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THE ROLE OF TIME-VARYING PRICE ELASTICITIES IN ACCOUNTING FOR VOLATILITY CHANGES IN THE CRUDE OIL MARKET

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SUMMARY

There has been a systematic increase in the volatility of the real price of crude oil since 1986, followed by a decline in the volatility of oil production since the early 1990s. We explore reasons for this evolution. We show that a likely explanation of this empirical fact is that both the short-run price elasticities of oil demand and of oil supply have declined considerably since the second half of the 1980s. This implies that small disturbances on either side of the oil market can generate large price responses without large quantity movements, which helps explain the latest run-up and subsequent collapse in the price of oil. Our analysis suggests that the variability of oil demand and supply shocks actually has decreased in the more recent past, preventing even larger oil price fluctuations than observed in the data. Copyright © 2012 John Wiley & Sons, Ltd.

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Supporting information may be found in the online version of this article.

1. INTRODUCTION

The rollercoaster ride of crude oil prices from values of around $50 per barrel at the beginning of 2007 to record highs of almost $150 in mid 2008 and then back to values as low as $40 at the end of the same year is a compelling illustration of the dramatic rise in oil price volatility that has been a salient feature of oil price behavior for the last two decades. A related aspect that has almost gone unnoticed in the literature is that, while oil price volatility has increased, the volatility of world oil production has decreased substantially over time. Figure 1(a) displays the quarter-on-quarter rate of change for the real price of crude oil and for world oil production over the period 1974:Q1 to 2010:Q4. Figure 1(b) shows the evolution of the unconditional standard deviation of these two oil market variables over time based on 5-year rolling windows and based on the empirical model introduced in Section 3.[1] As is evident from both graphs, the amplitude of quarterly oil price fluctuations increased significantly in recent periods. World oil production, on the other hand, exhibited larger fluctuations in the early part of the sample, especially during the 1970s, that gradually diminished over time. This diverging pattern is suggestive of a transformation in the structure of the global market for crude oil. In light of the mounting concern among policymakers and the public about rising oil price volatility, understanding the nature of the underlying causes of greater oil price volatility is important. This not only informs the development of suitable policy measures for dealing with such volatility, but can also provide insights into the volatilities of other commodity and asset prices. The goal of this paper is to analyze changes in oil market dynamics over time and to study the factors that are responsible for the observed rise in oil price volatility and the concurrent drop in oil production volatility.

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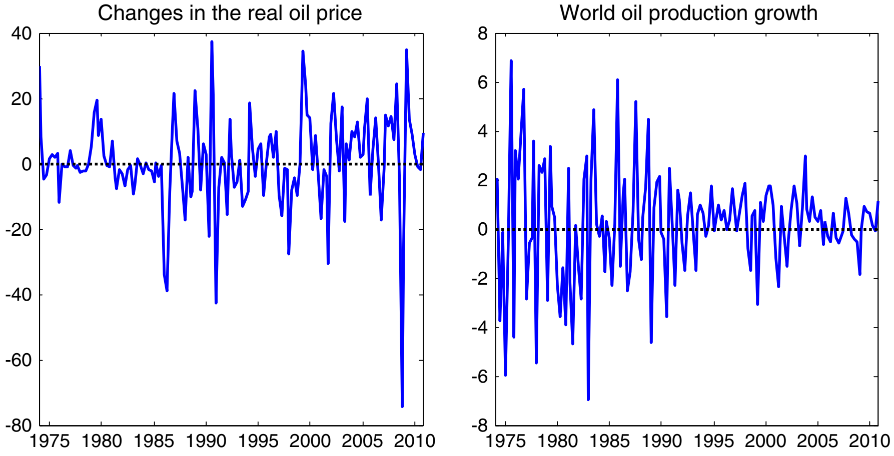
[1] Supporting information Figure 4A in the supplementary appendix on the journal's website reports the joint posterior distributions of the estimated volatilities for selected pairs of oil market episodes following the approach of Cogley *et al.* (2010), which reveal that changes in the volatility pattern are indeed an important feature of the data.

PANEL A



PANEL B

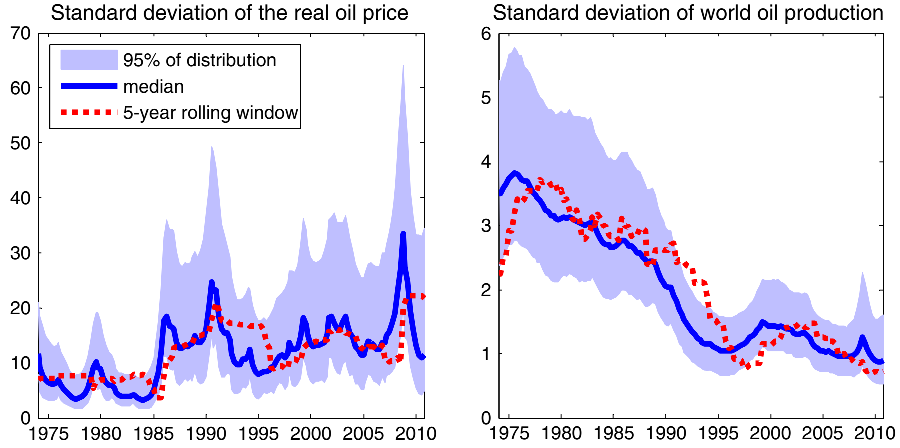


Figure 1. Volatility measures. (a) Volatility of the real refiners' acquisition cost of imported crude oil and of world oil production for 1974:Q1–2010:Q4. (b) Median time-varying unconditional standard deviation (solid line) of the real refiners' acquisition cost of imported crude oil and of world oil production based on the benchmark model estimated in Section 3 (solid line) and based on 5-year rolling windows (dotted line). Shaded areas indicate 95% coverage of the posterior distribution

Several hypotheses can conceivably account for these volatility changes. One natural explanation could be changes in the variances of shocks or in the relative importance of different types of shocks affecting the oil market. Increases or decreases in the size of the underlying shocks alone, however, cannot explain the *inverse* evolution of oil price and oil production volatilities. For instance, while larger demand shocks due to changes in inventory practices or speculative activities have the potential to account for the observed increase in oil price variability, such a hypothesis cannot explain the accompanying fall in oil production variability. Similarly, smaller oil supply disruptions in recent periods than in the 1970s and early 1980s can be a source of a decline in oil production volatility, but are incompatible with greater oil price fluctuations. Hence a combination of changes in the magnitude of the underlying shocks would be needed to explain the evolution of volatilities.

Another potential explanation for the structural changes in the oil market over time is a change in the price elasticities of oil demand or oil supply, corresponding to a steepening or flattening of the oil demand or oil supply curves. In particular, a fall in the short-run price elasticity of oil demand or oil supply can rationalize an opposite movement of oil price and production volatilities over time. For example, a less elastic oil demand curve implies that similar shifts of an upward-sloping oil supply curve are characterized by smaller adjustments in oil production and larger fluctuations of oil prices. Likewise, a steeper oil supply curve could be the reason for increased oil price volatility and decreased oil production volatility in the data for similar shocks at the demand side of the oil market.

Finally, a change in the degree of flexibility of oil prices might help explain the pattern of volatilities in the crude oil market. Before the collapse of OPEC in 1985, oil market transactions were to a large extent based on long-term contracts with predetermined oil prices. As a consequence, large production adjustments were needed to accommodate changes in the demand for crude oil, at least for the remaining period of the contract. The gradual transition to the current market-based system of spot contracts should be conducive to a more rapid transmission of oil supply and demand shocks into price changes. As a result, smaller shifts in global oil production would be required to clear the market.

The contribution of this paper is to evaluate these hypotheses in a unifying framework and to provide empirical evidence that the increase in oil price volatility can be reconciled with a decrease in oil production volatility, once we allow for time variation in the price responsiveness of oil supply and of oil demand, and in the variances of the underlying shocks. To this end, we propose a Bayesian time-varying parameter vector autoregression (TVP-VAR) model with stochastic volatility in the innovation process that we estimate over the sample period 1974:Q1–2010:Q4 in the spirit of Cogley and Sargent (2005) and Primiceri (2005). Within this TVP-VAR framework, we identify three types of structural disturbances that drive movements in world oil production and oil prices: oil supply shocks, oil demand shocks caused by unexpected shifts in global economic activity and other oil demand shocks in the global market for crude oil. These shocks are identified by means of sign restrictions to allow for an immediate effect of all three shocks on both oil prices and oil production that can change over time. [2]

While many models may potentially be able to account for some time variation in the parameters, there are at least three reasons why a TVP-VAR structure is the most compelling. First, changes in the structure of the oil market have been gradual. For example, as is well documented in the literature, the increase in the relative importance of spot market transactions as opposed to long-term oil contracts occurred over an extended period of time, pointing towards a gradual transition process (see, for example, Hubbard, 1986; Mabro, 2005). In addition, the gradual growth of oil futures markets since 1983, as evidenced by a slow increase in trading volume, reinforces the idea of a continuous evolution of the market structure. Second, investments in the oil sector involve long lead times, so new production in response to price incentives will come online only gradually and sometimes not at all (see, for example, Hamilton, 2009a; Smith, 2009) and capacity constraints in oil production may be binding to varying degrees (Kilian, 2008). Third, substitution away from oil to other sources of energy takes place over an extended period of time (see, for example, Sweeney, 1984; Dargay and Gately, 2010). Efforts toward increased energy conservation are also reflected in slow variation in the energy share over time. Moreover, even controlling for energy efficiency, the effects of oil prices on consumption will vary smoothly as the price moves the expenditure share of energy up and down (see Edelstein and Kilian, 2009).[3]

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[2] Kilian (2009) disentangles a similar set of shocks by imposing short-run zero restrictions. However, a recursive identification scheme is not appropriate for our purpose given that by construction the short-run elasticity of oil supply is zero in such a framework. Moreover, such a restriction would be less plausible in our quarterly model than in Kilian's monthly model.

