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Summary

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Keywords: Global Market for Crude Oil, Bayesian SVAR Model, Oil Futures-spot Spread, Oil Price Speculation

JEL Classification: Q40 ,Q41, Q43, E32

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Daniele Valenti*

Abstract

In this paper we develop a Structural Vector Autoregressive (SVAR) model of the global market for crude oil where the forward-looking expectations of oil traders are inferred from the financial markets. In this respect, we replace the global proxy for above-ground crude oil inventories with the oil futures-spot spread. The latter is defined as the percent deviation of the oil futures price from the spot price of oil and it represents a measure of the convenience yield but expressed with an opposite sign. The following model provides an economic interpretation of the residual structural shock, namely the financial market shock. This is designed to capture an unanticipated change in the benefit of holding crude oil inventories that is driven by financial incentives. We find evidence that financial market shocks have played an important role in explaining the surge of the real price of oil during the period 2003-2008.

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1 Introduction

In this work, we evaluate the importance of financial forces in driving the real price of crude oil, by relying on a sign-restricted SVAR model. It is widely accepted that crude oil represents the most important and traded commodity in the world.

As reported by the US Department of Energy Information Administration (EIA), in 2017 the total crude oil consumption amounted to 35.9 billion barrels of oil, and the North Sea Brent crude oil spot prices averaged 54 dollars per barrel [1]. As a result, the overall oil market size reached 1.9 trillion dollars in the previous year. Due to the growing flow of money into the global crude oil market [2] , understanding the economic factors behind oil price movements provides a useful content resource for policy makers and private organizations.

For example, central banks can take accurate actions with respect to monetary policy, while private companies can provide more reliable budgets to support their economic businesses. A common practice among researchers is to consider the endogeneity of the price of oil with respect to the global economy, as discussed in Kilian and Lutkepohl (2016). This implies that the real price of oil is being determined by worldwide supply-and-demand. The first analysis to take up this feature is a study by Kilian (2009). The author introduces a SVAR model for the global market for crude oil, which represents a novelty in terms of methodology and results. The model of interest includes monthly past data on three aggregate variables: the growth rate of global crude oil production, a measure of real economic activity based on the cost of shipping in the international

[1] The spot price is the price at which the barrel of crude oil is immediately available in a given region. The Brent spot price is produced in the North Sea region while the WTI spot price is sent via pipeline to Cushing (Oklahoma).

[2] The global crude oil market includes spot and forward markets. The spot market generally refers to a short-term commodity transaction where the barrels of oil change hands very quickly after the sellers receive payment. Typically, spot sales are surpluses or amounts that a producer has not committed to sell on a term basis. Buyers may also have under-or over-estimated their consumption and may have oil surpluses to sell or shortages. Most of the crude oil traded in the physical markets is usually decided in advance by stipulating one year term agreements. According to Smith (2009) only a small fraction of the total physical trading (5-10%) represents a spot deal between two counterparts. The forward market consists of contracts through which oil traders agree up-front on a price for a certain amount of oil barrels that will be delivered to a specific location in the future. Futures price is the price at which the commodity will be available for delivery at a specified future date and place.

commodity markets and the global real price of crude oil. [3]

The econometric approach is based on the idea that real price of crude oil is mainly determined by structural shocks associated with a global supply of oil, a world demand for industrial commodities and an oil market specific demand (or precautionary demand shock). The main finding of this work is that shocks to demand and/or supply have a different impact on the real price of oil. Numerous studies investigate the channels of transmission of oil price shocks by exploiting alternative econometric approaches based on SVAR models, see Kilian and Murphy (2012); Lutkepohl and Netsunajev (2014); Baumeister and Peersman (2013).

Early analysis have three features in common. First, they include the same set of variables proposed in Kilian (2009). Second, they show that unanticipated shocks to demand for crude oil are the most important drivers in explaining the fluctuations in the price of oil. Third, the implied structural models do not include a proxy for the forward looking behaviour of oil traders. In this case global oil market VAR models could fail to identify the speculative component [4]. Therefore, Kilian and Murphy (2014) introduce a SVAR model by adding to the set of endogenous variables a proxy for the global crude oil inventories above the ground. In this way, the speculative actions of oil players are related to unexpected changes in the demand for storage. The authors find no evidence supporting the existence of speculative activities rising the global price of oil between 2003 and mid 2008. These results are robust to changes in the proxy for global oil inventories, as discussed in Kilian and Lee (2014).

In contrast to this conclusion, Juvenal and Petrella (2015) investigate the role of speculation on oil prices by adopting a Factor Augmented VAR model (FAVAR). This analysis finds evidence that financialization of commodity markets [5] have played an important role

[3]We consider the US refiners' imported acquisition cost (RACi) as a proxy for the spot price in the global market for crude oil. This is available from the web-site of the EIA. For the sake of clarity, in this analysis the terms "spot price of oil" and "real price of oil" are treated as synonyms, unless otherwise specified.

[4]As discussed in Kilian and Lee (2014), if the economic agents respond to information about future state of demand and supply of crude oil, which are not currently included in the researcher's information set, the market expectations will differ from those inferred by researcher and this makes the VAR methodology to disentangle the economic fundamentals invalid.

