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Abstract

There has been much interest in the relationship between the price of crude oil, the value of the U.S. dollar, and the U.S. interest rate since the 1980s. For example, the sustained surge in the real price of oil in the 2000s is often attributed to the declining real value of the U.S. dollar as well as low U.S. real interest rates, along with a surge in global real economic activity. Quantifying these effects one at a time is difficult not only because of the close relationship between the interest rate and the exchange rate, but also because demand and supply shocks in the oil market in turn may affect the real value of the dollar and real interest rates. We propose a novel identification strategy for disentangling the causal effects of oil demand and oil supply shocks from the effects of exogenous shocks to the U.S. real interest rate and exogenous shocks to the real value of the U.S. dollar. We empirically evaluate popular views about the role of exogenous real exchange rate shocks in driving the real price of oil, and we examine the extent to which shocks in the global oil market drive the U.S. real exchange rate and U.S. real interest rates. Our evidence for the first time provides direct empirical support for theoretical models of the link between oil prices, exchange rates, and interest rates.

JEL Classification: E43, F31, F41, Q43

Keywords: Exchange rate, interest rate, oil price, global real activity, commodity, carry trade

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1. Introduction

There has been much interest in the relationship between the real price of oil, the real value of the U.S. dollar, and U.S. real interest rates since the 1980s.[1] This relationship remains poorly understood even today, however, because of the difficulty of identifying exogenous variation in these variables. We propose a structural vector autoregressive (VAR) model of the joint determination of these variables. This model is a generalization of the workhorse model of the global oil market in Kilian and Murphy (2014), which has been used in a number of recent studies.[2] Our analysis exploits a combination of sign restrictions, exclusion restrictions, and narrative restrictions motivated by economic theory and extraneous empirical evidence. We employ a novel identification strategy for disentangling the causal effects of oil demand and oil supply shocks from the effects of exogenous shocks to the real value of the dollar and to the U.S. real interest rate. This framework is rich enough to provide a comprehensive structural analysis of the interaction of the real price of oil with the real exchange rate and the U.S. real interest rate.

Our analysis sheds light on a range of issues that have been debated for many years, but have remained unresolved. For example, it has long been suspected that the real price of oil, through its effects on the terms of trade, could be a primary determinant of long swings in the trade-weighted U.S. real exchange rate (e.g., Amano and Van Norden 1998; Backus and Crucini 2000; Mundell 2002). Backus and Crucini (2000), for example, emphasized that "the question … is whether the … change in the variability of real exchange rates … is related to the similar change in the behavior of oil prices," while Mundell (2002) noted that "the question needs to be asked whether the cycle of the dollar against major currencies is related to the cycle of the dollar

[1] Early examples are Krugman (1983a,b), Golub (1983), Brown and Phillips (1986), and Trehan (1986). Recent examples include Fratzscher et al. (2014), Bützer et al. (2016), and Beckmann et al. (2018).
[2] Examples include Kilian and Lee (2014), Kilian (2017), Herrera and Rangarju (2018), Antolin-Diaz and Rubio Ramirez (2018), and Zhou (2018).

commodity prices".

At the same time, it has also been conjectured that exogenous real exchange rate fluctuations are responsible for major fluctuations in the real price of oil. For example, Brown and Phillips (1986) and Trehan (1986) suggested that the appreciation of the dollar in the early 1980s lowered the demand for oil outside of the United States and stimulated the supply of oil outside of the United States, contributing to the fall in the real price of oil. Similarly, the sustained surge in the real price of oil in the 2000 is often attributed in part to the declining real value of the dollar.

Moreover, there is a long-standing view in the literature on commodity markets that exogenous fluctuations in the U.S. real interest rate affect the real price of oil not only by shifting incentives for the storage and production of crude oil, but also by affecting the U.S. real exchange rate, further complicating the analysis (e.g., Frankel 2008; Frankel and Rose 2010). For example, the decline in the real price of oil in the early 1980s may also be explained by higher U.S. real interest rates. Finally, it has been shown that exogenous oil demand and oil supply shocks in turn cause fluctuations not only in the real price of oil, but also in the U.S. real interest rate (e.g., Kilian and Lewis 2011; Bodenstein et al. 2012).

Understanding cause and effect in the relationship between the real price of oil, the U.S. trade-weighted real exchange rate, and the U.S. real interest rate therefore requires a structural model. We first develop a structural VAR model of the relationship between the real price of oil and the real exchange rate. We then show how the insights obtained by this model may be generalized by extending this baseline model to include the U.S. real interest rate. Our analysis establishes four new facts. First, we find that all oil demand and oil supply shocks combined account for about one third of the unconditional variability in the real exchange rate, with U.S.

real interest rate shocks explaining an additional 26%. Thus, much of the variation in the U.S. real exchange rate is exogenous with respect to the global oil market, contrary to earlier conjectures.

Second, we find robust evidence of a systematic effect of exogenous real dollar movements on the real price of oil. While the effect of exogenous real exchange rate fluctuations is gradual and does not matter much for explaining sudden changes in the real price of oil, we show that it may have large cumulative effects over the course of several years. For example, we conclude that the real appreciation of the dollar in the early 1980s indeed helped gradually lower the real price of oil over time.

Third, our framework allows us to examine the impact of exogenous shocks to the U.S. real interest rate on the real price of oil. Although there is a large literature on how to model the relationship between interest rates and commodity prices, the problem of estimating the effects of exogenous changes in the U.S. real interest on the real price of oil has proved elusive to date, because fluctuations in global real activity and in the real exchange rate tend to confound these effects in the data. Our structural VAR analysis provides the first direct empirical evidence for a causal link from U.S. real interest rates to real commodity prices, as described by Frankel (1984, 2008, 2014) and Barsky and Kilian (2002), among others, while accounting for the endogeneity of all model variables. The structural VAR framework allows us to empirically evaluate the predictions of Frankel's commodity market model and to quantify the effects in question.

Our analysis provides support for some implications of Frankel's model, while showing others to be quantitatively unimportant or not robust to generalizations of this model. We show that an exogenous increase in the U.S. real interest rate causes only a modest decline in the real price of oil and this effect tends to be short-lived. The real value of the dollar appreciates strongly and persistently, and the level of global real activity declines. Notwithstanding the higher opportunity cost of holding inventories emphasized by Frankel, on balance, oil inventories increase slightly, reflecting the decline in global real activity. There is no appreciable response in global oil production, suggesting that the greater incentive for extracting crude oil emphasized by Frankel is offset by the higher capital cost of investing in future oil production. While exogenous changes to the U.S. real interest rate have important effects on the real exchange rate, U.S. real interest rates are much less sensitive to exogenous changes in the U.S. real exchange rate.

Fourth, our results raise the question of whether existing models of the global oil market that do not explicitly model real exchange rate dynamics and real interest rate fluctuations remain adequate for understanding the evolution of the real price of oil. We show that, with few exceptions, previous accounts of the ups and downs in the real price of oil remain approximately correct, although in some cases the mechanisms become more complicated. For example, our analysis sheds new light on how the surge in the real price of oil between 2003 and mid-2008 came about. We find that the real depreciation of the U.S. dollar helped reinforce the surge in flow demand caused by the economic boom in emerging economies. It is, in fact, the second most important explanation of this sustained surge in the real price of oil. By itself, it accounts for a cumulative increase of 50% in the real price of oil compared with a 65% cumulative increase caused by demand shocks directly associated with the global business cycle. In contrast, real interest rate shocks explain only a 9% cumulative increase in the real price of oil during this episode. Our evidence challenges the popular view that the U.S. Federal Reserve was responsible for rising real oil prices in the 2000s. Nor do we find support for the view that loose monetary policy contributed to the surge in the real price of oil in 1979/80 and its decline in the early

1980s (Barsky and Kilian 2002).

The remainder of the paper is organized as follows. In section 2, we discuss the difficulty of disentangling exogenous variation in the real price of oil and in the real value of the dollar. In section 3, we propose a structural econometric model of this relationship with particular attention to the economic rationale of the identifying restrictions. In section 4, we study the relationship between the real price of oil and the real value of the dollar through the lens of this structural model. In section 5, we extend the analysis to allow for a separate real interest rate channel and examine to what extent this extension affects the role of real exchange rate shocks as well as oil demand and supply shocks. The concluding remarks are in section 6.

2. The Identification Problem

Figure 1 shows the evolution of the trade-weighted U.S. real exchange rate (expressed in units of foreign currency per U.S. dollar) and of the real price of oil. The plot shows that, more often than not, the real price of oil increased, when the real trade-weighted value of the U.S. dollar declined, and it declined, when the real trade-weighted value of the U.S. dollar increased. This relationship is by no means strong nor does it hold at all points in time. For example, the contemporaneous correlation between the real price of oil and the U.S. trade-weighted real exchange rate is only -0.23 in log levels and -0.18 in growth rates. Moreover, there are many episodes during which there appears to be a systematic negative relationship at least at lower frequency.[3]

2.1. The Effects of Real Oil Price Shocks on the Real Value of the Dollar

[3] Fratzscher et al. (2014) argue that the negative relationship between the real price of oil and the real value of the dollar is only a recent phenomenon and may be an artifact of the financialization of oil futures markets. Leaving aside that there is no credible evidence of financialization having increased the real price of oil in physical markets, as shown in Fattouh et al. (2013), Kilian and Murphy (2014) and Knittel and Pindyck (2016), the evidence in Figure 1 shows that this negative correlation can be found even in the early 1980s, before oil futures markets were developed.

One interpretation of the relationship in Figure 1 has been that there is a causal link from the real price of oil to the real exchange rate. Interest in the effects of real oil price shocks on the real exchange rate dates back to the early 1980s. Golub's (1983) and Krugman's (1983a,b) work in this regard stands out in that it focuses on the implications of an exogenous oil price increase for the real value of the dollar relative to major currencies.[4] These studies concluded that the dollar will depreciate against other major currencies if the income transfer from the United States to foreign oil producers associated with an increase in the real price of oil lowers the demand for U.S. dollars and raises the demand for other major currencies, but the authors stress that, in practice, the timing, magnitude and direction of the response of the real exchange rate to an exogenous increase in the real price of oil is highly uncertain.

The response of the real exchange rate depends, first, on how quickly OPEC expenditures adjust to higher oil revenues. Second, it depends on how large the U.S. share in OPEC asset holdings is compared with the U.S. share in OPEC oil revenues. Third, it depends on whether the U.S. share of world oil imports is more or less than its contribution to OPEC oil exports. Fourth, it also depends on how high the U.S. price elasticity of oil demand is compared with that of other oil importing countries. Moreover, in practice, the analytical framework of Golub (1983) and Krugman (1983a,b) must be extended to account for market expectations about future changes in the real value of the dollar and central banks intervening in the foreign exchange market in an effort to stabilize the exchange rate or changes in the value of foreign asset holdings. In addition, standard theoretical models do not allow for the fact that the nominal exchange rates of many foreign oil producers are pegged with respect to the dollar. Nor do these models allow for the

[4] In contrast, some other theoretical studies relate not to the trade-weighted U.S. real exchange rate, but to the U.S. real exchange rate relative to oil- producing countries (Bodenstein et al. 2011). This distinction is important, not only because of the small share of crude oil in world trade, but because the adjustment of the real exchange rates depends on the multilateral trade links and capital flows between the countries included in the trade-weighted U.S. real exchange rate.

fact that the real price of oil is determined endogenously in global markets by the interplay of the forces of demand and supply or for general equilibrium effects.[5] Thus, it is important to assess the sign and magnitude of the response of the trade-weighted U.S. real exchange rate empirically.

2.2. The Effects of Exogenous Real Exchange Rate Shocks on the Real Price of Oil

An alternative explanation of the evidence in Figure 1 is that exogenous real exchange rate shocks drive the real price of oil. Because oil is traded in U.S. dollars, an exogenous depreciation of the U.S. dollar relative to its major trading partners lowers the cost of imported crude oil in these countries and thus stimulates the demand for crude oil, causing an increase in the real price of crude oil in global markets. In this sense, exogenous real exchange rate depreciations are similar to positive shocks to the flow demand for industrial commodities, as discussed in Kilian (2009) and Kilian and Murphy (2014). Both shocks are expected to raise global real activity and the real price of oil, although they differ in other dimensions.

In addition, a depreciation of the dollar may also cause a reduction in the production of oil abroad, reinforcing the upward pressure on the real price of oil. For example, a depreciation of the U.S. dollar relative to the Canadian dollar makes Canadian oil producers less profitable and may cause oil production to decline. This effect may be reversed, in practice, if oil producers seek to stabilize their oil revenue by increasing oil production. It may also be reversed to the extent that the real depreciation of the dollar increases the demand for crude oil because the resulting increase in the global real price of oil stimulates global oil production. Thus, the sign of the response of global oil production to real exchange rate shocks is ambiguous.

[5] A notable exception is the theoretical analysis in Bodenstein et al. (2011) which addresses the latter two concerns, but only in the context of a model of the value of the U.S. dollar relative to the currencies of oil exporting countries.

