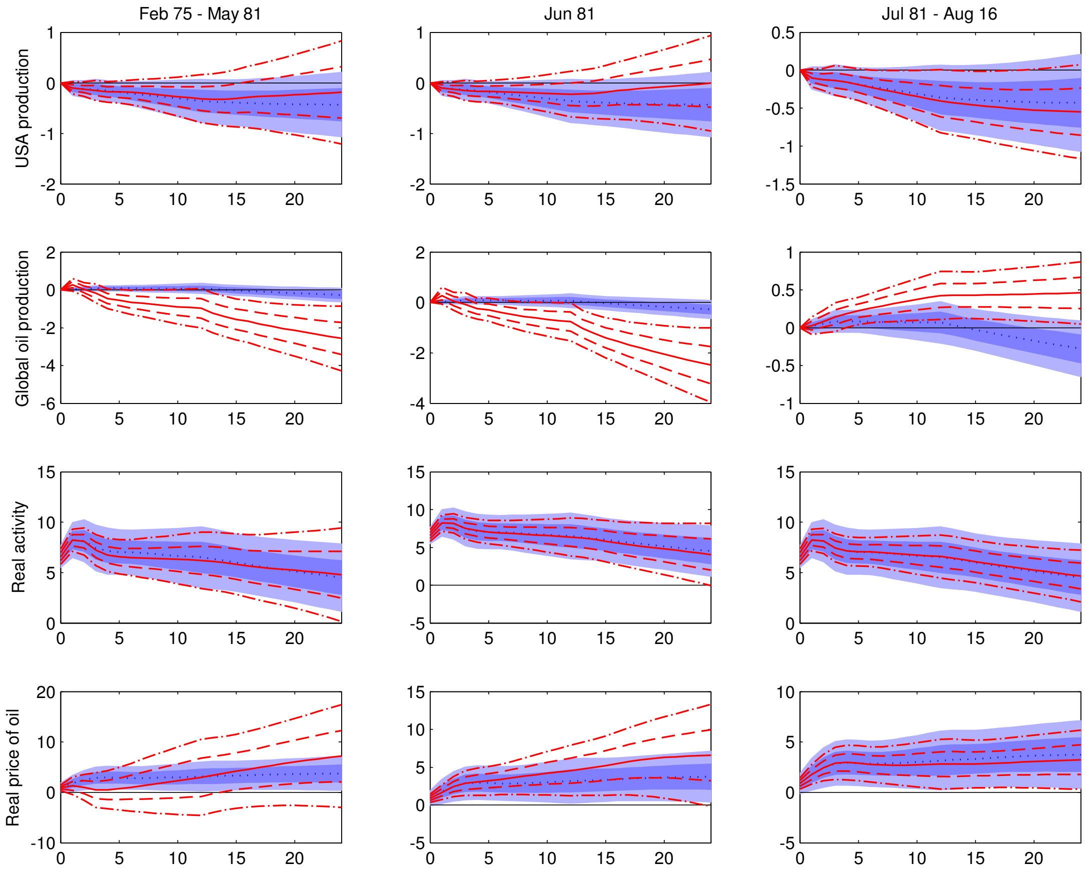
(a) Response to a U.S. supply shock



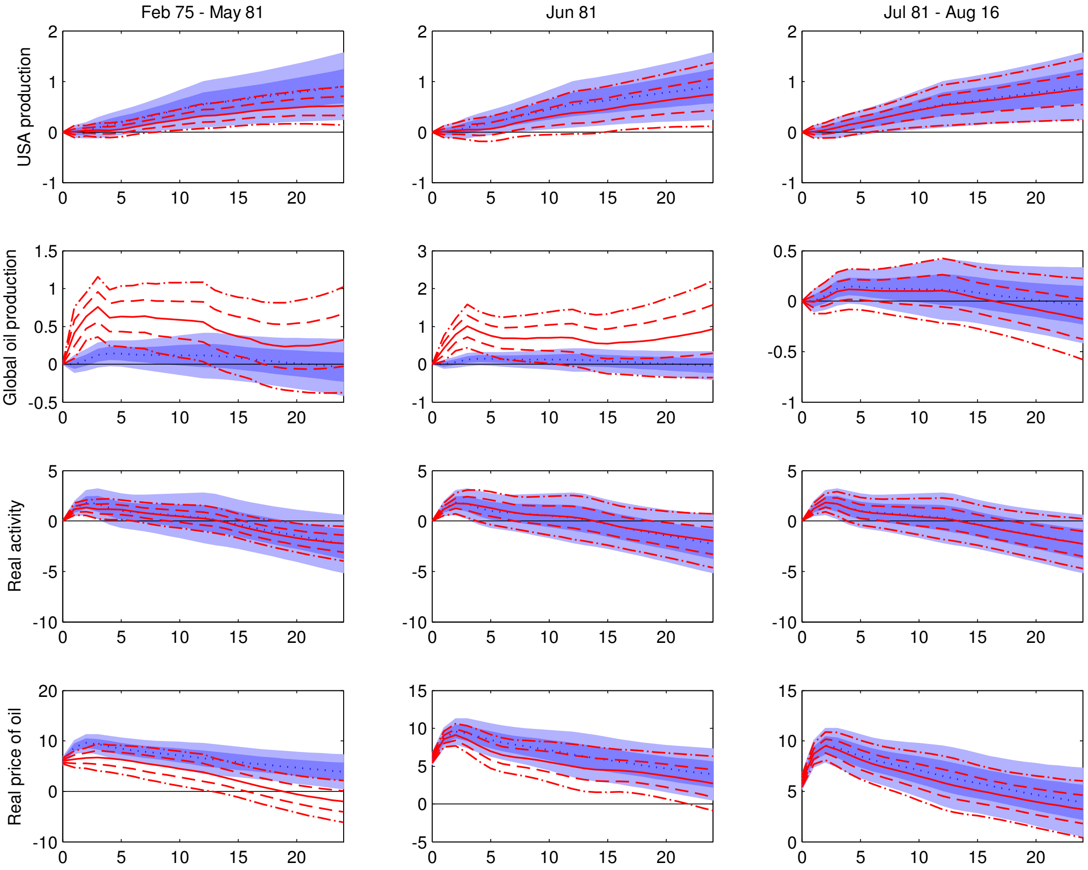
(b) Response to a global supply shock

Notes: Each graph shows the cumulated impulse responses to a shock of a common magnitude, equal to one standard deviation estimated over the whole sample with no breaks. Each of the two columns represents a sub-sample as defined by the coefficient break date of Table 3. Each plot includes one (blue dashed line) and two (blue dashed-dotted line) standard deviation confidence bands (see text). The background shaded areas provide corresponding confidence intervals around the responses (dotted line) for a constant parameter model estimated over the whole sample period.

Figure 3. Continued



(c) Response to a global demand shock



(d) Response to a oil-specific demand shock

Notes: See Fig. 3.