[5]In Fattouh et al. (2013) the authors state that financialization of commodity markets reflects the increasing acceptance of oil derivatives as a financial asset by a wide range of market participants including hedge funds, pension funds, insurance companies, and retail investors.

in driving the oil price surge between 2004 and 2008. Notwithstanding, the oil consumption demand, driven by economic activity, remains the main driver to capture the largest fraction of oil price fluctuations.

A work by Lombardi and Robays (2011) includes data on the oil futures prices to identify the speculation activities driven by non-fundamental forces. They use an augmented version of the model proposed by Kilian and Murphy (2014). The identification structure accounts for the existence of a destabilizing financial shock, which is defined as a structural shock that raises instantaneously the oil futures prices and the oil futures-spot spread.[6] The main result by Lombardi and Robays (2011) suggests that the destabilizing financial shocks can affect oil prices in the short run with negligible effects on either production and aggregate demand sides. According to Fattouh et al. (2013), the identification scheme leaves unrestricted the sign of the inventories casting doubts on the validity of all structural shocks.

Finally, a recent study by Baumeister and Hamilton (2017) consists of a Bayesian SVAR model with inventories and measurement error. This work sheds light on the importance of the supply shocks to the real price of oil. Moreover, this analysis provides evidence that structural shocks from supply and demand sides are equally important to drive much of the fluctuations in oil prices during the recent period.

In this work, we propose an analysis of the global market for crude oil based on a revised version of the SVAR model introduced by Kilian and Murphy (2014).

Our study widens the extant literature on modelling the global price of crude oil at least in two directions. First, as opposed to traditional oil market VAR models, we retrieve the expectations of forward-looking traders from the crude oil futures markets by replacing the proxy for global above-ground crude oil inventories with the oil futures-spot spread. The latter, defined as the percent deviation of the oil futures price from the spot price of crude oil, is a proxy for the convenience yield but expressed with an opposite sign.

In general, some OECD countries do not provide reliable and regular estimates about their level of inventories and data collections from non-OECD economies are publicly un-

[6]The oil futures-spot spread is defined as the difference between the impulse responses of the futures and spot prices of crude oil.

available. In this context the aggregation of world crude oil inventories is a big challenge. To solve this issue, Kilian and Murphy (2014) introduce a proxy for the global above-ground crude oil stocks by multiplying data of the US crude oil inventories and the ratio between the OECD and the US petroleum stocks. [7]

As pointed out by Kilian and Lee (2014) this proxy fails to take into account the existence of crude oil inventory stored at sea, in transit via pipelines, in the oil tankers and most important in those countries outside OECD regions. Moreover, even if the most accurate proxy for global crude oil inventories was available it would not address the question of how to deal with the lack of information induced by the incentive to hide some of the crude oil stored in each country.

The oil futures-spot spread can be used to deal with these issues by offering a reliable measure of the benefit of having ready access to crude oil stocks, anywhere they might be. There are several reasons to include the oil futures-spot spread in this analysis.

First, it is available in real time and is not subject to revisions as opposed to a proxy for global crude oil inventories. Second, the oil futures-spot spread is simple to derive and represents a reliable global market value of storage. Third, the crude oil futures contract with maturity 3-months ensures both the arbitrage-free hypothesis and the forward-looking property of the analysis [8]. As a result, the inclusion of the oil futures-spot spread represents the simplest way to establish a direct link between physical and financial markets within the context of the SVAR model.

The second contribution of this paper consists of the economic interpretation of the residual structural shock, namely the financial market shock. The latter can be derived from the combination between the oil futures-spot spread and a specific set of sign restrictions imposed on the elements of the impact multiplier matrix.

[7] Data for petroleum stocks are provided by the EIA and it includes crude oil as well as strategic petroleum reserves (SPR), unfinished oils, natural gas plant liquids and refined products.

[8] It is not surprising that a variety of investors trade paper barrels to exploit facilities in terms of cost-efficient trading, risk management opportunities and oil price discovery. Paper barrels consist of forward contracts which are traded by hedgers and speculators in an anonymous auction through futures brokers. These contracts do not require a physical delivery of the commodity. The New York Mercantile Exchange (NYMEX) and the Intercontinental Exchange (ICE) represent the two most important energy derivatives exchanges for futures, swap and options contracts. Trading is made only for speculation or hedging purposes and these instruments are typically closed out (or rolled over) before their expires dates. In other words in these markets it is not necessary to take the delivery of the commodity.

According to the theory of storage, we show that a positive financial market shock reflects an increase in the crude oil futures price relative to the current spot price. This shock drives up the residual demand for crude oil causing the amount of oil-stocks to build-up for reasons not already indicated by the previous three structural shocks of the model.

For example, an unexpected positive financial market shock might be driven by a speculative purchase of oil futures contracts, arbitrage mechanisms used to restore the equilibrium between financial and physical markets, and other forms of incentives that are implemented to keep crude oil off the physical market, causing the spot price of oil to rise.