2.3. Why it is difficult to interpret the correlation between changes in the real exchange rate and in the real price of oil

The possibility of two-way causality between the real exchange rate and the real price of oil makes the interpretation of the apparent negative correlation between the real price of oil and the trade-weighted U.S. real exchange rate difficult. We clearly need to be careful, in general, not to interpret the negative co-movement between the U.S. trade-weighted real exchange rate and the real price of oil as evidence for a causal relationship in one direction or in the other direction.

The empirical analysis of this relationship is further complicated by the fact that neither the real exchange rate nor the real price of oil is exogenous, as assumed in the few empirical studies studying this relationship.[6] To the extent that both variables are jointly determined by the same economic forces, it is unlikely that there exists any causal relationship between these variables. As Mundell (2002) recognized, "there is not necessarily a direct causal relationship between the strength of the dollar in currency markets and commodity prices. It could be that the same factors that cause the dollar cycle also cause the commodity cycle". For example, an increase in the flow demand for industrial commodities may both raise the real price of oil and depreciate the real value of the dollar. Understanding the empirical correlation between changes in the real price of oil and in the real value of the dollar thus requires a dynamic structural model of the joint determination of both variables, as discussed in the next section.

3. A Structural VAR Model of the Relationship between the Real Price of Oil and the Real Value of the Dollar

The starting point of our analysis is the global oil market model of Kilian and Murphy (2014),

[6] For example, Amano and van Norden (1998) postulated that the real price of oil is primarily determined by exogenous oil supply shocks associated with political events in the Middle East and hence may be viewed exogenous with respect to the real exchange rate. This view has long been overturned in the oil market literature (Kilian 2008).

which has become the workhorse model for assessing the relative importance of oil demand and oil supply shocks for the evolution of the real price of oil (e.g., Kilian and Lee 2014; Kilian 2017; Antolin-Diaz and Rubio-Ramirez (2018); Herrera and Rangaraju 2018).[7] This structural VAR model does not explicitly model the real exchange rate. It implicitly postulates that exogenous real exchange rate shocks have the same effects on the model variables as demand shocks associated with unexpected variation in the global business cycle. We relax this assumption.

Our baseline VAR model specification includes the percent change in the global production of crude oil (Δq_t), as reported by the U.S. Energy Information Administration; a measure of cyclical variation in global real economic activity (rea_t) originally proposed by Kilian (2009); a proxy for the change in global crude oil inventories, as discussed in Kilian and Murphy (2014) and Kilian and Lee (2104); and the log real price of oil (p_t) obtained by deflating the U.S. refiners' acquisition cost for imported crude oil by the U.S. CPI for all urban consumers.[8] We also include the log of the trade-weighted U.S. real exchange rate (rxr_t), as reported by the Federal Reserve Board (Loretan 2005).[9] Throughout the paper, real exchange rates are defined in foreign consumption units relative to U.S. consumption units, with an increase in the real exchange rate representing a real appreciation of the dollar. All data are monthly and have been seasonally adjusted. The sample extends from 1973.2 to 2018.6.

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[7] Unlike the earlier global oil market models such as Kilian (2009) or Kilian and Murphy (2012) this model explicitly incorporates shocks to storage demand reflecting shifts in oil price expectations.

[8] The Kilian index of global real economic activity is based on data for bulk dry cargo ocean shipping freight rates. It is arguably the most widely used indicator of global real economic activity in the oil market literature. As discussed in Kilian and Zhou (2018a), this index has several conceptual advantages compared with proxies for global industrial production when it comes to modeling the global market for crude oil. We use the corrected version of the index as discussed in Kilian (2019).

[9] Like the log real price of oil, the log real exchange rate exhibits persistent fluctuations about a constant mean, allowing us to treat these time series as covariance stationary. We do not employ unit root tests because unit root tests are known to lack power against persistent stationary alternatives (Kilian and Lütkepohl 2017).

Let $y_t = (\Delta q_t, \text{rea}_t, \text{p}_t, \Delta \text{inv}_t, \text{rxr}_t)'$ be generated by the covariance stationary structural VAR(24) model

$$B_0 y_t = B_1 y_{t-1} + ... + B_{24} y_{t-24} + w_t,$$

where the stochastic error w_t is mutually uncorrelated white noise and the deterministic terms have been suppressed for expository purposes. Setting the lag order to 24 allows the model to capture long cycles in the real price of oil and avoids the pitfalls of data-based lag order selection (Kilian and Lütkepohl 2017). The reduced-form errors may be written as $u_t = B_0^{-1} w_t$, where B_0^{-1} denotes the structural impact multiplier matrix,

$$u_t = y_t - A_1 y_{t-1} - ... - A_{24} y_{t-24},$$

and $A_l = B_0^{-1} B_l$, $l = 1, ..., 24$. The $\{ij\}th$ element of B_0^{-1}, denoted b_{ij}^0, represents the impact response of variable i to structural shock j, where $i \in \{1, ..., 5\}$ and $j \in \{1, ..., 5\}$. Given the reduced-form estimates, knowledge of B_0^{-1} suffices to recover estimates of the structural impulse responses, variance decompositions and historical decompositions from the reduced-form estimates, as discussed in Kilian and Lütkepohl (2017).

Let $w_t = \left(w_t^{\text{flow supply}}, w_t^{\text{flow demand}}, w_t^{\text{storage demand}}, w_t^{\text{other oil demand}}, w_t^{\text{rxr}} \right)'$, where $w_t^{\text{flow supply}}$ denotes a shock to the flow supply of oil, $w_t^{\text{flow demand}}$ denotes a shock to the flow demand for oil, $w_t^{\text{storage demand}}$ denotes a shock to storage demand (or, equivalently, speculative demand), and $w_t^{\text{other oil demand}}$ is a conglomerate denoting all other shocks to the demand for oil such as shocks to preferences for oil, shocks to the oil inventory technology, or politically motivated changes in the Strategic Petroleum Reserve. As in the related literature, our analysis focuses on the first three oil market shocks that have an explicit structural interpretation. Finally, w_t^{rxr} denotes an exogenous shock to the trade-weighted U.S. real exchange rate, defined as an unexpected change in the real exchange rate not caused by oil demand or oil supply shocks. All shocks are normalized to represent a shock that raises the real price of oil.

It is useful to elaborate on the nature of the real exchange rate shock. In standard open economy models with non-state contingent bonds, the exchange rate is governed by the uncovered interest parity (UIP) condition. This no-arbitrage condition pins down the nominal exchange rate. As long as UIP holds, there is no room for exogenous exchange rate shocks in these models. We can, however, interpret the exchange rate shock in the baseline VAR model as being driven by unmodeled shifts in global interest rate differentials that are not implicitly explained by the other structural shocks in the model. Moreover, even in the absence of shocks entering the UIP condition directly, many shocks can influence the nominal exchange rate. For example, with home bias in consumption, an exogenous consumption preference shock abroad would be indistinguishable from a shock that temporarily suspends the no-arbitrage condition underlying the UIP relationship, since we do not explicitly model consumption abroad. To the extent that such a shock is not captured by the demand shocks in the baseline VAR model, it would result in exogenous variation in the real exchange rate in the VAR model. In this sense, the real exchange rate shock may be viewed as a measure of exogenous variation in the unmodeled determinants of the real exchange rate.

3.1. Identifying Restrictions

The model consists of two blocks. One block includes the first four variables and describes the global oil market. The model imposes sign restrictions on the elements of the oil market block. These inequality restrictions render the model set-identified. The other block consists of the trade-weighted U.S. real exchange rate. The model is block recursive in that it imposes that there is no contemporaneous feedback from the real exchange rate to the oil market variables. The real exchange rate is allowed to respond contemporaneously to all structural shocks. The sign and exclusion restrictions on the elements of B_0^{-1} are described in expression (1):

$$u_t = \begin{pmatrix} u_t^{\Delta q} \\ u_t^{\text{rea}} \\ u_t^{\text{p}} \\ u_t^{\Delta inv} \\ u_t^{\text{rxr}} \end{pmatrix} = B_0^{-1} w_t = \begin{bmatrix} - & + & + & b_{14}^0 & 0 \\ - & + & - & b_{24}^0 & 0 \\ + & + & + & b_{34}^0 & 0 \\ - & - & + & b_{44}^0 & 0 \\ b_{51}^0 & b_{52}^0 & b_{53}^0 & b_{54}^0 & b_{55}^0 \end{bmatrix} \begin{pmatrix} w_t^{\text{flow supply}} \\ w_t^{\text{flow demand}} \\ w_t^{\text{storage demand}} \\ w_t^{\text{other oil demand}} \\ w_t^{\text{exogenous rxr}} \end{pmatrix}. \qquad (1)$$

We also impose bounds on the one-month price elasticities of oil demand and oil supply, which may be expressed as inequality restrictions on functions of selected impact responses. Finally, we impose dynamic sign restrictions on selected structural impulse response functions and narrative sign restrictions on the historical decompositions.

3.1.1. Exclusion restrictions

The exclusion restrictions on B_0^{-1} are central for disentangling the effects of exogenous real exchange rate shocks from oil demand and oil supply shocks. The block-recursive structure of B_0^{-1} embodies the assumption that the real price of oil is predetermined with respect to the trade-weighted U.S. real exchange rate. Put differently, innovations in the real price of oil may move the real exchange rate contemporaneously, but exogenous shocks to the real exchange rate will not affect the real price of oil within the same month, but only with a delay. The restriction that u_t^p does not depend on u_t^{rxr} implies that B_0 is block recursive and hence $b_{15}^0 = b_{25}^0 = b_{35}^0 = b_{45}^0 = 0$.

These exclusion restrictions are motivated by independent empirical evidence in Kilian and Vega (2011) who studied the response of the exchange rate and the price of oil to a wide range of daily U.S. macroeconomic news. News here is defined as the difference between announcements about the latest macroeconomic data releases and market expectations about these announcements immediately before their release. Kilian and Vega assessed the individual and joint effect on the price of oil of about 30 U.S. macroeconomic news including the nonfarm payroll, the Fed target rate, the unemployment rate, the consumer price index, and housing starts, for example. They found no response in the daily price of oil within the 20 business days following these news shocks, but a strong and statistically significant response in the exchange rate.[10] This evidence suggests that there cannot be indirect feedback from exogenous exchange rate variation to the price of oil at the one-month horizon because, if there were, the price of oil would have shown a strong and statistically significant response to U.S. macroeconomic news much like the exchange rate.[11] Thus, the price of oil is predetermined with respect to the exchange rate at monthly frequency. Although the evidence in Kilian and Vega (2011) regarding the exchange rate responses is based on the response of nominal dollar-Euro exchange rates, one would expect this result to extend also to the U.S. real exchange rate, given that much of the variation in the real exchange rate is driven by the nominal exchange rate.[12]

The identifying assumption that the real price of oil is predetermined with respect to the real exchange rate is also consistent with evidence from a natural experiment that took place in 1985. The Plaza Accord of September 1985 is widely considered the most dramatic policy

[10] Fratzscher et al. (2014) confirmed these results using more recent data. Datta et al. (2018), using a much smaller set of U.S. macroeconomic news than Kilian and Vega (2011) and restricting attention to the response of the price of oil to these news within the same day, show that during the six years when the zero-lower bound was binding, one of their twelve news variables had a much larger effect on the price of oil than reported in Kilian and Vega (2011). Unlike earlier studies, however, Datta et al. do not report data-mining robust p-values making it impossible to judge the statistical significance of their estimates, and the R^2 of their regression is only 3%, so the extent of the feedback appears negligible even during the zero-lower bound period.

[11] Our argument requires us to identify exogenous variation in the exchange rate. The source of this exogenous variation is not important for the argument. In particular, the macroeconomic news in question need not be global. U.S. macroeconomic news is sufficient.

[12] It is worth noting that this evidence refutes the popular view in the financial press that the U.S. dollar price of oil is determined by the nominal foreign exchange value of the U.S. dollar. For example, recently, the Wall Street Journal suggested that “oil prices … got a lift from a … slide in the dollar against other currencies” (“U.S. Oil Markets Rise as Saudis Dismiss Supply Concerns”, Wall Street Journal, July 19, 2018, by S. Said and D. Molinsky). While there is a slight negative correlation between these variables, the implicit assertion that depreciations are exogenous with respect to the oil market, allowing us to interpret this correlation as a causal relationship, is not only difficult to justify a priori, but is rejected by the data.

initiative in the dollar foreign exchange market since Richard Nixon floated the currency in 1973 (Frankel 2016). The left panel of Figure 2 shows that, between late 1980 and March 1985, the dollar had appreciated substantially in real terms. The Plaza Accord involved an agreement that central banks would act to depreciate the U.S. dollar against the Japanese Yen and the Deutsche Mark by coordinated interventions in currency markets. Arguably as a result of this agreement, the earlier appreciation was completely undone by April 1988. Given that the success of this intervention was by no means obvious ex ante, it makes sense to treat the resulting change in the real exchange rate as an exogenous shock with respect to the oil market. Yet, the real dollar depreciation between September and December 1985, before the collapse of OPEC in 1986, was not associated with an increase in the real price of oil. This fact suggests that the causal effect of an exogenous change in the real exchange rate must be quite small in the short run, consistent with the restriction that the instantaneous feedback from real exchange rate shocks to the oil market variables is zero in the impact period.