[3] It might seem that an alternative specification would be a Markov-switching (MS) model; however, there is no economic model of oil markets that supports an MS structure. Moreover, given the multiple sources of nonlinearities, the number of states required for approximating this type of process would have to be extremely large, whereas MS models require the number of regimes to be small in order to be tractable. Most importantly, MS models, unlike TVP-VAR models, imply a degree of regularity that is not found in the oil market.

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Our key finding is that the volatility changes in the crude oil market are driven by a considerable decrease in the price responsiveness of oil supply and oil demand in the short run starting in the second half of the 1980s. A direct implication of these low price elasticities is that even a small amount of excess demand or excess supply of crude oil requires large jumps in prices to clear the global oil market. Put differently, a steepening of the short-run oil supply and oil demand curves over time is the likely explanation of higher oil price volatility accompanied by lower oil production volatility. Hubbard (1986) makes the case that the gradual transition from long-term oil contracts to spot market deals and oil futures contracts during the 1980s has played a critical role in the rise of oil price variability. We complement this view by suggesting that this change in the pricing system has contributed to the decreases in the short-run elasticities of oil demand and oil supply which in turn could have propelled the shift from contractual arrangements to market transactions as a way to cope with the substantial swings in oil prices. We argue that the structural transformation in the oil market can be interpreted as the result of an interplay between several factors that tend to reinforce each other. On the one hand, uncertainties deriving from greater oil price volatility might have encouraged the development of derivative markets, stimulated the reliance on oil futures as risk reduction tools and led to the introduction of crude oil options as hedging devices. On the other hand, while these financial instruments were designed to deal with the rise in oil price volatility, it is likely that the expansion of hedging possibilities also played a role in lowering the sensitivity of oil consumers and oil producers to price fluctuations, thereby contributing to the steepening of the oil supply and demand curves which results in higher oil price volatility. If such an interplay exists, our results could extend to the volatility of other types of commodities and assets. Our analysis is facilitated by the fact that for the oil market a long time span of both price and quantity data is available, which are necessary to measure (time-varying) price elasticities.

The changes in the volatilities of key oil market variables over time are, however, not exclusively determined by lower short-run price elasticities of oil supply and oil demand but also by the magnitude of structural disturbances affecting the oil market. By means of simple back-of-the-envelope computations, we find that the variances of all three types of shocks have gradually decreased rather than increased, ruling out this competing explanation of increased oil price volatility. We show that the average variability of exogenous oil supply shocks was relatively high until the invasion of Kuwait in 1990, after which it declined steadily. The average variability of oil demand shocks reflecting changes in economic activity declined in the mid 1980s but has risen again since the 2000s. Interestingly, the variability of an average oil demand shock driven by shifts in expectations is smaller in recent times than in the 1970s and 1980s. This finding is in line with Kilian (2009) and Kilian and Murphy (2011), who conclude that oil demand shocks were important driving forces behind oil price fluctuations throughout the 1974–2009 period. Finally, our evidence reveals that the transition from administered prices to a market-based pricing system had hardly any impact on the speed of adjustment of crude oil prices and consequently oil price volatility when quarterly data are used. In other words, we observe little change in the degree of persistence of the real price of oil over the entire sample period.

The rest of the paper is organized as follows. In Section 2, we present a stylized time-varying parameter structural model of the crude oil market that allows us to illustrate the different hypotheses about the changing volatility of oil production and oil prices since 1974. Section 3 introduces the econometric framework, and the empirical results are reported in Section 4. In Section 5, we assess the sensitivity of our findings to changes in the model specification and the identification assumptions. We briefly discuss a number of factors that might have contributed to the steepening of the short-run oil supply and oil demand curves over time in Section 6. Our concluding remarks are in Section 7.

2. A STYLIZED MODEL OF THE CRUDE OIL MARKET

In its simplest form, the crude oil market can be represented by the following demand and supply equations, measured as deviations from steady state:

$$Q_t^{\mathrm{D}} = -d_t \cdot P_t^* + \varepsilon_t^d \tag{1}$$

$$Q_t^{\mathrm{S}} = s_t \cdot P_t^* + \varepsilon_t^s \tag{2}$$

where oil demand Q_t^{D} and oil supply Q_t^{S} at each point in time are respectively a negative and positive function of the equilibrium price of oil P_t^*. The parameters d_t and s_t are positive and measure the responsiveness of respectively the quantity of oil demanded and supplied to a change in the price of crude oil, i.e. the slopes of oil demand and supply curves at time *t*. Furthermore, the supply and demand for crude oil are driven by two mutually uncorrelated exogenous shocks: ε_t^d and ε_t^s, with $E\left[\varepsilon_t^d\right] = E\left[\varepsilon_t^s\right] = 0$, $E\left[\varepsilon_t^d\right]^2 = \sigma_{d,t}^2$, $E\left[\varepsilon_t^s\right]^2 = \sigma_{s,t}^2$ and $E\left[\varepsilon_t^d, \varepsilon_t^s\right] = 0$. In equilibrium, we can express the price and quantity variables as a linear combination of the structural shocks hitting the oil market:

$$P_t^* = \frac{\varepsilon_t^d}{s_t + d_t} - \frac{\varepsilon_t^s}{s_t + d_t} \tag{3}$$

$$Q_t^* = \frac{s_t \varepsilon_t^d}{s_t + d_t} + \frac{d_t \varepsilon_t^s}{s_t + d_t} \tag{4}$$

We allow the actual oil price to evolve gradually towards its equilibrium level:

$$P_t = \lambda_t \cdot P_t^* + (1 - \lambda_t) \cdot P_{t-1} \tag{5}$$

with $0 < \lambda_t < 1$ being the time-varying speed of adjustment to the new equilibrium price. If $\lambda_t = 1$, the price of oil immediately reflects its fundamental value, which is expected to be the case in the more recent decades. The actual (short-run) price and quantity equations of oil that clear the market at each point in time are as follows[4]:

$$P_t = \frac{\lambda_t \varepsilon_t^d}{s_t + d_t} - \frac{\lambda_t \varepsilon_t^s}{s_t + d_t} \tag{6}$$

$$Q_t = \frac{[s_t + (1 - \lambda_t) d_t] \varepsilon_t^d}{s_t + d_t} + \frac{\lambda_t d_t \varepsilon_t^s}{s_t + d_t} \tag{7}$$

When oil contracts are fully flexible, i.e. $\lambda_t = 1$, equations (6) and (7) are equal to their equilibrium counterparts (3) and (4).

According to this stylized model, and taking into account that oil supply and oil demand disturbances are uncorrelated, the variability of crude oil prices and oil production are respectively

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[4] Note that in equation (6) we assume that the oil market was in steady state before shocks occur, which implies that P_{t-1} is set to 0. This is in line with the use of conditional impulse responses in the empirical analysis.

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$$E[P_t]^2 = \frac{\lambda_t^2\left(\sigma_{d,t}^2 + \sigma_{s,t}^2\right)}{(s_t + d_t)^2} \tag{8}$$

$$E[Q_t]^2 = \frac{[s_t + (1 - \lambda_t)d_t]^2\sigma_{d,t}^2 + \lambda_t^2 d_t^2 \sigma_{s,t}^2}{(s_t + d_t)^2} \tag{9}$$

Relying on equations (8) and (9), we can formulate all possible hypotheses about the sources of the observed change in volatility of both oil market variables. We now discuss them one by one.