The rest of the paper is organized as follows. Section 2 describes the dataset and provides empirical evidence of the relationship between crude oil spot prices and oil futures-spot spread. Section 3 discusses the econometric method. Section 4 illustrates the empirical results and some robustness checks. Section 5 concludes.

2 Data and variables

The following study consists of four monthly aggregate variables based on time-series data that covers the period 1983:3-2016:7.

The global oil production is measured in thousands of barrels of crude oil and is expressed in percent changes.

The real price of oil is constructed from the US refiners' imported acquisition cost of crude oil (RACi) [9] which is deflated by the US consumer price index. In this analysis, the choice of RACi as proxy for the global price of crude oil is motivated by two main reasons. First, according to the extant literature on modelling the global price of oil, the RACi represents the most relevant measure for theories interpreting oil price shocks as terms of trade shocks. This is also consistent with the fact that standard macroeconomic models of the transmission of oil price shocks are specified in terms of the price of imported crude oil, as discussed in Kilian and Vigfusson (2011). Second, the existence of alternative oil price measures, such as the West Texas Intermediate (WTI) and the Brent crude oil spot

[9] The refiners' acquisition cost (RAC) for imported crude oil (RACi) can be defined as the average price paid by U.S. refiners for imported. It refers to non-U.S. crude oil booked into the refineries in accordance with accounting procedures generally accepted and consistently and historically applied by the refiners concerned. The RACi includes transportation and other fees paid by the refiner.

prices are not representative of the global demand and supply of crude oil. Since, the WTI spot price has been subject to government regulation it would represent a good proxy for the U.S. producer price index but it does not provide a accurate measure for oil price fluctuations in global oil market. The same applies to the Brent spot price of oil which is the main reference for the Northwest Europe oil market. For these reasons, the RACi is likely to be a better proxy for the global price of crude oil and following Kilian and Murphy (2014) we conduct our analysis by taking the real price of oil in log deviation from its sample mean.

The macroeconomic indicator adopted for this study is the real economic activity index (REA) as proposed by Kilian (2009). [10] The following measure represents a proxy for changes in the volume of shipping of industrial materials and it is representative for the state of the global economy. According to Kilian and Zhou (2017) the Kilian's index provides four important advantages.

First, the coverage of the index is global because it accounts for the emerging economies like China and India which have played a primary role in determining the demand of industrial commodities since 2000. Second, it is a direct measure because it incorporates shifting country weights. Third, the fact that it is a leading indicator with respect to several real-output measures, such as global real GDP and world industrial production might facilitate the identification of the demand of industrial commodities which are treated as inputs in the production process. Fourth, it is a monthly indicator and its frequency facilitates the economic interpretation of the identification scheme required by SVAR models.

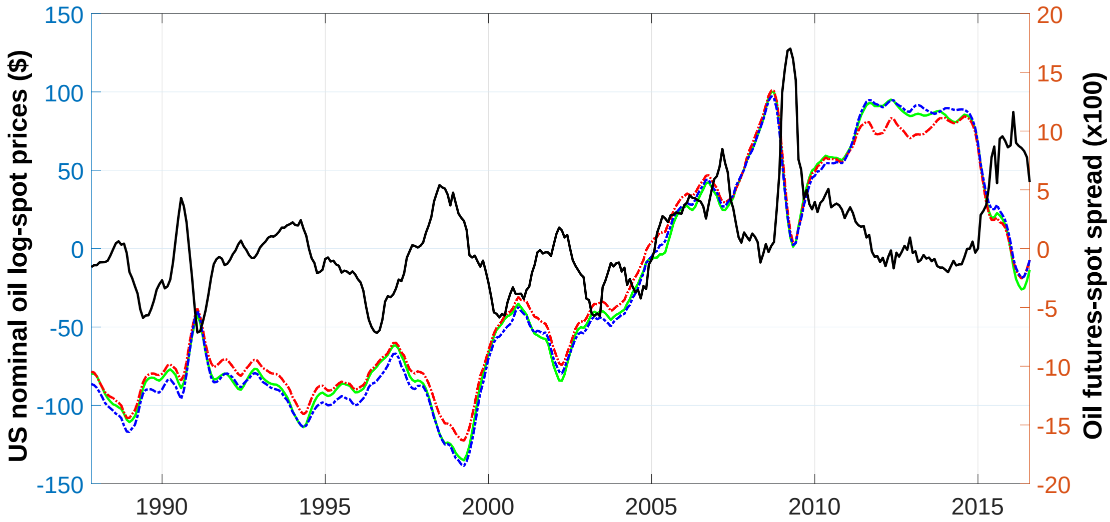
Finally, the oil futures-spot spread is defined as the percent deviation of the futures price

[10] Details about the construction of the real economic activity index are reported by Kilian (2009) and it is available from `http://www-personal.umich.edu/~lkilian/paperlinks.html`. Some concerns might arise because one cannot just use the index shown in Lutz Kilian's personal website if he is applying it with a different sample period. Because the mean of the sample period is different. However, having a look at the figure 1 reported in Kilian (2009), we point out that from 1960 to 1980 the equal-weighted average of these growth rates involves two time series. In 1980, four series entry in the construction of the index and they are the same until 1983, the period in which we start our analysis. Therefore, there is not much difference from the cross average of the raw data for individual freight rates and their cumulative average growth rate if the index is constructed starting in 1960 or in 1983. The only difference is the change in the normalization applied to the starting value of the index but this does not compromise the economic meaning of the indicator for the future periods.