The right panel of Figure 2 also allows us to examine an episode in which there is no apparent exogenous variation in exchange rate, but exogenous variation in the real price of oil. The invasion of Kuwait in August 1990 is a prime example of a shock in the global market for crude oil that is exogenous with respect to the real exchange rate. The effect of this shock was a spike in the real price of oil in the second half of 1990. The surge in the real price of oil in late 1990 coincided with a modest drop in the real exchange rate. Although the U.S. Federal Reserve and European central banks intervened repeatedly to stabilize the dollar in 1991-92, as the U.S. economy slid into recession, there were no similar interventions in the second half of 1990, so we can be fairly confident that the exogenous increase in the real price of oil was the determinant of the depreciation of the U.S. dollar in the second half of 1990.[13] Thus, the real price of oil appears predetermined with respect to the real value of the dollar, but the real value of the dollar responds even contemporaneously to oil demand and oil supply shocks, consistent with the structure of the baseline model.

3.1.2. Sign restrictions in the oil market block

The sign restrictions on the oil market block are conventional. An unexpected disruption of the flow supply of crude oil is represented as an unexpected reduction in global oil production that raises the real price of oil and lowers global real activity and crude oil inventories. As in related studies, the sign restriction on the response of global real activity to a negative flow supply shock is imposed not only on impact, but for the first 12 months. This additional dynamic sign restriction ensures that this response corresponds to conventional views of the effects of oil supply shocks.

An exogenous increase in flow demand raises global real activity, global oil production and the real price of oil, but lowers oil inventories. An exogenous increase in storage demand raises oil inventories, the real price of oil, and global oil production, while lowering global real activity. We also follow the recent literature in imposing the restriction that the response of the real price of oil to the first three shocks is positive not only on impact, but for the first 12 months (e.g., Inoue and Kilian 2013; Kilian 2017). The residual oil demand shock is implicitly defined as the complement to the other shocks.

3.1.3. Bounds on the impact price elasticities

The sign restrictions on the impact responses are strengthened by imposing bounds on the impact price elasticities of demand and supply. Since these elasticities can be expressed as functions of

[13] The only coordinated central bank exchange-rate intervention in 1990 took place in March 1990, well before the invasion of Kuwait.

the impact responses to exogenous supply and demand shocks, respectively, elasticity bounds can be written as inequality restrictions on nonlinear functions of the elements of B_0^{-1} (Kilian and Murphy 2012, 2014).

In defining the price elasticity of oil demand we avoid the common mistake of imposing the restriction that the production of crude oil equals the consumption of crude oil at each point in time. We instead incorporate the response of oil inventories in measuring changes in the use of oil in response to exogenous flow supply shocks, as discussed in Kilian and Murphy (2014). We impose that the implied impact price elasticity of demand cannot exceed the long-run price elasticity of oil demand, which is set to -0.8 based on extraneous microeconomic estimates in Hausman and Newey (1995) and Yatchew and No (2001).

We also impose a bound on the impact price elasticity of oil supply, following the arguments in Kilian and Murphy (2012). There are two motivations for imposing a bound close to zero. First, economic theory implies that this elasticity should be close to zero, given the high costs of shutting down and reopening conventional oil wells. In this case, the optimal response of oil producers to an oil price change induced by oil demand shifts is to adjust investment in future oil production rather than the level of oil production from existing wells (Anderson, Kellogg, and Salant 2018). A similar point was made by Kilian (2009) who attributed the sluggishness of the supply response to the "costs of adjusting oil production and the uncertainty about the state of the crude oil market" (p. 1059).

Second, although there are no microeconomic estimates of the global one-month price elasticity of oil supply, recent microeconomic estimates based on regional data from the United States are all close to zero and not significantly larger than zero, consistent with economic theory (Anderson et al. 2018). The largest estimate in this literature based on data for North Dakota with

0.035 is below our upper bound and statistically indistinguishable from zero (Bjørnland et al. 2017). Using a more comprehensive data set for U.S. oil producers from Texas, North Dakota, California, Oklahoma and Colorado, Newell and Prest (2017) estimate a one-month price elasticity that is effectively zero for conventional crude oil.[14] The upper bound of 0.04 that we impose on the aggregate global oil supply elasticity in the structural VAR model is larger than these oil supply elasticity estimates obtained from U.S. data.[15]

3.1.4. Narrative sign restrictions

These identifying restrictions are complemented by additional narrative sign restrictions. Narrative sign restrictions refer to restrictions in the signs or relative magnitudes of structural shocks or historical decompositions. They were first employed by Kilian and Murphy (2014) for selecting the most economically plausible models among the set of admissible structural models. This idea was subsequently generalized and formalized by Antolin-Diaz and Rubio-Ramirez (2018) and Zhou (2018).

Our narrative sign restrictions relate to events in 1990, when Iraq invaded Kuwait. It is uncontroversial that the resulting spike in the oil price in 1990 was caused by a combination of negative flow supply and positive storage demand shocks. We impose the restriction that not only the flow demand shock made at best a minimal contribution to this oil price increase, but that both the flow supply shock and the storage demand shock had some impact. In practice, we

[14] One potential concern is that the rise of U.S. shale oil production after 2008 may have increased the value of the impact price elasticity of oil supply in global markets in recent years (Kilian 2017). Bjørnland, Nordvik, and Rohrer (2017) report a one-month price elasticity of North Dakota shale oil producers of 0.076. If we take their point estimate at face value, given a share of 4% of shale oil production in global oil production in 2015, the global price elasticity of oil supply, defined as $0.035*0.96+0.076*0.04=0.037$ would be essentially the same as their baseline estimate of 0.035, illustrating that the price elasticity of oil supply is robust to the introduction of the shale oil technology. Based on the more comprehensive micro data set of U.S. producers of shale oil and conventional oil in Newell and Prest (2017), the implied aggregate price elasticity of oil supply is well below 0.01.

[15] Further discussion of the derivation of this bound and the sensitivity of the VAR estimates to relaxing this bound can be found in Kilian and Murphy (2012), Herrera and Rangaraju (2018), Zhou (2018), and Kilian and Zhou (2018b).

impose the narrative sign restriction that the cumulative effect of the flow supply shock from June 1990 to October 1990 exceeded 0.1 (or approximately 10%) on a log-scale and that of the storage demand shock also exceeded 0.1, while that of the flow demand shock is bounded from above by 0.1. Our results are robust to reasonable variation in these bounds. We include the month leading up to this war, given evidence in Kilian and Murphy (2014) that rising political tensions in the Middle East increased storage demand even before the war broke out.

3.2. Estimation and Inference

Given the inequality and exclusion restrictions, the set of admissible structural models is constructed, as discussed in Kilian and Lütkepohl (2017). Let $A = \left[A_1, ..., A_p \right]$ denote the autoregressive slope parameters and Σ_u the residual variance-covariance matrix. For a given realization of A and of the lower triangular matrix $P = chol(\Sigma_u)$ with positive diagonal elements, we draw realizations of the matrix Q from the space of $K \times K$ orthogonal matrices by generating at random many $(K-1) \times (K-1)$ matrices W consisting of $NID\left(0,1\right)$ draws, where K is the number of model variables. For each W, we apply the QR decomposition $W = \bar{Q}R$ with the diagonal of the upper triangular matrix R normalized to be positive, and let

$$Q = \begin{bmatrix} \bar{Q} & 0 \\ 0 & 1 \end{bmatrix}.$$

Then a candidate solution for B_0^{-1} is $PQ,$ since $QQ' = I_K.$ We use each of these candidate solutions in conjunction with A to construct the candidate structural models and their structural impulse responses. Given a diffuse Gaussian-inverse Wishart prior distribution for the reduced-form parameters, this procedure may be repeated for a large number of posterior draws for $\left(A, \Sigma_u\right)$ to account for parameter estimation uncertainty. The set of admissible structural models includes all candidate models whose responses satisfy the inequality restrictions.

Sign-identified VAR models generate no point estimates. Some users report so-called posterior median response functions instead. Several studies have observed that this practice confounds estimates from different structural models and tends to distort the dynamics implied by the estimated models (for a review see Kilian and Lütkepohl 2017). Moreover, the associated pointwise impulse response error bands understate the true uncertainty about the model estimates. There are readily available econometric solutions to this problem in sign-identified VAR models, as discussed in Inoue and Kilian (2013), but not for models including additional exclusion restrictions.

In this paper, we instead report the full set of impulse response functions for all admissible structural models. This approach is possible because in large models identified by many inequality, exclusion, and narrative restrictions the degree of uncertainty tends to be smaller than in lower-dimensional models. We illustrate the extent to which the impulse response estimates depend on identification uncertainty as opposed to estimation uncertainty. For variance decompositions, we report posterior means, given that pointwise posterior medians violate the adding-up constraint underlying the construction of variance decompositions. Finally, for historical decompositions, we report posterior median estimates for the cumulative contribution of each shock over selected subperiods. Inference is conducted based on the posterior quantiles for the cumulative contribution of each shock. This novel approach avoids confounding estimates from different structural models.[16]

4. Empirical Results

[16] In constructing the posterior distribution we bound the dominant root of the VAR process at 0.991019. This restriction implies that the effect of a one percent shock at the beginning of the sample on the model data is reduced to at most 1% at the end of a sample. This bound ensures that posterior draws from the historical decomposition closely resemble the actual historical data for the real price of oil. Without this bound, no meaningful analysis of the cumulative effects of the structural shocks on the real price of oil or the real exchange rate is possible.

Economic theory predicts that an unexpected exogenous real depreciation of the dollar lowers the cost of oil imports for other countries. The lower cost of oil in foreign consumption units is expected to stimulate the demand for crude oil and other globally traded commodities from abroad, causing an increase in global real activity and in the real price of oil. The expected response of global oil production is more ambiguous, as discussed in section 2. Likewise, economic theory does not generate clear-cut predictions for the response of the real exchange rate to oil market shocks that raise the real price of oil.

4.1. Identification Uncertainty in the Baseline Model

Figure 3 shows the impulse response function estimates for all admissible models obtained for 100,000 draws for the rotation matrix, conditional on the maximum likelihood estimate of the reduced-form VAR model. This approach allows us to first focus on the identification uncertainty inherent in the baseline model, before addressing parameter estimation uncertainty. Identification uncertainty here refers to the uncertainty about the value of the structural impact multiplier matrix B_0^{-1} arising from the use of inequality restrictions for identification.[17]

The responses within the oil market block of the model are very similar to those in related studies of the global oil market based on similar identifying assumptions (see, e.g., Kilian and Murphy 2014; Kilian and Lee 2014; Kilian 2017; Zhou 2018). Most interestingly, the last column suggests that oil market shocks that raise the real price of oil also cause a decline in the real value of the U.S. dollar in the short-run. At horizons beyond half a year, the sign of the responses tends to become more ambiguous.

An unexpected real depreciation of the U.S. dollar causes a decline in oil inventories and an increase in global real economic activity, global oil production and the real price of oil,

[17] Note that the responses to the real exchange rate shock are uniquely identified by the block recursive structure of the model. These responses are not subject to identification uncertainty.

consistent with the conventional wisdom that a lower value of the dollar stimulates foreign flow demand for commodities and hence the real price of commodities. The response of the real price of oil is smaller than the oil price responses to other shocks, however. The effect on global oil production is negligible in the short run, but positive at longer horizons.

Given that exogenous real exchange rate shocks affect the oil market, while oil market shocks affect real exchange rates, it is useful to decompose the historical evolution of the real price of oil into the cumulative effects of each of the structural shocks, as shown in Figure 4. Although there is some identification uncertainty in these estimates, generally the identification uncertainty tends to be small. For example, there is no question that the main explanation of the surge in the real price of oil in the 2000s was the cumulative effect of mostly positive flow demand shocks between 1999 and mid-2008. None of the other shocks in the model is able to explain this persistent increase. Qualitatively, the first three panels confirm the patterns found in conventional oil market models excluding the real exchange rate (Zhou 2018).

Exogenous real exchange rate shocks also help explain the evolution of the real price of oil. The bottom panel of Figure 4 provides evidence that exogenous real exchange rate shocks contributed to the decline in the real price of oil in the early 1980s and after June 2014, as conjectured by Brown and Phillips (1986) and Trehan (1986), while reinforcing the surge in the real price of oil between 2003 and mid-2008 and supporting higher real oil prices in the 1990s. The magnitude of these cumulative effects is much lower and more slowly building than for other shocks, however.