2.1. A change in the variance of oil market shocks.

A first possible source of time variation in the oil market volatilities are changes in the variances of the underlying shocks. Keeping all other parameters of the model fixed, a change in the variance of oil market disturbances should have the following impact on the variability of oil prices and oil production:

$$\frac{\partial E[P_t]^2}{\partial \sigma_{s,t}^2} > 0 \text{ and } \frac{\partial E[Q_t]^2}{\partial \sigma_{s,t}^2} > 0 \tag{10}$$

$$\frac{\partial E[P_t]^2}{\partial \sigma_{d,t}^2} > 0 \text{ and } \frac{\partial E[Q_t]^2}{\partial \sigma_{d,t}^2} > 0 \tag{11}$$

According to equation (10), a reduction in the standard deviation of oil supply shocks can be a source of reduced volatility of oil production over time, but cannot explain the opposite evolution of oil price volatility. In contrast, smaller oil supply disturbances should also result in lower variability of crude oil prices in more recent periods. Hence this hypothesis alone does not suffice to explain the observed volatility pattern.

The variance of average oil demand shocks might also have changed over time. On the one hand, the gradual transition from a system of posted OPEC prices to freely fluctuating spot market prices in the early 1980s prompted the development of oil futures markets as a means of hedging price risks (Mabro, 2005). This evolution is often seen as the source of the dramatic rise in oil price volatility (Hubbard, 1986). Equation (11) suggests that if the standard deviation of oil demand shocks resulting from, for example, increased speculative activities, precautionary buying or preference shifts, were indeed greater nowadays, they would have the potential to account for the observed increase in oil price variability. They do not, however, explain the concomitant drop in the variability of oil production.

On the other hand, at around the same time of the change in oil market volatility, a widespread reduction in macroeconomic volatility took place around the globe, commonly referred to as the ‘Great Moderation’. Several studies indicate that this remarkable decline in volatility was not limited to output growth and inflation but also extended to other macroeconomic variables (e.g. Herrera and Pesavento, 2009). As such, smaller fluctuations in oil production as a result of a decrease in the standard deviation of business-cycle driven oil demand shocks would accord well with this general phenomenon, but not with the observed increase in oil price volatility. Since both hypotheses relating to the demand side of the crude oil market predict that the variances of different oil demand shocks should evolve in opposite directions over time, in our empirical analysis we will make an explicit distinction between oil demand shocks driven by global economic activity and other oil demand shocks.

2.2. Time-varying price elasticities of oil demand and oil supply.

A change in the short-run price elasticities of oil demand and oil supply can also play a role, as can be inferred from the following derivations:

$$\frac{\partial E[P_t]^2}{\partial d_t} < 0 \text{ and } \frac{\partial E[Q_t]^2}{\partial d_t} > 0 \tag{12}$$

$$\frac{\partial E[P_t]^2}{\partial s_t} < 0 \text{ and } \frac{\partial E[Q_t]^2}{\partial s_t} > 0 \tag{13}$$

For example, a fall over time in the short-run price elasticity of oil demand in equation (12) could rationalize the observed pattern of higher oil price volatility and lower oil production volatility. Such a decline in the demand elasticity seems plausible a priori given the great strides oil-importing economies have made in recent decades in preserving their use of energy (see Dargay and Gately, 2010; Ramey and Vine, 2012).

Time variation in the short-run price elasticity of oil supply, with a lower elasticity in the more recent past, is another plausible hypothesis to explain the volatility data in Figure 1(a) (see equation (13)). In this regard, Kilian (2008) observes that world oil production has been close to its full capacity level since 1990, which has made it more difficult to raise production in the short run in response to oil demand shocks compared to the 1980s. Smith (2009) goes further and suggests that oil production responses have been sluggish in recent years owing to OPEC supplier's deliberate decision not to expand productive capacity despite ample oil reserves available for development in order to support cartel discipline. Further evidence on the recent stagnation in world oil production is provided by Hamilton (2009b) and Kilian (2010). According to equation (13), the limited ability of oil producers to adjust oil supplies results in higher oil price fluctuations and smaller oil production variability.

2.3. More flexible crude oil prices over time.

Finally, changes in the speed of oil price adjustment to oil demand and oil supply shocks are expected to affect oil market volatility. The shift in the pricing system from long-term oil contracts towards a more transparent system of spot and futures market trading and the collapse of OPEC in late 1985 are likely to have increased the flexibility of the real price of oil. If a greater fraction of oil transactions is carried out on the spot market, oil supply and demand variations are expected to translate quicker into price changes. According to our oil market model, an increase in the speed of adjustment of the actual oil price to its equilibrium value influences the variability of oil prices and oil production in the following way:

$$\frac{\partial E[P_t]^2}{\partial \lambda_t} > 0 \text{ and } \frac{\partial E[Q_t]^2}{\partial \lambda_t} = \frac{2d_t}{(s_t + d_t)^2}\left\{-[s_t + (1-\lambda_t)d_t]\sigma^2_{d,t} + \lambda_t d_t \sigma^2_{s,t}\right\} \lessgtr 0 \tag{14}$$

On the one hand, more flexible contracts do result in greater oil price volatility in the short run. On the other hand, the impact of a faster convergence to the equilibrium price level on oil production volatility is uncertain and crucially depends on the relative variance of supply and demand shocks in combination with the short-run price elasticities of oil supply and demand. Intuitively, since institutional arrangements in the oil market that prevailed until the mid 1980s relied on a fixed reference price for crude oil, adjustments to new demand conditions had to be carried out by adapting production volumes, leading to wide fluctuations in oil production. On the other hand, stipulating a fixed price should smooth oil production, which reduces the variability. The net effect on oil production volatility therefore depends on the relative importance of both shocks. If oil demand shocks were relatively more variable in earlier periods, for example, an increased speed of adjustment of the real price of crude oil toward its equilibrium value alone could explain the pattern of oil market volatility.

It is very likely that many of these potential explanations come into play simultaneously. While the theoretical demand and supply relationships are easily established, identifying them is more difficult. In the next section, we present an empirical framework that allows us to examine the three main hypotheses jointly.

3. EMPIRICAL METHODOLOGY

Previous empirical studies of oil price volatility (e.g. Barsky and Kilian, 2002; Regnier, 2007; Yang *et al*., 2002) have shown that surges in volatility typically are not one-time events but reflect sustained developments in the market. This feature is readily apparent from the standard deviations of the real oil price and oil production computed over 5-year rolling windows presented in Figure 1(b). Alquist *et al*. (2011) illustrate that evidence for changes in oil price volatility is highly sensitive to the choice of break date. This reinforces the case that associating changes in volatility with regime shifts might not be the appropriate modeling strategy. Even conceptually, abrupt shifts are less likely to occur in light of the transitional nature of processes characterizing adjustments in the global market for crude oil as laid out in the Introduction. As observed by Primiceri (2005), models with discrete breaks are hard to reconcile with the idea of adaptive behavior of market participants, in particular given that aggregation among agents' assessments tends to result in smooth changes since not all agents would be expected to update their beliefs at the same time. In fact, interpreting this gradual adjustment as the outcome of an ongoing learning process on the part of oil producers and oil consumers is in sharp contrast with the regularity that a switching process implies. This would suggest that the best modeling approach is one that allows for slow-moving but continuous change as well as for possible jumps.

We accommodate these potential features of the underlying data-generating process by means of a VAR model that features time-varying coefficients and stochastic volatilities in the innovation process as an encompassing model specification. As pointed out by Benati and Mumtaz (2007) and as illustrated in the supplementary appendix, drifting coefficient models are able to track processes subject to sudden breaks successfully. Consequently, our specification can be expected to work reasonably well both for periods of smooth evolutions and for periods of abrupt shifts.[5]

Given its flexibility, the TVP approach enables us to evaluate time variation in the variances of shocks, the short-run price elasticities of oil supply and oil demand, and the speed of oil price adjustment. We disentangle the structural shocks by means of sign restrictions. In particular, we identify exogenous oil supply shocks, oil demand shocks associated with unexpected changes in global economic activity, and other oil demand shocks that capture shifts in expectations about future oil market conditions.

3.1. A Bayesian VAR with Time-Varying Parameters and Stochastic Volatility

We consider the following VAR(p) model with time-varying parameters and stochastic volatility in the spirit of Cogley and Sargent (2005), Primiceri (2005), Benati and Mumtaz (2007), and Canova and Gambetti (2009):

$$y_t = C_t + B_{1,t}y_{t-1} + \ldots + B_{p,t}y_{t-p} + u_t \tag{15}$$

where y_t is a 3×1 vector of observed endogenous variables that contains quarterly data on global oil

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[5] We demonstrate this by conducting a Monte Carlo simulation. Additional support for our specification is provided by the methodology of Koop *et al*. (2009), which allows one to determine the frequency of breaks endogenously. As reported in detail in the supplementary appendix, both exercises lend support to our modeling choice.