[11] from the spot price of oil. To derive the oil futures-spot spread we also include prices from WTI futures market, although the Brent futures contracts are known as the world's crude oil benchmark. The main reason is that, WTI prices allow us to extend the dataset from 1983, since the Brent spot prices became available only in 1986. Therefore for the first period (April 1983 - January 2002) we use futures and spot prices from WTI market with delivery at Cushing, Oklahoma. As regards the second period (February 2002 - July 2016) we use prices from Brent futures and spot markets.

One might be skeptical of the oil futures-spot spread as a reliable proxy for international

Figure 1: Crude oil spot prices and oil futures-spot spread



Note: Blue and red lines denote 6-months moving average of Brent and WTI oil spot prices, respectively. Green line refers to 6-months moving average of US refiners' acquisition cost imported (RACi). Black line indicates the 6-months moving average of oil futures-spot spread.

crude oil inventories market value. The main reason is that the futures-spot spread is derived from prices referred to some specific locations around the world. With respect to this, we highlight that both WTI and Brent futures prices represent financial instruments for hedging or speculative actions and they are usually closed out (or rolled over) before their expires date. For this reason the futures contracts are globally traded and their prices are mainly driven by expectations on worldwide oil economic fundamentals. Further, one might argue that the validity of global coverage related to the oil-futures spot spread

[11] A monthly measure of oil futures price is the end-of-month value of the last trading day of the futures contract with maturity 3 months. The monthly spot price of oil is derived by taking the end-of-month value of the daily oil spot prices. Both prices are available from Datastream provider.

could be undermine by the presence of different types of oil spot prices. This is not the case because there exist a strong pairwise correlation between the spot prices used to construct the spread and the RACi. In a storable commodity market, like crude oil, the theory of storage helps to explain the price-setting of some commodities, focusing on the role of stocks, under arbitrage conditions. Basically, the management of oil inventories requires an intertemporal balance between demand and supply of oil. This implies that the value of the inventory changes will depend on the relationship between the current and the expected future spot price.

Figure 1 plots the six months moving average of four series: the nominal monthly spot log-prices [12] of WTI, Brent blends, RACi and the oil futures-spot spread. It shows that, if the physical market is subject to an unexpected increase in demand for crude oil, the rise in global spot prices might be likely followed by a reduction in the level of inventories in order to meet the current demand. This causes an increase in the global value of storage which is reflected by the negative of the oil futures spot spread. Thus, oil companies have strong incentives to carry on the optimal management of oil stocks in order to reduce adjustment costs of production and facilitate the delivery of the commodity. As discussed in Pindyck (1994), if a refiner had a small amount of crude oil in its storage it would face with an higher risk of stocks-out and the benefit of holding an extra barrel of oil would be very high. Conversely if the refiner had a large and full storage of crude oil the benefit accruing from the marginal unit of inventory would decline and the marginal storage cost would increase. This last case would be reflected by a positive value of the oil futures-spot spread. Therefore, it is not surprising to note that increases in the real price of oil are often followed by declines in the oil futures-spot spread, as shown in figure 1. A study of Alquist and Kilian (2010) provides empirical evidence that oil futures-spot spread was highly correlated with cumulative effect of precautionary demand shocks on the real price of oil. The authors show that the pairwise correlation became weaker between 2004 and 2006, raising concerns about the relationship between the financial forward-looking variable and the real price of oil mainly triggered by precautionary demand shocks. The VAR model

[12] Time series are available from the web site of the EIA: nominal brent and wti oil spot prices can be downloaded from `https://www.eia.gov/dnav/pet/PET_PRI_SPT_S1_M.htm` while for the imported RAC series the link is `https://www.eia.gov/dnav/pet/pet_pri_rac2_dcu_nus_m.htm`

discussed in the next section offers an economic explanation to changes in the oil futures-spot spread. This is based on the idea that understanding the co-movements between the financial forward-looking variable and the global price of oil requires a structural model that takes into account the endogenous relationship among variables.

3 The econometric method

In this paper we conduct an empirical analysis of the global real price of crude oil based on the following SVAR model:

$$B_0 y_t = \alpha + \sum_{j=1}^{24} B_j y_{t-j} + v_t \tag{1}$$

where α is vector of constant terms [13] and B_0 is a matrix capturing the simultaneous relations among the endogenous variables [14] which are collected in the vector $y_t = (q_t, rea_t, p_t, s_t)'$. The set of aggregate variables includes: the percent change in the crude oil production (q_t), a measure of cyclical fluctuations in the real economic activity (rea_t) as proposed by Kilian (2009), the real price of crude oil (p_t) and the oil futures-spot spread (s_t). The model reported in this work sets two years' lags [15] and includes dummies variables to remove any seasonality effect. The vector v_t collects the orthogonal structural innovations of the model.