Figure 5 shows the corresponding historical decomposition for the trade-weighted U.S. real exchange rate. It illustrates that oil demand and supply shocks are not an important determinant of the real value of the dollar. There is little identification uncertainty about this point. Rather, much of the variation in the real exchange rate is caused by exogenous real exchange rate shocks. The bottom panel shows the variation in the U.S. real exchange rate that is exogenous with respect to the oil market. Starting in late 1980, the dollar exogenously appreciated in real terms, reaching a peak in February 1985, a few months before the Plaza Accord, before depreciating. Starting in 1995, the dollar appreciated again for reasons unrelated to global oil markets, reaching a peak in 2002.10. From late 2002 to early 2008, the dollar depreciated persistently. Finally, from 2011 until the end of 2016, the real dollar value recovered. Figure 5 thus tentatively suggests that there is large exogenous variation in the real exchange rate that oil market models need to take into account.

4.2. The Baseline Model with Parameter Estimation Uncertainty

The results thus far have been designed to help us illustrate the identification uncertainty about the relationship between oil and foreign exchange markets. These preliminary results ignore the fact that the reduced-form VAR model parameters are not estimated precisely and hence understate the full extent of the uncertainty about the structural model. Having examined the identification uncertainty about the model responses in isolation, we now allow for both identification and parameter estimation uncertainty based on 100,000 draws from reduced-form posterior with 20,000 draws of the rotation matrix each. Figure 6 shows that allowing for estimation uncertainty does not materially change the response estimates in the oil market block other than to widen the set of admissible models. The patterns of the responses remain economically plausible.

The responses of the real exchange rate to oil market shocks become much less precisely estimated to the point that their sign is indeterminate. In contrast, the responses to an unexpected real depreciation of the dollar remain robust. There is clear evidence for a decline in oil inventories. The responses of global oil production, the real price of oil, and global real activity are only imprecisely estimated, but much of the posterior probability mass is in the positive range. The response of global oil production to a real depreciation is close to zero in the short run, consistent with supply being inelastic, but tends to be positive at longer horizons much like the response to a positive flow demand shock. This evidence suggests that the transmission of real exchange rate shocks works through the demand side rather than the supply side.

In general, the responses of the oil market variables to exogenous real exchange rate shocks look similar to the responses to flow demand shocks. One key difference is in the magnitude of the response of global real activity, especially on impact, which suggests that the distinction between flow demand shocks and exogenous real exchange rate shocks is potentially important.

4.2.1. What drives the real exchange rate in the long run?

It has been suggested that the real price of oil, through its effects on the terms of trade, could be one of the primary determinants of long swings in the trade-weighted U.S. real exchange rate (e.g., Amano and Van Norden 1998, Backus and Crucini 2000). Prior empirical analysis of this question postulated that the real price of oil is primarily driven by exogenous oil supply shocks and hence can be treated as exogenous with respect to the real exchange rate. This premise is unrealistic (Kilian 2008). In recognition of this fact, we use our structural model to examine how shocks in the global oil market that raise the real price of oil affect the U.S. trade-weighted real exchange rate.

The upper panel of Table 1 shows that 69% of the variability in the real exchange rate is accounted for by exogenous real exchange rate shocks. The combined effect of the flow supply, flow demand and storage demand shocks is 24%, with the latter two shocks reflecting actual and expected demand shifts in the global economy more broadly. This estimate is far lower than suggested by the reduced-form correlation evidence for the U.S. real exchange rate in Amano and Van Norden (1998), but still substantial, considering that previous efforts to explain real exchange rate fluctuations have met with limited success. The exogenous shocks to the flow supply of oil highlighted in earlier studies only account for 9% of the variability of the trade-weighted U.S. real exchange rate.

4.2.2. What drives the real price of oil in the long run?

It is frequently asserted in the financial press and in policy discussions that exogenous real exchange rate shocks are one of the primary drivers of the real price of oil. This view is also prevalent among many macroeconomists (Brown and Phillips 1986; Trehan 1986). Of course, none of the studies making this case allowed for the possibility that both the real price of oil and the real exchange rate are endogenous. Table 1 shows that exogenous real exchange rate shocks account for only 14% of the variability in the real price of oil, suggesting that exogenous real exchange rate fluctuations are not nearly as important as is commonly perceived. This evidence, of course, does not rule out that real exchange rate shocks were perhaps more important during specific historical episodes. We will return to this point in section 4.2.4.

4.2.3. What drives the global real economic activity in the long run?

The primary channel by which a real depreciation of the dollar is thought to affect the global oil market is by raising the demand for oil from countries other than the United States. If so, one would expect exogenous real exchange rate shocks to account for a substantial fraction of the variance of global real economic activity. Table 1 confirms that the effect of exogenous real exchange rate shocks on the variability of global real activity is 17%, which is close to the corresponding share for the real price of oil. This evidence supports the view that the transmission works through higher demand for commodities from countries other than the United States.

4.2.4. How important are exogenous real exchange rate swings for the real price of oil?

Figure 5 highlighted the existence of long exogenous swings in the real exchange rate. The same pattern is also found after accounting for estimation uncertainty. Table 2 focuses on time periods corresponding to persistent exogenous real appreciations and real depreciations of the dollar. It summarizes the cumulative impact of real exchange rate shocks during each of these episodes on the real price of oil. The upper panel of Table 2 shows robust evidence of a systematic contribution of real exchange rate shocks to real oil price dynamics. For example, it confirms the conjecture of Brown and Phillips (1986) and Trehan (1986) that the real appreciation of the dollar in the early 1980s substantially lowered the real price of oil. The cumulative effect over the period 1980.10-1985.3 is -32%. Likewise, the real appreciation of the dollar caused a 45% decline in the real price of oil during 1995.7-2002.10 and a 15% decline in the real price of oil during 2011.6-2016.12. The latter evidence helps explain the slowdown in global commodity trade after 2011 that was documented in Kilian and Zhou (2018a). At the same time, the real depreciation of the dollar during 1985.3-1995.7 accounted for a 34% cumulative increase in the real price of oil, and the exogenous real depreciation of the dollar during 2002.10-2008.3 accounted for a 36% increase in the real price of oil. Of course, it has to be kept in mind that these cumulative effects are computed over extended time periods. On a month-by-month basis, the effects of real exchange rate shocks are typically dwarfed by those of oil demand and oil supply shocks.

4.2.5. Implications for the historical narrative of the ups and downs in the real price of oil

A question of obvious interest is whether the substantial effects of real exchange rate shocks documented in Table 2 change the historical narrative of what caused the ups and downs in the real price of oil since the late 1970s. Table 3 shows that the historical narrative remains remarkably robust with one important exception. There is widespread agreement that the primary cause of the sustained surge in the real price of oil starting in 2003 was growing flow demand associated with a global economic expansion led by emerging economies in Asia (see, e.g., Kilian 2008; Hamilton 2009; Kilian and Hicks 2013) rather than reduced oil supplies. Although the baseline model confirms that by far the most important determinant of the surge in the real price of oil between 2003.1 and 2008.6 was positive flow demand shocks (+101%), it also shows that the second most important determinant has been the unexpected real depreciation of the dollar (+37%). The original Kilian and Murphy (2014) model conflated these two effects.

Perhaps surprisingly, real exchange rate shocks did not play a dominant role during any of the other episodes. For example, Table 3 shows that the inclusion of the real exchange rate in the baseline model does not change the fact that much of the 1979/80 surge in the real price of oil must be attributed to flow demand and storage demand shocks, with flow supply shocks coming in a distant third. Likewise, we replicate the standard finding that the decline in the real price of oil in 1986 was mainly caused by lower flow demand and lower storage demand, while the oil price spike in 1990 reflected lower flow supply and higher storage demand. Table 3 also confirms that the sharp drop in the real price of oil in late 2008 during the financial crisis reflected a combination of lower flow demand and lower storage demand, while the decline in the real price of oil can be attributed in roughly equal measure to flow supply, flow demand and storage demand shocks. Although real exchange rate shocks add an extra 8% decline in the real price of oil during 2014.6-2015.12, that effect is comparatively small and imprecisely estimated.

5. The Role of the U.S. Real Interest Rate

It has been common to associate increases in the real price of oil price not only with declines in the real value of the dollar, but also with exogenous declines in the U.S. real interest rate (e.g., Frankel and Hardouvelis 1985; Barsky and Kilian 2002; Frankel 2008, 2012, 2014; Frankel and Rose 2010; Akram 2009). For example, Frankel (1984) attributes the decline in real commodity prices in the early 1980s not to the real appreciation of the dollar, as stressed by Brown and Phillips (1986) and Trehan (1986), but to high U.S. real interest rates.

This relationship may be explained by three channels. First, low real interest rates discourage oil production. The lower the real interest rate, the smaller is the incentive for oil producers to extract oil from below the ground because the proceeds from the sale are earning less interest. Second, low real interest rates may cause speculation in real assets such as commodities in the form of inventory holdings. Conversely, high real interest rates raise the opportunity cost of holding oil inventories and lower the demand for oil storage. For example, in the early 1980s, oil inventories were liquidated, as the expected demand for oil fell and real interest rates rose, putting downward pressure on the real price of oil. Third, low real dollar interest rates (relative to the interest rate abroad) may cause the U.S. dollar to depreciate, which in turn stimulates demand for oil and raises the real price of oil. Thus, real exchange rate fluctuations, rather than being exogenous, may in turn be caused by real interest rate shocks.

Although the theoretical arguments that exogenous real interest rate shocks affect the real price of oil are strong, quantifying these effects empirically has been difficult because fluctuations in global real activity and in the real exchange rate tend to confound the effects of U.S. real interest rate shocks. Thus, more often than not, empirical research has simply abstracted from real interest rate dynamics.

In this section, we extend the baseline structural VAR model specification of section 3 to incorporate the real U.S. interest rate and an additional exogenous shock to the real U.S. interest rate. Following Frankel (2008), the real interest rate (r_t) is defined as the one-year nominal U.S. Treasury rate, adjusted for the one-year inflation rate over the preceding year. Implicit in this definition is the assumption that the expected rate of inflation equals the most recent inflation rate.[18] The extended model is:

$$u_t = \begin{pmatrix} u_t^{\Delta q} \\ u_t^{\text{rea}} \\ u_t^{\text{p}} \\ u_t^{\Delta inv} \\ u_t^{\text{r}} \\ u_t^{\text{rxr}} \end{pmatrix} = B_0^{-1} w_t = \begin{bmatrix} - & + & + & b_{14}^0 & 0 & 0 \\ - & + & - & b_{24}^0 & 0 & 0 \\ + & + & + & b_{34}^0 & 0 & 0 \\ - & - & + & b_{44}^0 & 0 & 0 \\ b_{51}^0 & b_{52}^0 & b_{53}^0 & b_{54}^0 & b_{55}^0 & 0 \\ b_{61}^0 & b_{62}^0 & b_{63}^0 & b_{64}^0 & b_{65}^0 & b_{66}^0 \end{bmatrix} \begin{pmatrix} w_t^{\text{flow supply}} \\ w_t^{\text{flow demand}} \\ w_t^{\text{storage demand}} \\ w_t^{\text{other oil demand}} \\ w_{\text{t}}^{\text{exogenous r}} \\ w_t^{\text{exogenous rxr}} \end{pmatrix}. \qquad (2)$$

The identification of the oil demand and supply shocks in model (2) mirrors that in the baseline model. The exogenous real interest rate shock is identified by imposing the exclusion restrictions $b_{15}^0 = ... = b_{45}^0 = 0.$ These exclusion restrictions are implied by evidence in Kilian and Vega (2011) that long-term U.S. bond rates respond to U.S. macroeconomic news within 20 business days, while the price of oil does not, which implies that there is no feedback within the current month from exogenous variation in the U.S. real interest rate to the real price of oil. An analogous argument was used in section 2 for the real exchange rate shock. Finally, the identification of the exogenous real exchange rate shock relies on the same exclusion restrictions as in model (1) plus the restriction that the real U.S. interest rate responds to exogenous shocks to the trade-weighted U.S. real exchange rate only with a delay of one month such that $b_{56}^0 = 0.$

The motivation for the latter restriction is that exogenous real exchange rate shocks do

[18] This interest rate is intended to reflect the cost of borrowing in financial markets. We are not modeling monetary policy or the link from policy rates to market interest rates. Our specification allows us to circumvent the fact that this link is not stable during the period of quantitative easing. Our focus on the one-year rate is also dictated by constraints on the availability of historical interest rate data for longer maturities.

not materially change expectations of U.S. inflation and real output because the United States is a relatively closed economy. Standard monetary policy rules for the United States stipulate that the Federal Reserve adjusts the policy rate in response to shifts in expected inflation and real output (Clarida, Gali and Gertler 1998). If an exogenous real dollar appreciation does not affect expectations of U.S. inflation and real output, there is no reason for the central bank to lower its policy rate. As a result, the real market rate of interest remains unchanged on impact, justifying the restriction $b_{56}^{0} = 0$.