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production, the real US refiners' acquisition cost of imported crude oil and world industrial production,[6] C_t is a vector of time-varying intercepts, $B_{p,t}$ are 3×3 matrices of time-varying coefficients on the lags of the endogenous variables, where the number of lags is set to $p = 4$ to allow for sufficient dynamics in the system, and u_t are heteroskedastic reduced-form innovations that are normally distributed with a zero mean and a time-varying covariance matrix Ω_t. The overall sample spans the period 1947:Q1–2010:Q4. The first 25 years of data are used as a training sample to calibrate the priors for estimation over the actual sample period, which starts in 1974:Q1.[7]

The drifting coefficients are meant to capture possible time variation in the lag structure of the model reflecting adaptive behavior on part of the economic agents. The multivariate time-varying covariance matrix allows for heteroskedasticity of the shocks and time variation in the simultaneous relationships between the variables in the system. Including the stochastic volatility component appears appropriate given the marked changes in volatility of our two key variables documented above, since ignoring heteroskedasticity of the disturbance terms could lead to fictitious dynamics in the VAR coefficients, as emphasized by Cogley and Sargent (2005). In other words, movements originating from the heteroskedastic covariance structure would be picked up by the VAR coefficients leading to an upward bias. Thus, allowing for time variation in both the coefficients and the variance–covariance matrix implies that time variation can derive from changes in the magnitude of shocks and their contemporaneous impact as well as from changes in the propagation mechanism. We estimate this model using Bayesian techniques described in Kim and Nelson (1999).[8]

3.2. Identification of Oil Supply and Oil Demand Shocks

The identification of the structural oil market shocks builds in part on Baumeister and Peersman (2012) in that we achieve identification by means of sign restrictions. Our model allows a more comprehensive analysis of the demand side of the crude oil market.[9] Specifically, we place theoretically plausible sign restrictions on the time-varying impulse responses to recover the three underlying structural shocks which drive world oil production and the real price of crude oil in the model presented in Section 2. An advantage of sign restrictions is the absence of a restriction on the magnitude of the contemporaneous impact of the shocks. Moreover, in our model this impact effect as well as the short-run price elasticities can vary over time.[10] The sign restrictions on the impact responses of oil production, the real price of oil and world industrial production are summarized in Table 1.

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[6] All variables are transformed to non-annualized quarter-on-quarter rates of growth by taking the first difference of the natural logarithm. The chosen oil price variable may be viewed as the best proxy for the free market global price of crude oil. The nominal refiners' acquisition cost has been deflated by the US consumer price index. Our approach deviates from Peersman and Van Robays (2009), who use the nominal price of crude oil. For a discussion of the choice between the nominal and the real price of oil, see Alquist *et al*. (2011). World industrial production is the broadest available index at quarterly frequency to capture the state of the global economy. A detailed description of all the data used in this paper can be found in the supplementary appendix.

[7] This is the earliest possible starting date. As discussed in Barsky and Kilian (2002) and demonstrated more formally in Alquist *et al*. (2011), the regulation of the oil price prior to 1974 undermines the validity of standard time series models of the oil market even when allowing for time variation. Moreover, the fact that the price of crude oil was not determined by market forces invalidates the sign restrictions based on the competitive market model proposed in Section 2 and discussed more fully in Section 3.2.

[8] Technical details regarding the model set-up, the prior specifications and the estimation strategy (Markov chain Monte Carlo algorithm) are provided in the supplementary appendix.

[9] The key difference between this paper and Baumeister and Peersman (2012) lies in the economic question that each paper addresses. Whereas Baumeister and Peersman (2012) investigate the transmission of oil supply shocks to the US economy without taking a stand on the difficult problem of disentangling different oil demand shocks, the current paper abstracts from the effects on the US economy and focuses on understanding changes in the responses of the oil market variables to both oil supply and oil demand shocks.

[10] See Uhlig (2005) and Peersman (2005) for alternative applications of this identification strategy, and Fry and Pagan (2011) for a critical assessment of the sign restriction methodology in general.

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Table I. Identification restrictions

	Q_{oil}	P_{oil}	Y_{world}
Negative oil supply shock	-	+	-
Positive aggregate demand shock	+	+	+
Other positive oil demand shock	+	+	-

Oil supply shocks are disturbances that shift the oil supply curve and could be the result of oil production disruptions due to wars, for example. According to equations (6) and (7) of our model, such an oil supply shock moves oil quantity and the real price of oil in the opposite direction. After a negative oil supply disturbance, the reaction of world industrial production is restricted to be non-positive.

Oil demand shocks are disturbances that displace the oil demand curve and hence move oil production and oil prices in the same direction. As already mentioned, there are two oil demand shocks in the model. We make an explicit distinction between oil demand shocks associated with unexpected fluctuations global economic activity ('aggregate demand shocks') and oil demand shocks driven by forward-looking behavior ('other oil demand shocks'), building on Kilian (2009). The latter type of shock can be thought of as arising from revisions to expectations which are not limited to future demand and supply conditions in the crude oil market alone, but extend to the global business cycle, e.g. a deterioration in the economic outlook or the anticipation of faster growth in emerging Asia. In order to disentangle these two kinds of demand disturbances, we impose the restrictions that positive aggregate demand shocks unambiguously increase world industrial production, whereas other positive oil demand shocks that are related to shifts in perceptions or news about the future induce a reduction in current real activity as a result of the oil price increase.[11]

In a recent contribution Kilian and Murphy (2010) make the case that sign restrictions alone might be too weak to derive economically meaningful implications in the context of oil market models and that the identification strategy needs to be supplemented by additional information to sharpen the results. Kilian and Murphy (2010) propose to use boundary restrictions on the magnitudes of the implied short-run price elasticities of oil demand and oil supply as auxiliary identification criteria to eliminate those structural models that are associated with implausibly high elasticities. We follow Kilian and Murphy (2010) in imposing that the short-run price elasticity for oil demand cannot exceed its long-run counterpart, which may be inferred to be about -0.8 using cross-sectional evidence from US household surveys (see, for example, Hausman and Newey, 1995). This long-run estimate imposes only weak prior beliefs on the short-run oil demand elasticity, which is crucial given that we are interested in its evolution over time.

Although it is a widely accepted view among oil economists that the price elasticity of oil supply is low in the short run (e.g. Hamilton, 2009a; Kilian 2009), deriving a suitable upper bound for the quarterly supply elasticity is not straightforward. For one thing, we cannot rely on the bound introduced by Kilian and Murphy (2010) based on monthly data and there is no direct mapping to the quarterly frequency. More importantly, it is conceivable that different bounds are economically relevant during different historical episodes. In particular, given that we want to assess to what extent the slope of the oil supply curve has varied over time, we need to remain relatively agnostic on this bound. Subject to the constraint that at least one model at each point in time has to satisfy the upper bound, we restrict the short-run price elasticity of oil supply to be at most 0.6 in the baseline model. We also provide sensitivity analysis for other bounds.[12]

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[11] We explore the robustness of our results to the assumption of a zero impact on world industrial production after the other oil demand shock in Section 5.

[12] In section 4.2.2, we illustrate that our findings are robust for any empirically reasonable bound on the oil supply elasticity.

The computation of impulse responses and the implementation of the sign and boundary restrictions are discussed in detail in the supplementary appendix.

4. EMPIRICAL RESULTS

4.1. Changes in Oil Market Dynamics over Time

Figure 2 displays the evolution of the median impact responses of global oil production and the real price of imported crude oil to one-standard-deviation structural shocks spanning the period 1974:Q1–2010Q:4, along with 68% and 95% posterior credible sets and the full set of admissible models. All responses have been normalized such that the structural innovations raise the real price of oil. There is evidence of considerable time variation in the dynamic responses of the oil market variables for all three types of disturbances. The decline in world oil production after an unexpected oil supply disruption weakens steadily over time, whereas the reaction of the real price of oil becomes more pronounced. The time