An "oil supply shock (S)" is related to unexpected changes in the world oil production. For example, an oil supply disruption is associated with wars and concerns about stability of oil supplies from the Middle East, strategic decisions from OPEC members and other

[13] The seasonal dummies have been suppressed for notional convenience.

[14] This analysis does not include the global proxy for crude oil inventories above the ground for three main reasons. First, we emphasize the original idea of this work where the forward looking expectations of oil traders are inferred from financial side by exploiting the information embodied in the oil futures-spot spread. Therefore the inclusion of the physical forward-looking variable would lead to a redundancy of information. Second, the inclusion of crude oil inventory proxy complicates the identification strategy and the interpretation of the structural shocks. Third, the economic theory suggests that the oil futures-spot spread is not a linear and convex function of the level of inventories, see Fama and French (1987); Pindyck (1994) and Gorton et al. (2013). Therefore, we do not specify a model with both variables (oil futures-spot spread and a proxy for crude oil inventories) because their linear relationship implied by model 1 may be a poor approximation.

[15] Applying high lag order (24 months of lags) is relevant to capture the dynamic of the economic business cycle and to allow the model for proper transmission of the structural shocks, in accordance with Kilian (2009); Kilian and Lutkepohl (2016).

exogenous events in the oil-producing countries.

An "aggregate demand shock (AD)" is associated with changes in the global demand for crude oil and other industrial commodities mainly driven by fluctuations in the real economic activity. For example, a positive AD shock reflects an unexpected increase in the demand for crude oil for current consumption driven by emerging oil-consuming countries.

A "precautionary demand shock (PD)" is related to scheduled changes in the convenience yield triggered by uncertainty about shortfalls of expected supply relative to future demand. For example, a positive PD shock reflects an unexpected increase in the demand for storage due to wars, political tensions in the Middle East or other economic factors related to the physical oil markets, as discussed in Kilian (2009); Alquist and Kilian (2010) and Kilian and Murphy (2014).

A "financial market shock (FM)"is designed to capture a change in the benefit of holding crude oil inventories for reasons not already indicated by the previous three structural shocks of the model.

For example, an unexpected positive FM shock might be driven by a speculative purchase of oil futures contracts, arbitrage mechanisms used to restore the equilibrium between financial and physical markets, an increase in the global strategic petroleum reserves and other forms of financial incentives that are implemented to keep crude oil off the spot market, causing a slow reduction of the convenience yield and an increase in the real price of oil.

3.1 The identification

The estimation of the structural model reported in equation 1 follows the algorithm as is typical of the SVAR model identified based on sign restriction discussed in Rubio-Ramirez et al. (2010). Appendix A provides a description of the estimation and the implementation of the identification strategy. The latter is based on a combination of sign restrictions and bounds on the ratio of the elements of the impact multiplier matrix. Boundary restrictions are often interpreted in terms of contemporaneous price elasticity of oil demand and supply. This procedure allows the identification of a unique model among a set-identified structural global oil market VAR models.

3.1.1 The economic interpretation of sign restrictions

Table 1 reports the sign restrictions on the impact responses of crude oil production, economic activity, real price of oil and oil futures-spot spread to each structural shock identified by the SVAR model. The compounded expression of the oil futures-spot spread can be defined as follow:

$$s_t = \frac{F_{t,T} - P_t}{P_t} = r_{t,T} + k_{t,T} - \psi_{t,T} \tag{2}$$

where $F_{t,T}$ is the oil futures price observed at time t for delivery at a specified future date T, P_t is the spot price of crude oil at time t and $r_{t,T}$ is risk-free interest rate for the period from time t to T. Moreover, the marginal cost of storage per unit of inventory is $k_{t,T}$ and $\psi_{t,T}$ represents the marginal convenience yield per unit of storage. [16]

In the theory of storage the notion of marginal convenience yield reflects the flow of benefits accruing from one extra barrel of crude oil and is thought of as a decreasing and convex function of the amount of inventories. It is important to point out that the existence of the marginal convenience yield raises the possibility of the oil futures-spot spread to be negative. This implies that the spot price of oil will exceed the current futures price. A stylised theoretical model in the spirit of Eastham (1939) is discussed in appendix B. This helps to motivate the sign restrictions on impact responses reported in table 1 and the empirical results presented in section 4.

An unanticipated oil supply disruption represents a shift to the left of the contemporaneous oil supply curve along the oil demand curve mainly triggered by exogenous events in oil-producing countries.

This shock causes an instantaneous reduction in the global oil production and in the real economic activity followed by an increase in the real price of oil.

[16] The algebraic sum of $\psi_{t,T}$ and $k_{t,T}$ is known as the convenience yield at net of the cost of storage namely the net-marginal convenience yield.

Table 1: Sign restrictions on impact responses in the SVAR model

Variables & Shocks	Negative supply shock	Positive aggregate demand shock	Positive precautionary demand shock	Positive financial market shock
Oil production	-	+	+	()
Real economic activity	-	+	-	()
Real price of oil	+	+	+	+
Oil futures-spot spread	-	-	-	+

Note: All shocks are normalized to obtain an increase in the price of oil. Missing entries mean that no sign restriction on the elements of the impact multiplier matrix is imposed.