The assumption of sluggish inflation expectations is consistent with the conclusion of Mishkin (2008) that even large depreciations exert only small effects on consumer prices in industrialized economies. Time series evidence for a broad set of industrialized economies indicates that, on average, a 10 percent nominal depreciation is associated with only a 2 percent rise in the consumer price level in the long run. Even highly open economies have experienced little upward pressure on inflation following large depreciations of their currencies. The more closed the economy, the less responsive are inflation expectations likely to be. Likewise, the effect of real depreciations on real output declines. For example, Clarida, Gali and Gertler (1998) in their comparative analysis of monetary policy rules for major economies, explicitly noted that the U.S. real exchange rate is not particularly helpful in predicting U.S. inflation and real output, providing support for our exclusion restriction $b_{56}^{0} = 0$.

5.1. Incorporating the Insights of Frankel's (2012) Model of Real Commodity Prices

Frankel (2012) summarized the predictions of his model of real commodity prices as follows: (1) An exogenous increase in U.S. real interest rates stimulates global oil production by raising the opportunity cost of keeping the oil below the ground. (2) Higher real U.S. interest rates lower commodity inventories, as the cost of carrying inventories rises. (3) Global real economic activity falls, as higher real U.S. interest rates appreciate the real value of the dollar. None of these restrictions have been imposed on the model thus far. The upper panel of Figure 7 shows the responses of the model variables to an exogenous positive U.S. real interest rate shock in model (2) with the same dynamic restrictions and elasticity bounds imposed as in the baseline model.[19] Although the response functions in panel (a) do not contradict the implications of Frankel's model of commodity prices, they are by no means supportive of this model. There is substantial uncertainty about the sign of all responses, except for the own-response of the U.S. real interest rate.

Inference may be sharpened, if we are willing to impose, as a working hypothesis, the additional restriction that a positive real interest rate shock must lower the real price of oil for at least 12 months. This specification allows us to examine the internal consistency of the responses with the predictions of the Frankel model. Panel (b) shows that in this case, the dollar appreciates in real terms, as predicted by Frankel (2012). However, the response functions of global oil production and global real activity remain imprecisely estimated, and inventory holdings increase rather than decline, making this specification inconsistent with Frankel's model. There are two reasons why it is so difficult to match all of Frankel's predictions. First, while a higher U.S. real rate of interest may stimulate higher global oil production over time, it also raises the capital cost of oil extraction and, hence, reduces oil investment and hence future global oil production. The latter effect is not accounted for in Frankel's model. This additional transmission channel renders the sign of the effect on oil production ambiguous. Second, while higher U.S. real interest rates increase the carrying cost of holding inventories and hence discourage inventory holdings, a reduction in global real activity in response to the higher real

[19] The other impulse responses in the extended model are qualitatively similar to those in the baseline model and will be ignored for now.

value of the dollar is likely to cause an accumulation of oil inventories, which may overpower the direct effect on inventory demand stressed by Frankel. Thus, the sign of the response of oil inventories is ambiguous as well.

The problem with the results in panel (b) is that a decline in the real price of oil in response to higher real interest rates is difficult to reconcile with rising global real activity and the accumulation of inventories. The latter can only be explained by falling global real activity, given that global oil production remains largely unchanged. Thus, we know some of the models implied by the specification in panel (b) are not consistent with Frankel's model.

A more plausible approach is to restrict instead the response function of global real activity to be negative. As shown in panel (c), this specification produces estimates for the responses of oil production, the real value of the dollar, and oil inventories that are consistent with Frankel's analysis, as augmented above. Moreover, the real price of oil declines in response to an exogenous increase in U.S. real interest rates, if only slightly, in the short run. At longer horizons, there is more uncertainty about the sign of the response. We conclude that the effect of higher real interest rates through the cost of carrying inventories highlighted in Frankel (2012) is dominated by other effects, as are the increased incentives for global oil production. In contrast, the effect of higher U.S. real interest rates on global real activity and on the real value of the dollar comes through clearly. Finally, the negative effect on the real price of oil is quantitatively small.

For the remainder of the paper, we focus on the specification underlying panel (c) and examine how incorporating the insights of Frankel (2012) affects the conclusions based on the baseline model in section 4.

5.2. The Extended Model with Identification and Parameter Estimation Uncertainty

Figure 8 provides estimates of all impulse responses for the extended model. The responses in the oil market block are qualitatively unchanged. In this regard, the extended model replicates the findings in the baseline model. Likewise, the responses to an unexpected fall in the real value of the dollar remain qualitatively unchanged. There is little response in the real interest rate to an exogenous real exchange rate shock. The U.S. real market interest rate tends to decline in response to unexpected oil supply disruptions as well as positive oil demand shocks, at least in the short run.

5.2.1. The long-run determinants of the model variables

Extending the VAR model to include the U.S. real interest rate allows us to examine the extent of exogenous variation in the U.S. real interest rate. The lower panel of Table 1 shows that only 39% of U.S. real interest fluctuations are explained by exogenous real interest rate shocks. The remainder is split between the other structural shocks with flow demand shocks accounting for the largest share (20%). This result should not be interpreted as saying that the oil market is driving 51% of the variation in the U.S. real interest rate. The global oil market is not an isolated market. Since much of the explanatory power for the U.S. real interest rate comes from flow demand and storage demand shocks that reflect the global business cycle, our results suggest that the global business cycle is important for the U.S. real market interest rate. In contrast, the explanatory power of flow supply shocks that are narrowly associated with the oil market is only 12%.

A key difference from the baseline model is that including real interest rate shocks lowers the importance of exogenous real exchange rate shocks for the variability of the real exchange rate. The lower panel of Table 1 shows that the explanatory power of real exchange rate shocks declines substantially from 69% to 39%. Real interest rate shocks account for 26% of the variance of the real exchange rate. Flow supply, flow demand and storage demand shocks combined account for 31% of the variability of the real exchange rate (up from 24% in the baseline model). As in the case of the U.S. real interest rate, this result does not mean that the oil market is driving one third of the variation in the U.S. real exchange rate, since flow demand and storage demand shocks reflect the global economic environment. Rather it supports Mundell's (2002) conjecture about the real price of oil and the real exchange rate being jointly determined by the same global economic determinants. In fact, the contribution of flow supply shocks that are narrowly associated with the global oil market is a much more modest 8%.

Including real interest rate shocks in the model also lowers the explanatory power of flow demand shocks for global real economic activity from 39% to 30%, while leaving the contribution of real exchange rate shocks largely unchanged (16%). In contrast, extending the model does not affect much the explanatory power of storage demand shocks for the real price of oil. The explanatory power of storage demand shocks drops from 29% to 22%. The contribution of flow demand shocks to the real price of oil declines from 36% to 31% and that of flow supply shocks from 12% to 10%. With 12% the U.S. real interest rate shock has sizable explanatory power for the variability in the real price of oil. The contribution of the real exchange rate shock is 16%. In general, the contribution of individual structural shocks is less precisely estimated in the extended model, however.

5.2.2. Revisiting the role of real exchange rate shocks

The lower panel of Table 2 suggests that the real oil price decline in the early 1980s, for example, was much less influenced by exogenous real exchange rate shocks (-16%) than suggested by the baseline model (-32%), implying that Brown and Phillips (1986) and Trehan (1986) were right, but that the effect in question was much smaller than suggested by the baseline model. Similarly, during 1995-2002, exogenous real exchange rates shocks explain only a 25% cumulative decline in the real price of oil compared with the 45% decline implied by the baseline model. It is not always the case that the extended model downplays the role of exogenous real exchange rate fluctuations, however. During 2002-2008 and 2011-2016, for example, the extended model suggests larger cumulative effects of exogenous real exchange rate shocks than the baseline model, while the estimate for 1985-95 is largely unaffected.

5.2.3. Revisiting the historical narrative

Leaving aside the average contribution of each structural shock to the variability in the real price of oil, does extending the model to include U.S. real interest rate shocks affect the historical narrative of the large oil price fluctuations? This question is addressed in Table 4. Table 4 provides seven insights, organized in chronological order: (1) The two main determinants of the 1979/80 oil price increase remain flow demand and storage demand shocks, although the cumulative effects of all shocks are much less precisely estimated in the extended model. (2) Except for the storage demand shock, the cumulative effects of all other shocks in late 1980 are imprecisely estimated. (3) The oil price decline following the collapse of OPEC in late 1985 continues to be explained primarily by a combination of flow demand and storage demand shocks. The added contribution of U.S. real interest rate shocks (-14%) is only imprecisely estimated. (4) For the 1990/91 episode, the extended model reaffirms that this oil price spike is explained by a combination of flow supply (+12%) and storage demand shocks (+28%). (5) As in Table 4, the most important determinant of the 2003-08 real oil price surge is flow demand shocks. Flow demand shocks and exogenous real exchange rate shocks together are more than 25 times as important as flow supply shocks during this episode, reaffirming the substantive conclusions from the baseline model. (6) The extended model assigns little importance to flow supply shocks (or for that matter to exogenous U.S. real interest rate and real exchange rate shocks) during the oil price crash of late 2008. Flow demand shocks and storage demand shocks remain the primary explanation of the oil price decline during the global financial crisis. (7) Likewise, the determinants of the 2014-15 oil price decline remain largely affected. Although the model attributes a 14% decline in the real price of oil to U.S. real exchange rate shocks, that effect is only imprecisely estimated. The remainder is largely accounted for by flow demand shocks (-27%), flow supply shocks (-18%), and storage demand shocks (-37%).

5.3. Does U.S. monetary policy affect the real price of oil?

There is a long tradition of linking U.S. real interest rate fluctuations to shifts in monetary policy and in the credibility of the Federal Reserve (e.g., Barsky and Kilian 2002; Frankel 1984, 2008, 2012, 2014; Frankel and Hardouvelis 1985; Kilian 2010). If we think of shocks to the one-year U.S. real interest rate as reflecting at least in large part shifts in U.S. monetary policy, is there evidence that shifts in monetary policy regimes have contributed to oil price fluctuations and, if so, how much?

One long-standing conjecture has been that loose monetary policy resulting in low U.S. real interest rates contributed to the commodity price surges in 1979/80, along with a booming global economy (Barsky and Kilian 2002). We are now in a position to address this concern, while properly controlling for all relevant shocks. Table 4 provides no empirical support for the view that exogenous shifts in U.S. real interest rates fueled the boom in the oil market (and more generally in other global commodity markets) in the late 1970s and early 1980s. Likewise, there is no reliable evidence that between 1985 and 1995 higher real interest rates driven by tighter monetary policy substantially lowered the real price of oil, although the estimates are imprecise enough not to preclude this possibility.

Another widely held view has been that the U.S. Federal Reserve encouraged the commodity price boom between 2003 and 2008 by being too lenient for too long. Again, the extended model allows us to formally evaluate this conjecture. Table 4 provides little support for this interpretation. Although real interest rate shocks account for a 9% increase in the real price of oil, that increase is dwarfed by the cumulative effect of flow demand and real exchange rate shocks of 115% combined over the same period. Moreover, the 68% credible set in Table 4 suggests that the cumulative effect of real interest rate shocks could be anywhere between -13% and +28%. Thus, there is no reliable evidence that loose monetary policy was responsible for the sustained surge in the real price of oil after 2002.

Finally, although there is some evidence that tightening credit markets and higher real interest rates, respectively, contributed to the declines in the real price of oil in late 2008, but these cumulative effects are too imprecisely estimated to give these estimates much credence, whereas the contribution of other structural shocks is larger and more precisely estimated.

6. Conclusion

There is a large literature on the empirical relationship between the dollar exchange rate and the price of oil, both in nominal and in real terms. This literature focuses on the predictive content of these variables, on estimating dynamic reduced-form correlations and on testing for the existence of cointegration.[20] None of these studies sheds light on the determinants of these two time series. There is a much smaller literature seeking to model the structural shocks that determine the real price of oil, the real interest rate, and the real trade-weighted U.S. dollar exchange rate using structural vector autoregressive (VAR) models.[21] Our work differed from these earlier structural

[20] For a comprehensive survey of this literature see Beckmann et al. (2018).
[21] For example, Akram (2009) and Fratzscher et al. (2014) proposed structural VAR models of the real and nominal relationship, respectively, between the price of oil, the interest rate and the value of the dollar without

VAR studies in the methodology used, in the choice of the data and model specification, and in the questions we seek to answer.

Our analysis allowed us to disentangle exogenous variation in the U.S. real interest rate and in the trade-weighted U.S. real exchange rate, while accounting for exogenous shocks to the demand and supply for crude oil. This fact enabled us to formally evaluate the empirical support for the model of the determination of real commodity prices proposed by Frankel (1984, 2008, 2012, 2014). We showed that some implications of this model are strongly supported by the data, while others are not robust to allowing for additional channels of transmission.