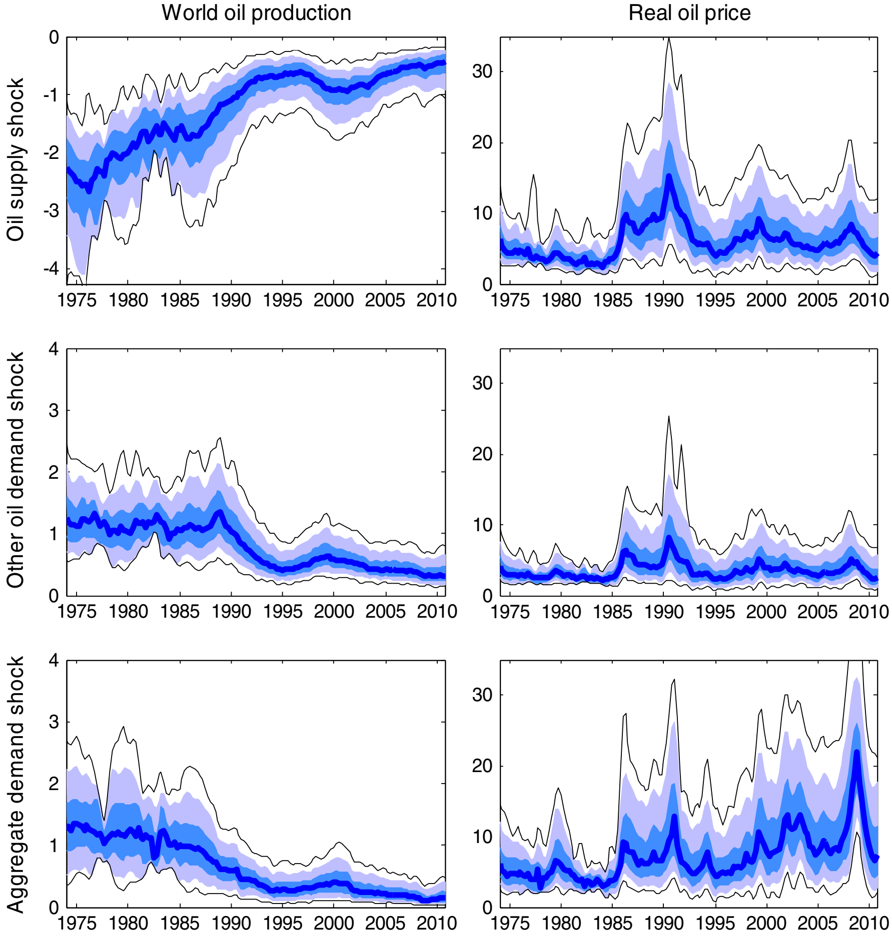

Figure 2. Time-varying median impact impulse responses (thick solid lines) of world oil production and the real price of crude oil after oil supply shocks (1st row), other oil demand shocks (2nd row) and aggregate demand shocks (3rd row), where the dark and light shaded areas indicate respectively 68% and 95% posterior credible sets and the thin black lines indicate the range of admissible models

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profiles observed after the two demand-induced shocks are similar, with a gradual reduction of the effect on world oil production and a consistently stronger price response from the mid 1980s onwards, in particular after an aggregate demand shock. The most striking regularity is the declining trend of the responses of world oil production after all three structural shocks, which is suggestive of the fact that the global market for crude oil has experienced a structural transformation.

4.2. Evaluation of Hypotheses

4.2.1. Speed of Adjustment

To assess whether faster convergence to the equilibrium price level is at the origin of the observed volatility pattern, it is instructive to look at the persistence of real oil price inflation, measured as the normalized spectrum at frequency zero. Following Benati and Mumtaz (2007) and Canova and Gambetti (2009), we compute the spectral density in the following way:

$$f_{\pi,t|T}(\omega) = s_{\pi}\left(I_3 - \theta_{t|T}e^{-i\omega}\right)^{-1}\frac{\Omega_{t|T}}{2\pi}\left[\left(I_3 - \theta_{t|T}e^{-i\omega}\right)^{-1}\right]' s_{\pi}' \tag{16}$$

which is normalized by dividing by the variance (the integral of (16)) for $\omega = 0$, with s_{π} being a row vector selecting oil price inflation. Figure 3 displays the time-varying median of the normalized spectrum of real oil price inflation for the period 1974:Q1–2010:Q4. If sluggishness in the oil price adjustment were an important feature only in the early part of the sample, we would expect to see a fall in persistence coinciding with changes in the institutional structure of the oil market. Instead, the degree of persistence appears to have been stable over time. Thus we can discard the hypothesis of changes in the speed of adjustment as one explanation for larger oil price fluctuations.

4.2.2. Evolution of Short-Run Price Elasticities

As first stressed by Barsky and Kilian (2002) and recently highlighted by Kilian (2008) and Hamilton (2009a), among others, it is difficult to trace the slope of the oil demand and oil supply curves from the observed movements in oil quantity and oil price because these two variables are subject to a myriad of

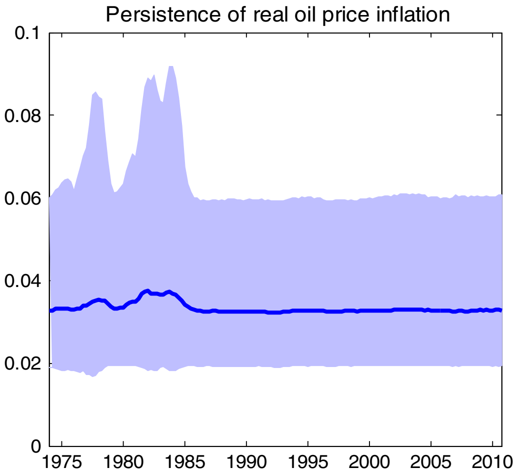

Figure 3. Time-varying normalized spectrum of real oil price inflation as a measure of persistence, where the shaded area covers 95% of the posterior distribution and the solid line is the median

influences that are hard to disentangle.[13] But since we have identified the structural shocks in our empirical model that induce reactions in the oil market variables by shifting either the oil demand or oil supply schedule, we can derive direct estimates for the implied short-run price elasticities of oil demand and oil supply at each point in time from the impulse responses as the percentage change in world oil production divided by the percentage change in oil prices.

Figure 4 reports the evolution of the median impact elasticities of oil supply and oil demand together with the 68% and 95% posterior credible sets and the range of elasticity estimates for all admissible models over the entire sample. Note that, since we identify two different types of demand shocks, we trace the curvature of the oil supply schedule once with the shock to global economic activity and once with the other oil demand shock. While the oil supply curve is relatively more elastic in the first part of the sample period with median elasticities in the range 0.3–0.5, the responsiveness of oil quantities supplied to changes in crude oil prices subsides from 1983 onwards and reaches very low levels in the most recent past. This earlier period experiences a temporary drop in the price elasticity of oil supply in 1979, during which the adjustment in the aftermath of demand-side shocks has taken place more via prices than quantities. Notably, since the late 1980s, the median value for the oil supply elasticities falls between 0.02 and 0.25, indicating that the supply of crude oil has become highly insensitive to changes in its price. While qualitatively similar, the estimated magnitudes of the short-run price elasticities for the supply of crude oil derived with the two demand-side shocks are somewhat different, a finding which might point to a different reaction of oil production depending on the source of demand.

Similarly, the impact price elasticity of oil demand is relatively high and stable during the 1970s, with a median estimate of around -0.55, but gradually declines from a high of -0.65 in 1983 to a low of -0.07 in 1990. The sensitivity of oil demand to price changes remains low thereafter, with median elasticities ranging from -0.06 to -0.16. The sample average of our median estimates of oil demand elasticity of -0.26 accords well with recent estimates derived from alternative structural models reporting elasticity estimates between -0.26 and -0.41 (Bodenstein and Guerrieri, 2011; Kilian and Murphy, 2011; Serletis *et al*., 2010). These elasticity estimates clearly provide evidence in favor of the hypothesis that attributes the oil market volatility pattern to a decrease in the responsiveness of, respectively, oil demand and supply to price changes.[14]

Based on Figure 4, we can also assess the evolution of the range of time-varying elasticity estimates, which we will link to historical developments in Section 6. We observe that our model implies that the short-run price elasticity of oil supply derived with aggregate demand must have been at least 0.1 for most of the period 1980–1985, although the data also support estimates as high as 0.6. For the later period this range narrows substantially, going from slightly above 0 to about a maximum of 0.2 for most of 1990–2010. While oil supply elasticities obtained with the other oil demand shock can fall between 0.02 and 0.6 in the latter part of the sample, before 1986 the lowest attainable value was 0.25 with the exception of the 1979 episode. The smallest demand elasticity (in absolute value) for 1974–1985 was 0.2, but it could also reach magnitudes as high as 0.8 over the same period. From 1990 onwards, the range shifts considerably upward, covering values from 0.01 to 0.4 at best in most instances.

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[13] Nevertheless, Hamilton (2009a) tries to infer the slope of the oil demand curve by selecting historical episodes in which a shift of the supply curve was the primary factor for fluctuations in oil price and production (i.e. political events or war activities) and computes elasticities from the subsequent changes in quantities and prices. However, no single episode in the oil market is an exclusive supply-side story. Hence this way of recovering a measure for the demand elasticity constitutes a rough approximation. However, interestingly, Hamilton's measure conveys the same message, i.e., that the price elasticity of oil demand is even smaller now than it was in 1980.

[14] Further evidence in support of a systematic change in the estimated impact elasticities over time is presented in Section 5.1 of the supplementary appendix.