In the financial market the futures price will likely rise but by less than the spot price and the effect of the shock on the oil futures-spot spread will be negative, on impact.

An unanticipated positive aggregate demand shock represents a shift to the right of the contemporaneous oil demand curve along the oil supply curve mainly driven by fluctuations in the global business cycle.

This shock causes an instantaneous increase in the real economic activity. Moreover, the unexpected increase in the demand for crude oil will cause the spot price of oil to rise and the oil futures-spot spread to drop. The latter reflects an increase in the marginal convenience yield motivated by the reduction in the level of the inventories in order to mitigate the adverse effects of the shock on the global market for crude oil.

A unanticipated positive precautionary demand shock represents a shift to the right of the oil demand curve along the oil supply curve, mainly driven by an increase in the demand for storage.

The structural shock is designed to capture the benefit of having an extra barrel of oil as insurance against uncertainty about future supply shortfalls relative to expected demand. As pointed out by Kilian (2009), the interruption of the global production of crude oil might happen because of concerns over unexpected growth of demand, over unexpected declines of supply, or over both. In other words this shock coincides with precautionary changes in the level of inventories driven by a scheduled increase in the convenience yield of any given amount of stock.

As a consequence positive precautionary demand shocks cause the oil futures-spot spread to decline and real price of oil to increase, on impact. The following result is consistent with the general equilibrium model discussed in Alquist and Kilian (2010). [17]

An unanticipated positive financial market shock represents an accumulation of crude oil inventories triggered by a rise in the crude oil futures price, for reasons not already embodied by the previous three structural shocks. A positive FM shock causes oil-futures spot spread and real price of oil to rise instantaneously.

As reported in the last column of table 1, the impact responses of production and real economic activity to a positive financial market shock is ambiguous.

On the one hand, oil producers might increase their level of production if they are interested in earning current profits. On the other hand, they might reduce global oil production, store it and wait to sell crude oil at the highest expected price. Therefore, the accumulation of crude oil inventories might cause an increase in the real price of crude oil followed by a reduction in the real economic activity. Alternatively, the increase in the price of oil triggered by a positive FM shock might also anticipate a global economic expansion, as discussed in Sockin and Xiong (2015).

3.1.2 The financial market shock

This new shock is designed to capture an instantaneous reduction of the convenience yield (as opposed to a positive precautionary demand shock) and/or a sharp increase in the cost of storage during the inventories' build-up.

Therefore a positive financial market shock represents an instantaneous increase in the oil futures-spot spread followed by a rise in the real price of oil. As a result, this new shock explicitly links the financial and physical markets for crude oil.

For example, let us suppose that some traders bet on the rising price of crude oil. They start buying futures contracts in order to sell them in the future at a higher price, leaving the storage of the commodity to someone else.

[17] Alquist and Kilian (2010) develop a two-country general equilibrium model of the oil futures and oil spot markets in which an oil-producing country exports oil to an oil-consuming country. The authors show that the oil futures-spot spread can be interpreted as an index of shift in expectations about future oil-supply shortfalls. Moreover Alquist and Kilian (2010) prove formally that a sufficient increase in uncertainty about a future oil supply disruption causes a drop of the oil-futures spot spread and an increase in the current real spot price of crude oil, as precautionary demand for crude oil inventories increases.

By arbitrage mechanisms and ignoring the negligible effects of the interest rate [18] the speculative purchase of futures contracts drives their prices up and causes an accumulation of oil stocks.

The inventory build-up is followed by an increase in the oil futures-spot spread because of a reduction in the marginal net-convenience yield. As a result, the futures prices are greater than current spot prices in order to compensate the inventory holders for the high cost associated with storage. Therefore, the financial incentives that are implemented to keep crude oil off the physical market cause an increase in the real price of oil.

The other channel through which a speculative purchase of futures contracts might rise the real price of oil in the spot markets is represented by opposite and simultaneous shifts of both contemporaneous supply and demand curves, as presented in the theoretical model discussed in appendix B and in Juvenal and Petrella (2015). This case requires a shift to the left of the production curve greater enough to prevail over a shift to the right of the demand curve causing the real price of oil to rise, the global production to decline and the oil-inventories to build-up. The latter is reflected by an increase in the oil futures-spot spread.

3.1.3 Boundary restrictions

Following Kilian and Murphy (2014), we start to generate a set of 5 million structural models and retain only those that satisfy all sign restrictions reported in table 1.

At this stage we end up with a subset of identified-models. Then we impose on the elements of the instantaneous multiplier matrix boundaries restrictions that are interpreted in terms of impact price elasticity of oil demand and supply.

The impact price elasticity of oil demand [19] must be greater than 0 but lower than -0.8. This last value represents a possible benchmark of the long-run price elasticity as reported by Hausman and Newey (1995). In this work we set three times the upper bound [20] of

[18] Frankel and Rose (2010) do not provide evidence of a relevant role played by the real interest rate in influencing the price of the commodities.