Our structural VAR model also allowed us to formally evaluate common views in the literature about the determinants of the variability of the real exchange rate and the real price of oil. For example, a long-standing conjecture in the literature has been that the real price of oil, through its effects on the terms of trade, is the primary determinant of long swings in the trade-weighted U.S. real exchange rate. We showed that this conjecture is not supported by the data. Much of the variation in the U.S. real exchange rate, unlike that in the U.S. real interest rate, is exogenous with respect to the global oil market. Our analysis provided the first tangible evidence that real exchange rate shocks are an important determinant of real commodity prices. We also showed, for the first time, that exogenous fluctuations in the U.S. real interest rate have quantitatively important effects on the real price of oil. Our analysis furthermore revealed that exogenous changes to the U.S. real interest rate have important effects on the real exchange rate, but not the other way around.

Although our model is considerably richer than previous models of the global oil market

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differentiating between oil demand and oil supply shocks. In contrast, Bützer et al. (2016), along with a number of similar studies, focused on the effect of oil demand and oil supply shocks on bilateral exchange rates and other macroeconomic aggregates with special attention to differences between oil importers and oil exporters and the flexibility of the nominal exchange rate.

and provides a more nuanced understanding of global oil markets, we largely confirmed earlier accounts of the limited role of oil supply shocks in explaining the ups and downs in the real price of oil since the 1970s. The key difference is that our models provided a richer characterization of oil demand shocks, allowing us to differentiate among oil demand shocks that were effectively conflated in previous models. Conventional historical narratives of the causes of the major oil price fluctuations since the 1970s are quite robust to introducing exogenous real exchange rate shocks and shocks to the U.S. real interest rate, but there are some notable differences. For example, our analysis supports the argument that the real depreciation of the dollar was a major additional determinant of the surge in the real price of oil between 2003 and mid-2008. The contribution of exogenous real exchange rate shocks to this surge is second only to that of flow demand shocks. In contrast, during other oil price shock episodes, the role of exogenous real exchange rate shocks was quite small.

We also provided evidence that exogenous U.S. real interest rate shocks did not play a large role during 1979/80, refuting the common conjecture that the rise in oil demand and hence the surge in the real price of oil in 1979/80 is partially explained by the persistent effect of loose monetary policy in the late 1970s on U.S. real interest rates. Likewise, we found no support for the claim that the U.S. Federal Reserve materially contributed to rising real oil prices between late 2002 and mid-2008.

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Table 1: Variance decompositions (Percent)

	Shocks				
	Flow supply	Flow demand	Storage demand	Real exchange rate	Real interest rate
Baseline model:					
Real price of oil	12.4	35.7	29.3	13.7	-
	(9.0)	(13.7)	(14.5)	(9.3)	
U.S. real exchange rate	9.3	7.9	6.9	68.7	-
	(7.3)	(5.4)	(5.6)	(11.8)	
Global real economic activity	21.0	38.7	8.9	16.5	-
	(10.4)	(12.1)	(5.6)	(7.7)	
Extended model:					
Real price of oil	10.2	31.1	22.0	16.2	12.3
	(7.2)	(17.7)	(17.5)	(8.6)	(10.7)
U.S. real exchange rate	8.3	12.7	10.3	39.1	25.9
	(4.4)	(9.7)	(8.8)	(9.8)	(6.6)
Global real economic activity	19.3	30.3	8.8	16.2	11.0
	(13.0)	(9.4)	(4.4)	(5.6)	(6.3)
U.S. real interest rate	11.8	19.7	9.1	9.7	38.9
	(6.4)	(14.1)	(6.3)	(5.6)	(11.7)

NOTES: Posterior mean based on admissible models (with posterior standard error in parentheses). The difference between 100% and the sum of the percent contributions of all shocks in Table 1 is the contribution of the residual oil demand shock.

Table 2: Cumulative effects of exogenous shocks to U.S. trade-weighted real exchange rate on the real price of oil (Percent)

	1980.10-1985.3	1985.3-1995.7	1995.7-2002.10	2002.10-2008.3	2011.6-2016.12
Baseline VAR model:	-32.0	34.4	-44.7	35.7	-14.9
	(-59.5, -14.4)	(14.1, 66.0)	(-72.7, -19.5)	(12.2, 62.7)	(-39.9, 2.2)
Extended VAR model:	-15.8	37.8	-24.8	42.3	-37.7
	(-45.7, -3.1)	(-11.5, 65.5)	(-54.2, -6.6)	(13.6, 87.4)	(-61.0, -16.3)

NOTES: Posterior median based on admissible models (with 16% and 84% quantiles in parentheses). The subperiods correspond to successive phases of real appreciations and real depreciations of the U.S. dollar, starting with the real appreciation of the early 1980s.

Table 3: Cumulative effects on the real price of oil in the baseline VAR model (Percent)

	1979.1-1980.9	1980.9-1980.12	1985.12-1986.12	1990.1-1990.11	2003.1-2008.6	2008.6-2008.12	2014.6-2015.12
Flow supply shock	8.9	1.5	-2.0	13.4	3.5	1.3	-21.0
	(-7.1, 19.5)	(-2.6, 4.2)	(-18.2, 5.7)	(3.6, 27.5)	(-19.4, 24.2)	(-3.8,8.1)	(-35.1,-8.5)
Flow demand shock	24.1	4.0	-28.0	-10.4	101.0	-81.0	-27.2
	(6.7, 44.8)	(-0.9, 8.4)	(-40.3,-12.1)	(-19.7, -3.5)	(61.7, 125.1)	(-96.9,-61.8)	(-38.3,-9.3)
Storage demand shock	15.3	0.7	-19.0	24.8	-21.9	-39.7	-33.6
	(3.2, 33.3)	(-4.6, 5.3)	(-30.8, -4.5)	(14.0, 37.8)	(-47.1, -0.5)	(-56.4,-17.2)	(-52.7,-20.4)
U.S. real exchange rate	4.2	1.8	-2.9	-0.8	37.4	-3.2	-8.4
shock	(-2.5, 14.2)	(-2.5, 4.7)	(-14.8, 10.7)	(-8.1, 7.8)	(14.7, 58.1)	(-9.8, 5.6)	(-17.5,0.3)

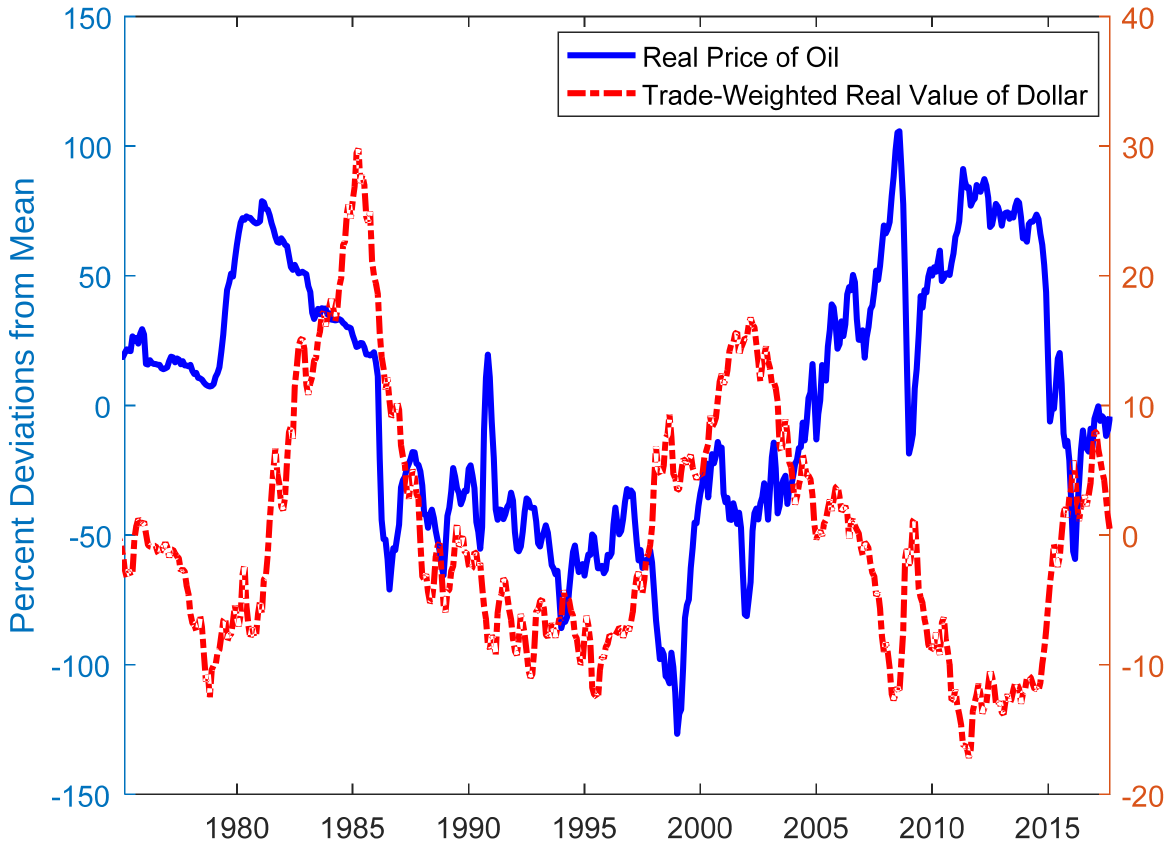
NOTES: Posterior median based on admissible models (with 16% and 84% quantiles in parentheses)

Table 4: Cumulative effects on the real price of oil in the extended VAR model (Percent)

	1979.1-1980.9	1980.9-1980.12	1985.12-1986.12	1990.1-1990.11	2003.1-2008.6	2008.6-2008.12	2014.6-2015.12
Flow supply shock	0.3	3.1	1.9	12.4	4.4	2.9	-18.0
	(-5.9, 14.8)	(-1.9, 6.3)	(-21.7, 12.5)	(6.5, 21.1)	(-5.5, 13.7)	(-2.6, 7.1)	(-34.8, -7.4)
Flow demand shock	23.2	-0.1	-21.2	-4.1	64.9	-63.4	-26.8
	(-8.1, 38.6)	(-7.0, 2.5)	(-49.5, -13.4)	(-10.4, -0.4)	(33.8, 87.3)	(-92.4, -38.0)	(-35.2, -9.3)
Storage demand shock	11.5	4.2	-16.2	21.0	-28.7	-48.4	-37.1
	(-21.6, 35.1)	(0.3, 11.8)	(-36.7, 4.8)	(12.1, 34.1)	(-53.0, 8.9)	(-71.1, -6.4)	(-46.0, -21.4)
U.S. real interest rate shock	0.8	0.6	-13.7	-4.8	8.8	-7.5	-1.5
	(-18.2, 8.8)	(-3.6, 8.2)	(-21.0, 3.3)	(-11.1, 0.6)	(-12.9, 27.7)	(-14.9, -0.3)	(-10.2, 3.2)
U.S. real exchange rate	1.1	0.4	-2.9	4.5	50.4	-10.2	-13.8
shock	(-18.9, 13.1)	(-2.2, 5.4)	(-20.0, 28.6)	(-7.7, 21.1)	(14.2, 86.0)	(-18.0, -1.4)	(-17.6, 0.7)

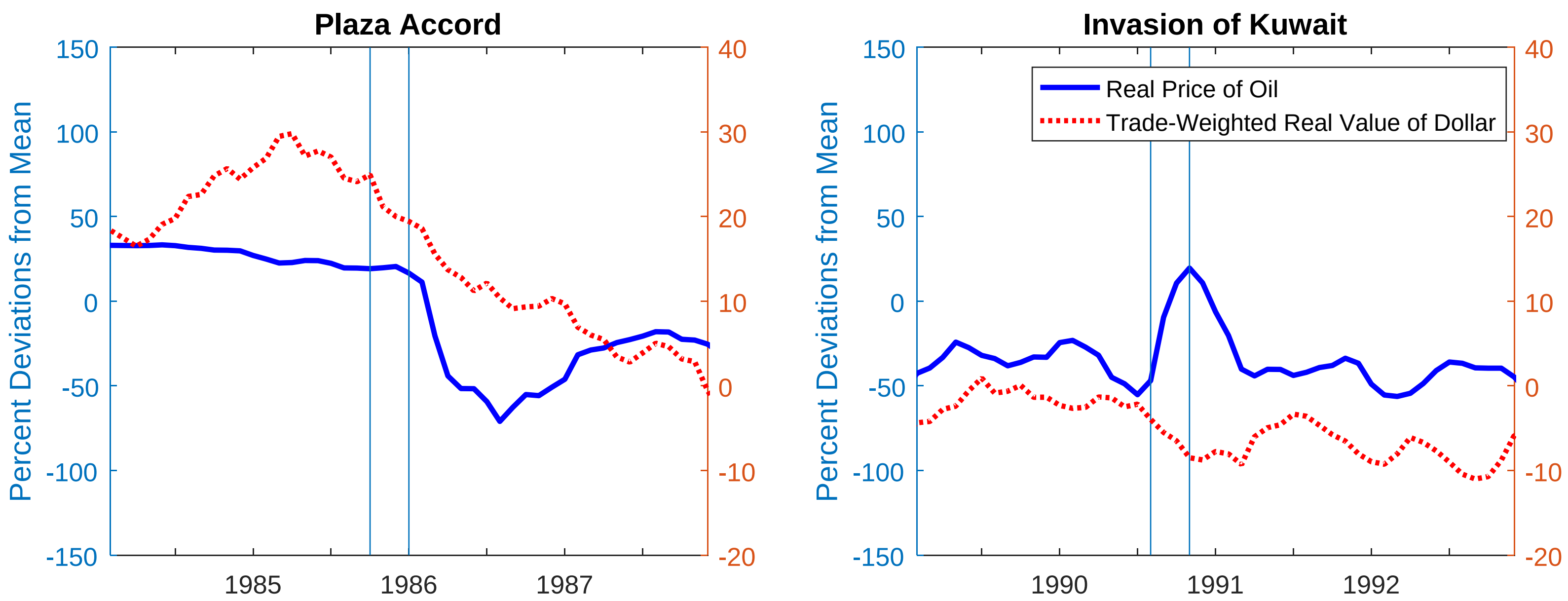
NOTES: Posterior median based on admissible models (with 16% and 84% quantiles in parentheses)