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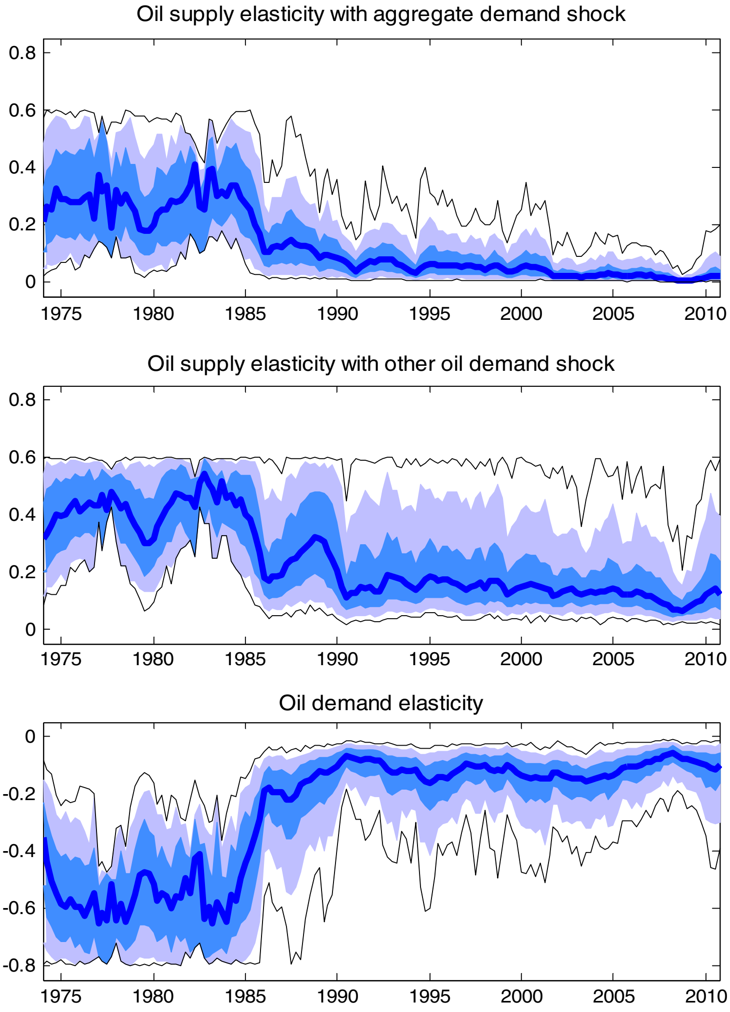

Figure 4. Median short-run price elasticities of oil supply and oil demand (bold solid lines) together with the 68% and 95% posterior credible sets (dark and light shaded areas) and the range of admissible models (thin solid lines). The slope of the oil supply curve is derived with aggregate demand shocks and other oil demand shocks

Figure 5 shows that the evolution of the median elasticity estimates for oil supply and oil demand over time are robust to variations in the upper bound on the oil supply elasticity. Relaxing the upper bounds to 0.8 and 1 does not affect the estimates of the oil demand elasticity and the oil supply elasticity derived with aggregate demand shocks, but slightly raises the median elasticity of oil supply obtained with other oil demand shocks in the periods 1976–1978 and 1981–1985. However, the qualitative features of the changes in the elasticity estimates over the sample period remain intact. We do not consider values above 1, based on the observation that supply elasticities greater than 1 are not plausible for a commodity like crude oil with limited adjustment possibilities of current production and long lead times for capacity expansion. This additional evidence confirms that the time profile of the elasticities is not driven by the specific elasticity bound used in the baseline model.

A striking feature of our results is the similarity in the evolution of the slopes of both the oil supply and oil demand schedules, with a marked decline of both short-run price elasticities over the period 1983–1990. In Section 6 we provide some potential explanations for the concurrence of these developments.

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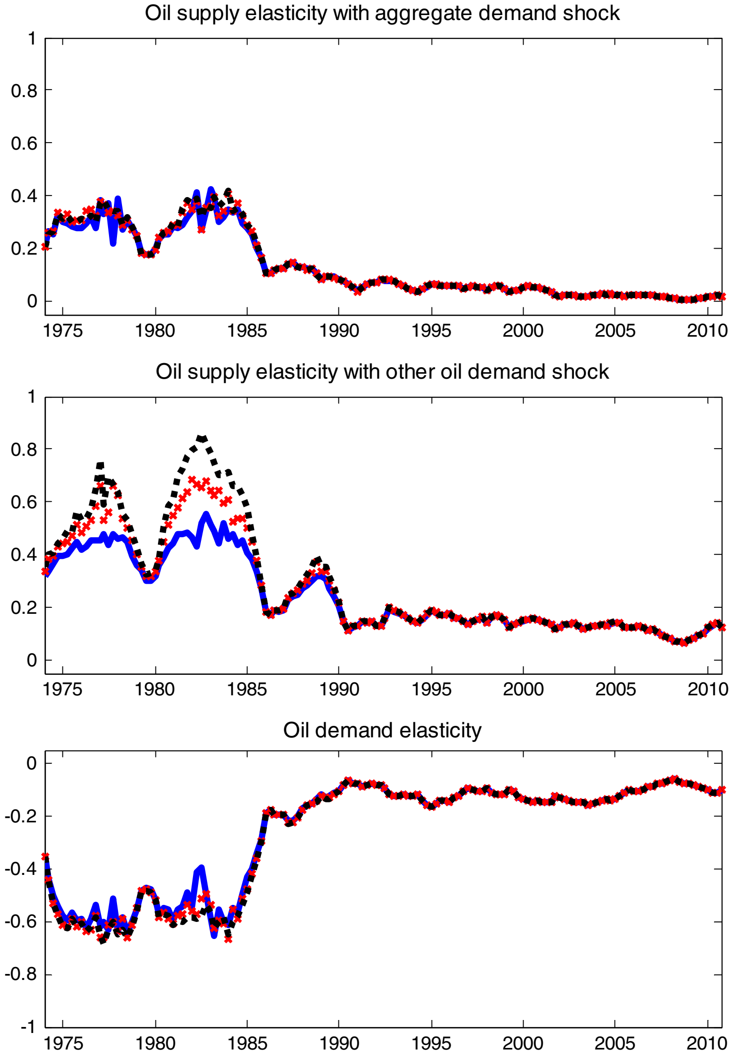

Figure 5. Median short-run price elasticities of oil supply and oil demand with an upper bound on the oil supply elasticity of 0.6 (solid line), 0.8 (crosses) and 1 (dots)

4.2.3. Evolution of Shocks

Within an SVAR framework, it is not possible to separately measure the underlying volatility of shocks; only the contemporaneous impact of a one-standard deviation shock on the variables, which is a combination of the magnitude of the shock itself and the immediate reaction of the variable to that shock, can be measured. To get an approximation of the magnitudes of one-standard-deviation structural shocks over time, we perform some simple back-of-the-envelope calculations. More specifically, given the short-run price elasticities recovered from the estimated impulse responses, we can compute the time-varying magnitudes of average underlying shocks by means of equations (1) and (2) from our stylized model of the oil market. Given the simplified nature of the model, the results should, however, be interpreted with caution.

Figure 6 depicts the changes in the variability of average structural shocks for all admissible models. As emerges from the graphs, all structural oil market shocks have become smaller in size during the

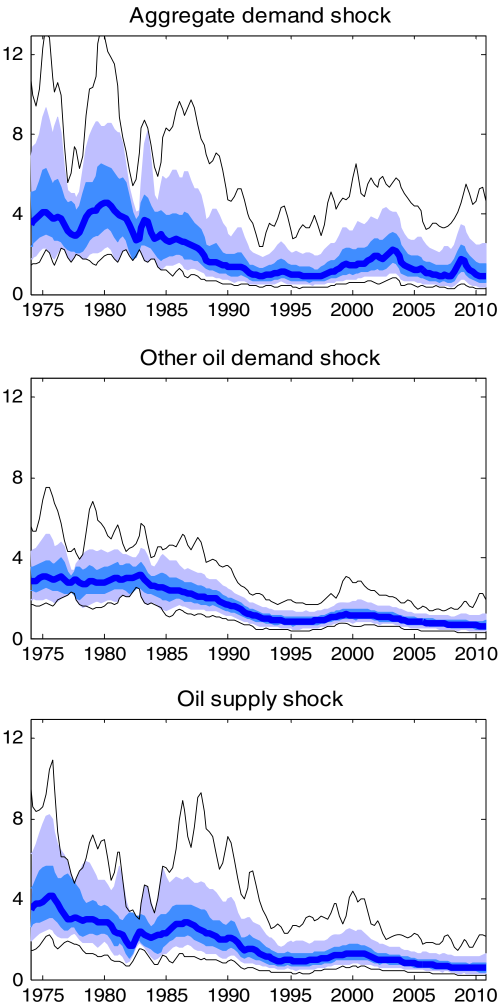

Figure 6. Set of structural residuals derived with back-of-the-envelope calculation for all admissible models (thin solid lines), the 68% and 95% posterior credible sets (dark and light shaded areas), with the median shown as bold solid line

latter part of the sample. While the variance of oil demand shocks driven by global real activity has been relatively high in the early part of the sample, it has been steadily diminishing since the mid 1980s, which is in line with the onset of the 'Great Moderation'. Around the same time, substitution effects took hold, thereby lowering the oil intensity of industrial production, which might induce smaller shifts of the oil demand curve deriving from greater economic activity. However, aggregate demand shocks seem to have gained somewhat in size again since the early 2000s.