[19] The impact price elasticity of oil demand is computed as the ratio between the impact response of global oil production and the impact response of the real price of crude oil to an oil supply shock.

[20] The identification of the supply elasticity requires an exogenous shift of the demand curve along the supply curve. In order to compute the lower bound of the impact price elasticity of oil supply Kilian and Murphy (2012) compute a ratio between the percentage changes of the global oil production (excluding

the impact price elasticity of oil supply, originally imposed by Kilian and Murphy (2014). Therefore the new value of short-run price elasticity of oil supply is 0.0774 and is motivated by the following reasons.

First, the authors propose a suggestive value of the supply elasticity which refers to a specific event occurred in August 1990, during the Persian Gulf war. Nevertheless, it is unlikely that the same value could necessarily hold after twenty years. Moreover, studies from Baumeister and Hamilton (2017), Knittel and Pindyck (2016) and Caldara et al. (2016) discuss episodes where some oil producer countries, like Saudi Arabia, could react rapidly to oil exogenous events. All these cases imply a short run supply elasticity even three times grater than the upper bound suggested by Kilian and Murphy (2014).

Second, the short-run oil supply curve should be coherent with all structural shocks. Kilian and Murphy (2014) impose an upper bound for the supply elasticity ignoring the existence of the residual structural shock. It can be shown that such approach yields a set of models where the supply curve is much more elastic in response to residual shock than what implied by the first-three structural shocks.

In our analysis we ensure that the elasticity of oil supply cannot significantly vary across different changes in the global demand for crude oil.

At this step, we end up with a set of models satisfying the sign restrictions on the impact multiplier matrix and the elasticity of oil demand and supply. Moreover, we impose a boundary restriction on the elements of the impact multiplier matrix that is related to the real economic activity. In particular we rule out all cases where the response of real economic activity to financial market shocks are larger than aggregate demand shocks.

The short run price supply elasticity is defined as the ratio between the impact response of the global oil production and the impact response of the real price of oil to each structural demand shock. Therefore, we have three different values of price supply elasticities lower than 0.0774. For the sake of consistency, we focus on that specification that yields the lowest coefficient of variation for the impact price elasticity of oil supply and we select the model satisfying the short-run price demand elasticity closest to the posterior median

Iraq and Kuwait) and the percentage change of the oil price increase. The outcome of this ratio is 0.0258 for the period between July and August 1990. All details can be found in the on-line appendix of Kilian and Murphy (2012).

demand elasticity of the set-identified models. This allows to pin-down a value for the price elasticity of oil demand coherent with the choice of admissible models.

4 Empirical results

4.1 Impulse response analysis

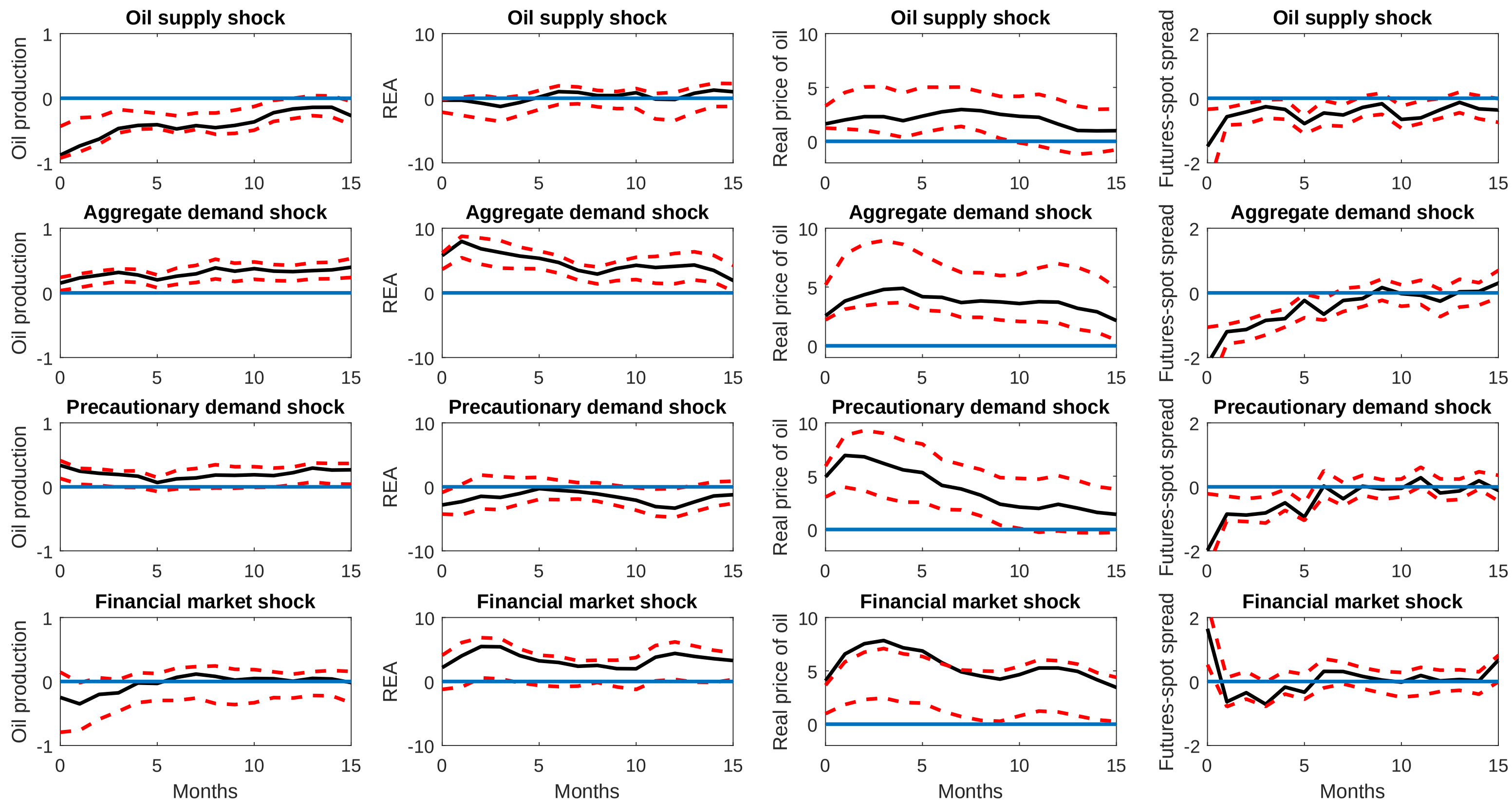
In this section we proceed to the analysis of the dynamic responses of the endogenous variables to each structural shock. Figure 2 plots the results obtained from the orthogonalized impulse response functions of the SVAR model reported in equation 1.