Figure 1: The co-movement between the real price of oil and the real value of the U.S. dollar



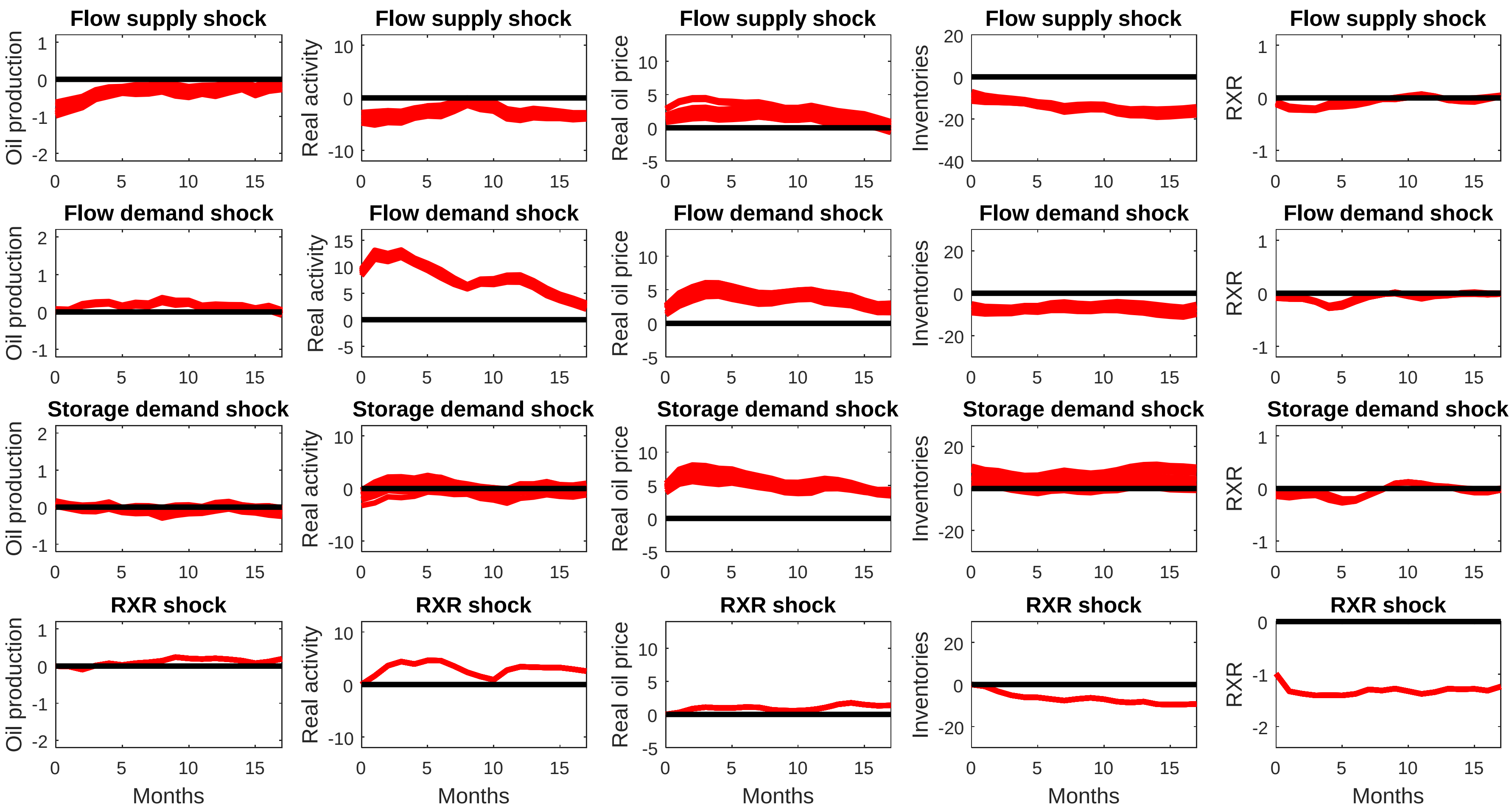
NOTES: The real price of oil is defined as the U.S. refiner's acquisition cost for imported crude oil, deflated by the U.S. CPI for all urban consumers. The U.S. trade-weighted real exchange rate was obtained from the Federal Reserve Board.

Figure 2: Examples of exogenous variation in the real value of the U.S. dollar (left) and in the real price of oil (right)



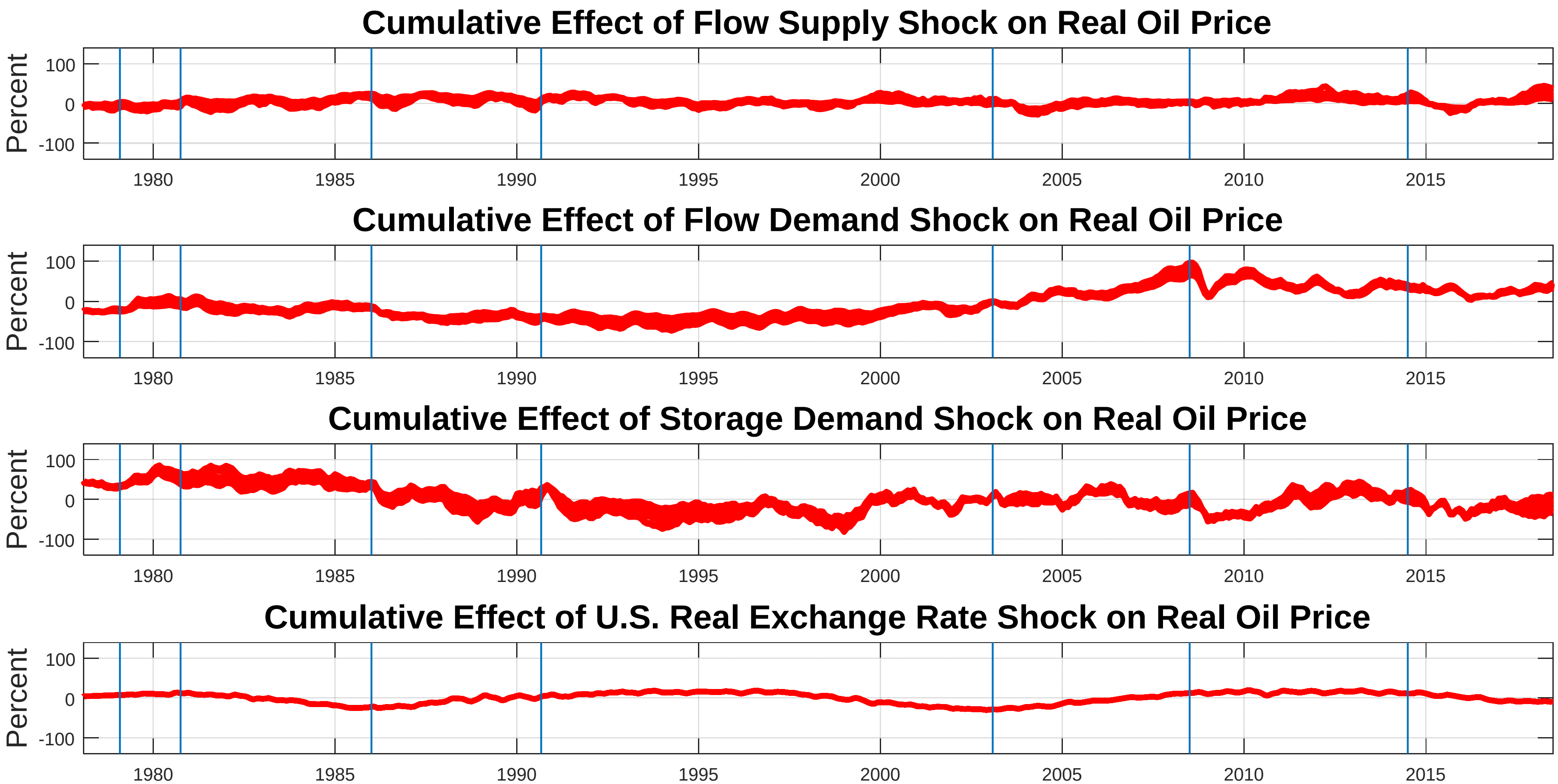
NOTES: The real price of oil is defined as the U.S. refiner's acquisition cost for imported crude oil, deflated by the U.S. CPI for all urban consumers. The U.S. trade-weighted real exchange rate was obtained from the Federal Reserve Board. The Plaza Accord episode extends from September-December 1985, since the collapse of OPEC in 1986 contaminates the identification. The 1990 oil price increase caused by the invasion of Kuwait extends from July-October 1990.

Figure 3: Impulse responses in baseline model without estimation uncertainty



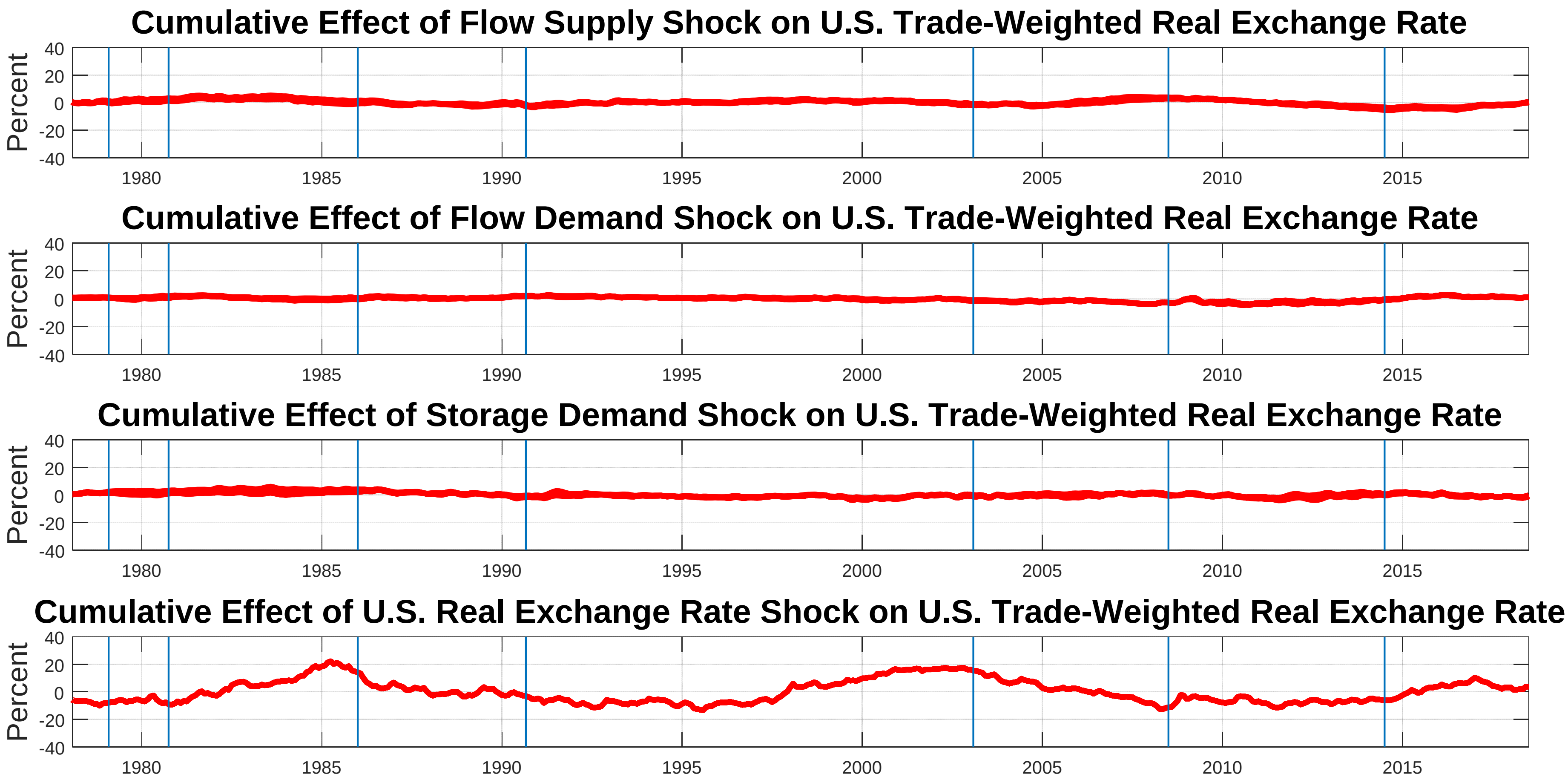
NOTES: The shaded area captures the identification uncertainty about the structural VAR model, but not the parameter estimation uncertainty. The responses to the exogenous real exchange rate shock are not subject to identification uncertainty by construction.