The evolution of the variance of other oil demand shocks depends on the quantitative importance of fears about future oil supply shortfalls. This speculative component of the real price of oil has received increased scrutiny when oil futures markets experienced an unprecedented surge in the share of non-commercial traders after 2003 (see Alquist and Kilian, 2010). However, it is not obvious to what extent trading in 'paper barrels' will spill over to the physical market (Smith, 2009). Proponents of the existence of such a link might have expected increased speculative activities to be associated with a higher variance of the other oil demand shock. Instead, we find that this shock has decreased since the late 1980s.

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Finally, the variance of the oil supply disturbances has been quite large during the early part of the sample but started to decline gradually from the mid 1980s to the mid 1990s, being considerably lower since 1995. [15] Consequently, smaller shocks have to some extent tempered the volatility increase in the real price of oil, which could have been even larger had the variances of these shocks remained the same as during the 1970s and early 1980s.

5. SENSITIVITY ANALYSIS

5.1. Model Specification

One contribution of our paper is to introduce a new world industrial production index for measuring global real activity. An alternative specification that has been widely used in structural oil market models (e.g. Kilian, 2009; Kilian and Murphy, 2010, 2011) relies on a different indicator of the global business cycle based on shipping rates to capture shifts in the demand for all industrial commodities in combination with the real price of crude oil being specified in log-levels to preserve the low-frequency covariation in the data. It might be of concern that filtering out this low-frequency co-movement by first-differencing the data as we do in our benchmark VAR model could drive the results. It is therefore of interest to assess the robustness of our findings to this alternative model specification that includes the real refiners' acquisition cost of oil imports in log deviations from its mean and replaces world industrial production growth with the quarterly averages of the business cycle index of global real economic activity proposed in Kilian (2009), which is expressed as percent deviation from a linear trend, representing increasing returns to scale in shipping. Our conclusions remain largely unchanged for this competing specification. The general pattern of the impulse responses over time and the considerable decline in both impact price elasticities are robust.[16]

5.2. Identification Assumptions

The other oil demand shock captures shifts in the market's assessment related to uncertainty about future developments. While this expectation-driven component of oil demand is readily reflected in instantaneous movements in the price and quantity of oil, its effect on world industrial production is ambiguous. In fact, it may take some time until the repercussions of such a shock are felt on the global business cycle. To explore the sensitivity of our results to a delayed response in world industrial production after the other oil demand shock, we impose a contemporaneous zero restriction instead of postulating that economic activity should decline on impact.[17] Our findings are remarkably robust to this modification in the identification assumptions.[18] We still obtain the same time profile for both the impulse responses and the short-run price elasticities of oil demand and supply as in the benchmark case.

6. ANALYSIS OF THE DECLINE IN ELASTICITIES

So far we have documented a remarkable change in the magnitudes of the short-run price elasticities of oil supply and of oil demand over time, in particular a joint decline around the mid 1980s. In this section, we propose several mechanisms that have the potential to account for the observed evolution

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[15] Given the modest difference in the estimates for the variance of oil supply innovations obtained with the two demand specifications, we only report results obtained with the aggregate demand set-up.

[16] Further evidence is presented in Figures 6A and 7A in the supplementary appendix.

[17] For details regarding the implementation of a single zero restriction, we refer the reader to the supplementary appendix.

[18] Figures 8A and 9A in the supplementary appendix report the impulse responses and the elasticity estimates obtained with this new identification scheme.

of both price elasticities. More specifically, we offer a set of explanations for the changes in the slopes of oil demand and oil supply curves based on historical developments in the oil market which are not mutually exclusive, to show that the joint steepening of both curves is not coincidental but the result of a confluence of structural changes that tend to interact in complicated ways and even reinforce each other. This analysis not only provides insights into what kind of factors might be at the origin of the decline in elasticities, but also helps address concerns about whether our time-varying model is a good description of the underlying data generation process. We show that the observed time variation in the estimated elasticities matches our a priori beliefs about the timing and direction of these changes based on historical accounts. This coincidence in timing provides suggestive evidence that our results are not driven by the empirical methodology. These proposed explanations for changes in the short-run price elasticities constitute potentially promising avenues for future research, not just in relation to understanding oil prices but asset prices more in general. We first discuss the interplay between the development of the oil futures market and the price elasticities, before moving to a more specific interaction between the price elasticities of oil supply and of oil demand.

6.1. Oil Futures Markets and the Short-Run Price Elasticities of Oil Demand and Supply

At the time of the onset of the decline in both impact price elasticities in the early 1980s, an important structural transformation occurred in the oil market when the market moved from a system of administered oil prices to a market-based system of spot trading and the subsequent development of derivatives markets. Hubbard (1986) considers this shift as the source of greater oil price volatility, which attracted speculators and fostered the creation and expansion of oil futures markets. On the other hand, Smith (2009) argues that oil futures trading by speculators and hedgers should hardly exert any effect on the physical oil market, unless the buoyant futures market fuels a revision of expectations about spot prices, which induces a reaction from market participants such as an accumulation of oil inventories or a fall in production that should influence current oil prices.

While the development of oil futures markets might not have a direct impact on the physical market, the availability of oil futures contracts as a risk management tool has the potential of indirectly altering the behavior of commercial traders on both sides of the oil market. More specifically, refineries and other oil consumers engage in oil futures trading to protect their business operations against unfavorable price movements by entering into a hedging contract. For instance, an airline company that wants to eliminate price risks associated with its future fuel purchases has to buy oil futures today to lock in the desired price for future delivery. Likewise, oil producers can lock in future sales revenues and profit margins and hedge themselves against declines in prices by selling oil futures contracts given their long position in physical oil. As a result, both consumers and producers will become less responsive to price changes because physical purchases and sales of crude oil are hedged by offsetting financial positions in the oil futures market.

Figure 7 shows the total quarterly trading volume of oil futures contracts with less than one year to maturity traded on the New York Mercantile Exchange (NYMEX) for the period 1983:Q2–2010:Q4.[19] The steady decrease in the short-run price elasticities of oil demand and oil supply uncovered in our empirical analysis coincides with the creation and expansion of oil futures trading during 1983–1990, which provided increasing opportunities for market participants to shield themselves from adverse future price developments. The observed rise in hedging activities is consistent with the perception of a diminished sensitivity of commercial dealers to oil price fluctuations in the spot market, contributing to less

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[19] Crude oil futures contracts based on West Texas Intermediate (WTI) grade were launched on the NYMEX in March 1983. Up to 1989, the longest maturity for those contracts was 12 months, but even after the introduction of longer-dated contracts trading was concentrated in maturities up to one year, which makes our volume measure a good indicator of overall activity in the oil futures market (see also Neuberger, 1999; Alquist and Kilian, 2010).

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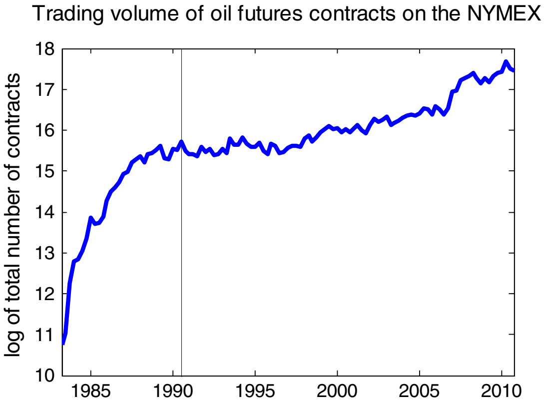

Figure 7. Total quarterly trading volume of WTI futures contracts with less than one year to maturity. The vertical line indicates the point in time when the lowest oil demand elasticity was reached

elastic oil demand and supply curves. The reduced price elasticities of demand and supply result in increased oil price volatility which further encourages the development of derivatives markets.