Figure 4: Cumulative effects on the real price of oil in baseline model without estimation uncertainty



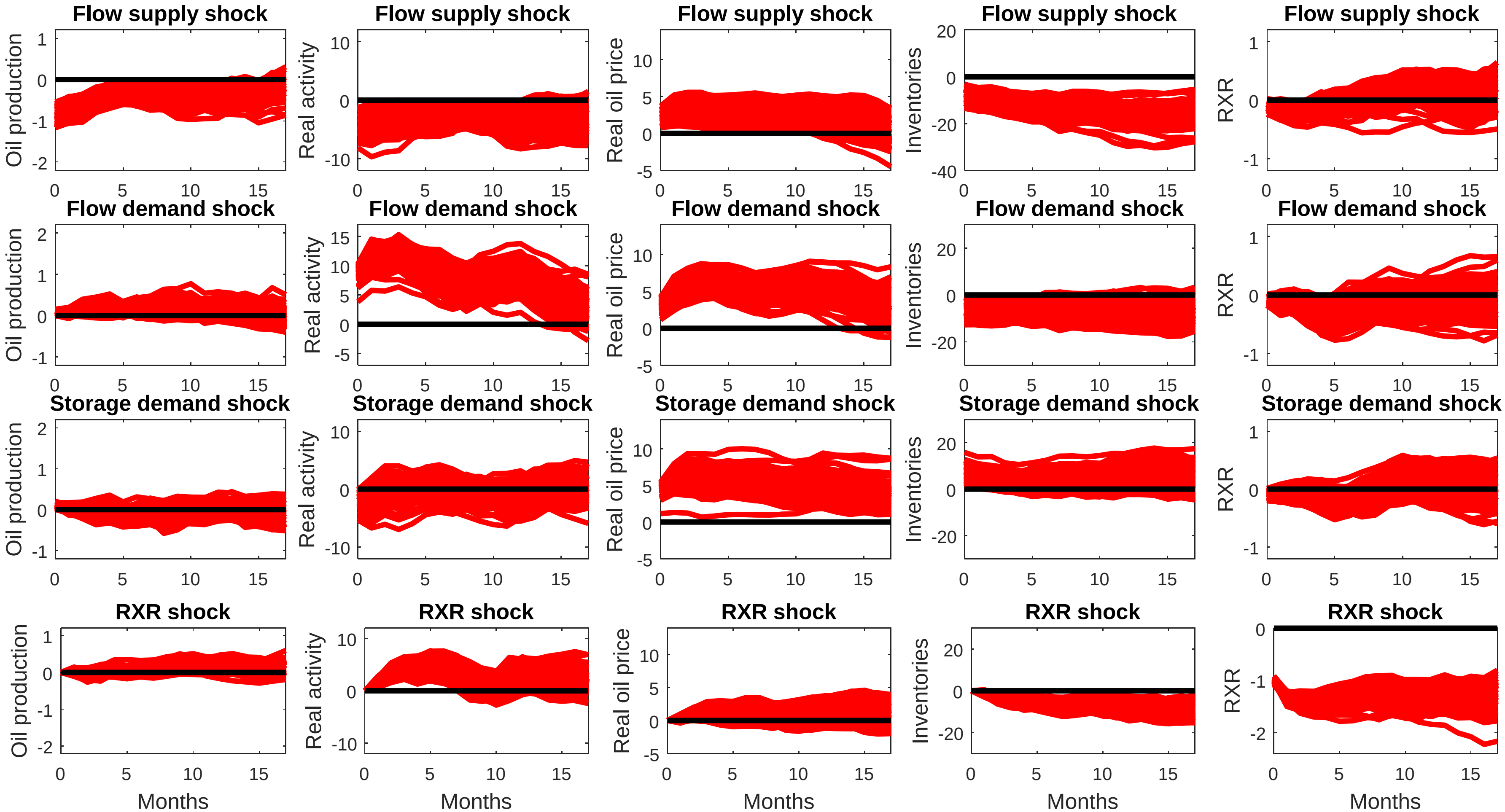
NOTES: The shaded area captures the identification uncertainty about the structural VAR model, but not the parameter estimation uncertainty. Major events in oil markets are marked as vertical lines. They refer to the Iranian Revolution in 1978/79, the outbreak of the Iran-Iraq War in 1980, the collapse of OPEC in 1986, the invasion of Kuwait in 1990, the beginning of the 2003 oil price surge, the 2008 financial crisis, and the start of the oil price decline in 2014.

Figure 5: Cumulative effects on U.S. trade-weighted real exchange rate in baseline model without estimation uncertainty



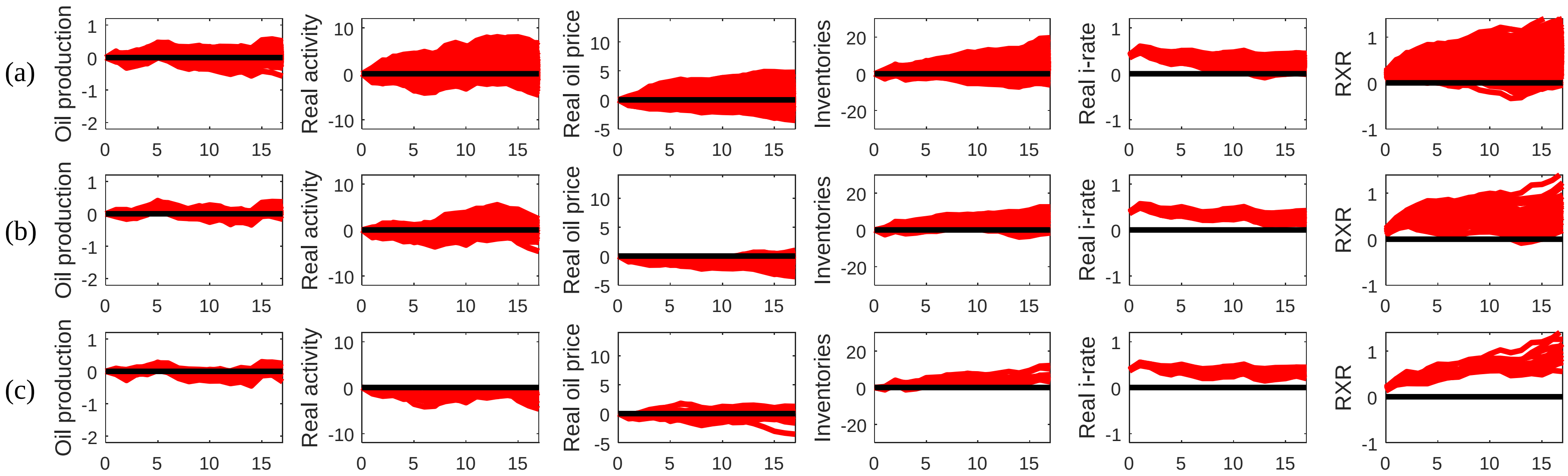
NOTES: The shaded area captures the identification uncertainty about the structural VAR model, but not the parameter estimation uncertainty. Major events in oil markets are marked as vertical lines. They refer to the Iranian Revolution in 1978/79, the outbreak of the Iran-Iraq War in 1980, the collapse of OPEC in 1986, the invasion of Kuwait in 1990, the beginning of the 2003 oil price surge, the 2008 financial crisis, and the start of the oil price decline in 2014.

Figure 6: Impulse responses in baseline model with identification and estimation uncertainty



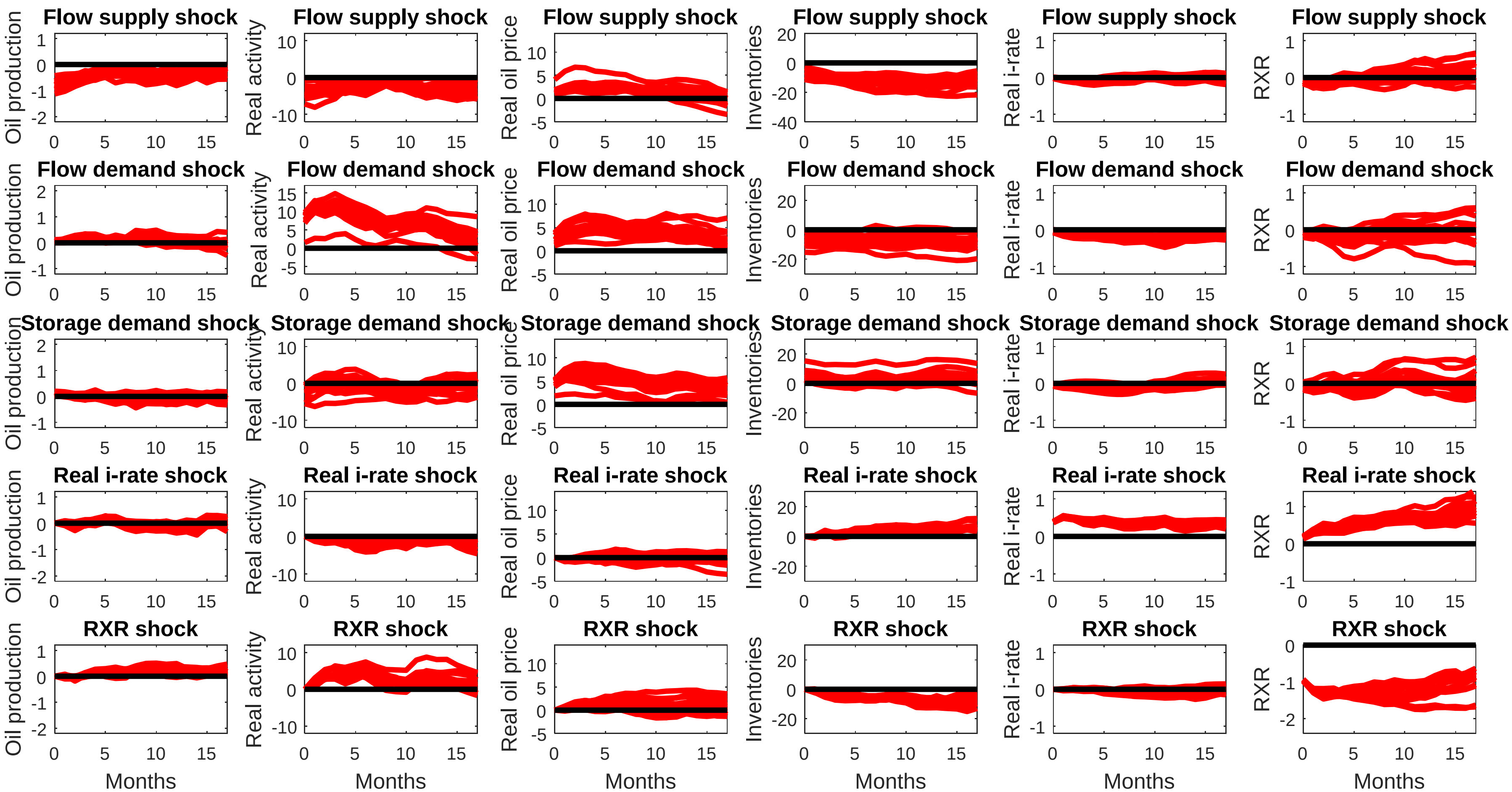
NOTES: The shaded area captures both the identification uncertainty about the structural VAR model and the parameter estimation uncertainty.

Figure 7: Responses to exogenous U.S. real interest rate shock in extended model with identification and estimation uncertainty



NOTES: The shaded area captures both the identification uncertainty about the structural VAR model and the parameter estimation uncertainty. Model (a): No identifying restrictions based on Frankel's work. Model (b) in addition restricts the response function of the real price of oil to be negative for months 1 through 12. Model (c) instead restricts the response function of global real activity to be negative (which is equivalent to restricting the response of the real exchange rate and the real price of oil to be of opposite signs).

Figure 8: Impulse responses in the extended model with identification and estimation uncertainty



NOTES: The shaded area captures both the identification uncertainty about the structural VAR model and the parameter estimation uncertainty.