6.2. Influence of Investment and Capacity Constraints on Supply and Demand in the Oil Market

The joint decline of both short-run price elasticities over the period 1983–1990 is also consistent with an interplay between developments on the demand side of the crude oil market that trigger reactions on the supply side, which in turn affect demand.[20] Following the oil price shocks of the 1970s, the delayed consequences of increased energy conservation and substitution processes away from oil to alternative sources of energy are likely to have contributed to a reduction in the short-run price elasticity of oil demand from the early 1980s onwards.[21] According to Gately (2004), if the price elasticity of crude oil demand is relatively low, oil producers may purposefully refrain from expanding production capacity at a rapid pace to preserve the revenues from higher oil prices. Thus the price elasticity of oil demand feeds back into the supply behavior of oil producers by reducing the incentives to bring new capacity on stream, which leads to less investment in infrastructure and a gradual erosion of idle capacity. Moreover, the geographic concentration of proven oil reserves in a limited number of OPEC countries, where investment decisions are not purely determined by economic considerations but also political factors, might have impaired the necessary investments in the oil sector.[22] In fact, Smith (2009) advances the view that OPEC members pursue the deliberate strategy of limiting the growth of productive capacity in the interest of the common good of the cartel. This evolution is illustrated in Figure 8. Figure 8(a) shows worldwide active rig counts for the period 1975:M1–2010:M12, which can be considered as one of the primary measures of exploratory activity in the oil industry and hence a good indicator for investment in productive capacity. Figure 8(b) displays the annual global capacity utilization rates of crude oil production from 1974 to 2010. The substantial drop in investment activities during the early 1980s goes hand in hand with the notable decrease in the price elasticity of oil

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[20] Hamilton (2009b, p. 228) exemplifies this interaction by stating that ‘it is a matter of conjecture whether the decline in Saudi production in 2007 should be attributed to depletion, [. . .or] to a deliberate policy decision in response to a perceived decline in the price elasticity of demand.’

[21] We refer to Baumeister and Peersman (2012) and references therein for a more detailed description of developments in oil-importing countries that are in line with a decrease in the short-run price elasticity of oil demand.

[22] Political impediments for the expansion of capacity can be sought in the fear of expropriation, a resurgence of ‘resource nationalism’, i.e. refusal of foreign direct investments, and concerns about rapid depletion of oil resources, i.e. preservation of oil reserves for future generations.

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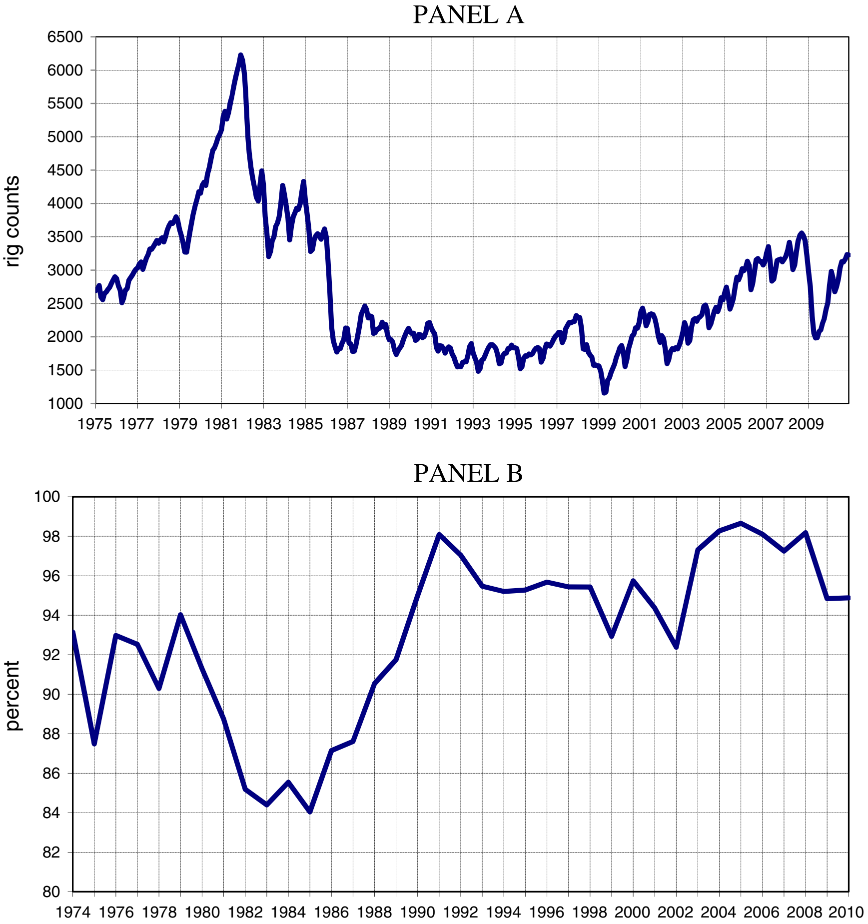

Figure 8. Investment and capacity constraints in the oil sector. (a) Monthly worldwide oil rig counts. (b) Global capacity utilization rates in crude oil production by year

supply in anticipation of a reduction in flexibility of oil producers to offset unexpected oil market disturbances by raising oil production, which is reflected in the subsequent increase in the utilization of existing capacity. [23] In addition, the increased oil price volatility may increase uncertainty, causing investment in exploration and development to be postponed.

The lack of investment and the presence of capacity constraints do not only affect the supply side of the global oil market but also have the potential to induce a different behavior on the demand side. In fact, high rates of capacity utilization can put considerable strain on oil consumers in that they signal market tightness and hence raise fears about future oil scarcity, which makes market participants willing to pay a higher insurance premium for the same quantity of oil to shield themselves from potential shortfalls in oil delivery (Alquist and Kilian, 2010).[24] This

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[23] Geroski *et al*. (1987) and Smith (2005) make the case that also the market structure plays an important role in determining the extent to which individual oil producers are willing to offset supply losses that occur elsewhere in the system and that their conduct (cooperative vs. competitive) varies in the function of excess capacity, among other factors.

[24] This induced change in demand behavior (which concerns the slope of the curve) has to be clearly distinguished from other oil demand shocks; in the former case, oil consumers assign a greater value to the *same* amount of oil, i.e. they pay a premium to ensure that they get this amount, whereas in the latter case they effectively want to increase the quantity demanded (i.e. a shift of the oil demand curve) for stockbuilding.

means that the share of precautionary demand in total oil demand increases when the oil sector is operating close to full capacity because agents anticipate that in case of a major oil shock, a shortfall in production volumes cannot be replaced by other producers since no idle capacity is left that could act as a buffer against abrupt disruptions. As a result, overall oil demand becomes less elastic. This is reflected in the sustained decline in the short-run price elasticity of oil demand observed over the period 1985–1991 which closely follows the increase in global capacity utilization rates. Oil demand remains less price sensitive thereafter because of consistently low spare capacity.

7. CONCLUSIONS

In this paper, we documented the previously unnoticed fact that the increase in oil price volatility since the mid 1980s has been accompanied by a significant decline in oil production volatility. We derived a set of potential hypotheses from a stylized demand and supply model for the crude oil market to explain this observation and assessed their validity in a unified empirical framework. Since the evolution of the oil market volatilities can be accounted for by changes in the variances of structural shocks, changes in the speed of adjustment as a result of modifications in the institutional structure of the oil market and/or changes in the demand and supply behavior for crude oil, we estimated a time-varying vector autoregression model for the period 1974:Q1–2010:Q4 that captures potential time variation in the dynamic relationships and the volatility of the structural shocks. For the identification of oil supply shocks, of oil demand shocks caused by shifts in global economic activity and of other oil demand shocks driven by forward-looking behavior, we proposed a set of sign restrictions. The model was used, first, to derive short-run price elasticities of oil supply and demand that are not a priori restricted to be zero on impact and, second, to trace the evolution of the slopes of oil supply and demand curves, the volatility of structural shocks and the degree of price flexibility over time.

We found that the variances of the structural shocks decreased over time and hence changes in the shock variances cannot explain the increased oil price volatility. Instead, the main reason for the higher oil price volatility and smaller oil production volatility in more recent times is the substantial decrease in the short-run price elasticities of oil supply and of oil demand. Put differently, both curves have become so inelastic that even small disturbances on either side of the market generate large price jumps but only moderate quantity adjustments.

We provided a non-exhaustive list of historical developments in the oil market that are consistent with the joint evolution of the price elasticities and help rationalize our results. We conjectured that the steepening of the oil supply and demand curves since the mid 1980s is the result of an interplay between several factors. In particular, the absence of excess oil production capacity and the lack of investment in the oil sector may have contributed to a decline in the price elasticities of oil supply and of oil demand. The corresponding surge in oil price volatility may have fostered the deepening of oil futures markets to cope with the increased uncertainty, which in turn further reduced the sensitivity of oil supply and demand to changes in crude oil prices.

In our analysis we have maintained that oil consumption equals oil production abstracting from the possibility that part of the oil output available today might be put into storage for consumption in the future. In recent research, Kilian and Murphy (2011) proposed an alternative definition of the oil demand elasticity that takes changes in oil inventories into account, but their model postulates a stable relationship over the entire post-1973 period. It would be interesting to explore how much the inclusion of oil inventories matters for this elasticity estimate and how much this has varied over time. We consider this an interesting avenue for future research. Another question that emerges is whether time variation in volatilities or price elasticities is an important feature of other types of assets such as exchange rates, stock, house or commodity prices.

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