An unexpected oil supply disruption reflects an instantaneous reduction in the global oil production associated with a persistent increase in the real price of oil within the first year. The impact responses of the real economic activity and the oil futures-spot spread to an oil supply disruption is negative. The drop of the financial forward-looking variable reflects an increase in the convenience yield driven by a decline of the crude oil inventories. An unexpected positive aggregate demand shock causes permanent rises in the real economic activity and in the real price of oil which are followed by a slight increase in the global oil production. The impact response of the oil futures-spot spread is negative as suggested by the economic theory.

An unexpected positive precautionary demand shock causes a sharp increase in the real price of oil. This shock is also associated with a drop in the real economic activity combined with a slight increase in the global oil production. The negative and large response of the oil futures-spot spread to a positive precautionary demand shock is consistent with an upward shift of the convenience yield. Since the benefit of having an extra barrel of crude oil is very high, futures price must be lower than current spot price of crude oil in order to maintain the equilibrium between spot and futures markets.

An unexpected positive financial market shock causes an increase in the oil futures-spot spread and in the real price of oil, on impact. A positive value of the spread reflects a situation where the futures price is greater than corresponding current spot price of oil. For example, oil speculators bet on rising prices and they start buying futures contracts.

Figure 2: Structural impulse responses based on the SVAR model



Note: Figure 2 plots the path-responses to one-standard deviation structural shocks. Black lines indicate the impulse response estimates based on admissible structural models satisfying the identification structure. Dashed lines indicate the corresponding pointwise 68% posterior error bands. The errors bands are based on 50 draws from the posterior distribution of the reduced-form parameters with 200,000 rotations each. Oil production refers to the cumulative percent change in oil production.

The speculative purchase provides financial incentive for oil companies to buy even more oil and place it in storage causing the real price of oil to rise.

The accumulation of oil stocks might be reinforced by the negative response of the global oil production to a positive financial market shock. This result suggests that oil producers are induced to accumulate inventories in order to sell them at the highest price. Beyond the impact period, the oil futures-spot spread exhibits a sharp reduction followed by a persistent increase in the real price of crude oil. [21]

4.2 Forecast error variance decomposition

In this subsection we provide some empirical results of the forecast error variance decomposition (FEVD) [22] of the endogenous variables implied by model 1.

In the short run the real price of oil is mainly driven by financial market shocks, accounting for up to 44% of oil price variability. Shocks to precautionary and aggregate demand represent the second and third drivers of oil price fluctuations, with 34% and 17% respectively. Supply shocks have negligible impact on oil price fluctuations, explaining for up to 5%. Interestingly, shocks to the aggregate demand explain up to 39% of oil futures-spot spread fluctuations while precautionary demand shocks contribute up to 15%.

In turn, the explanatory power of shocks to oil supply and financial market represent 15% and 16% of the fluctuations in oil futures-spot spread, respectively. These results imply that, on average, shocks to aggregate demand play an important role in explaining the variability of the oil futures spot spread.

[21]It is important to note that whenever the increases in the oil futures prices are driven by reasons not strictly related to economic fundamentals the arbitrage mechanism can be exploited. The optimal response of the arbitragers is to buy crude oil in the physical market and to sell simultaneously the corresponds amount of futures contracts in the financial market. This strategy is reflected by a contemporaneous increase in the real price of oil and a reduction in the futures prices causing the oil futures-spot spread to decline.

[22]The FEVD allows to quantify the average contribution of a given structural shock to the variability of the data.

4.3 Historical decomposition

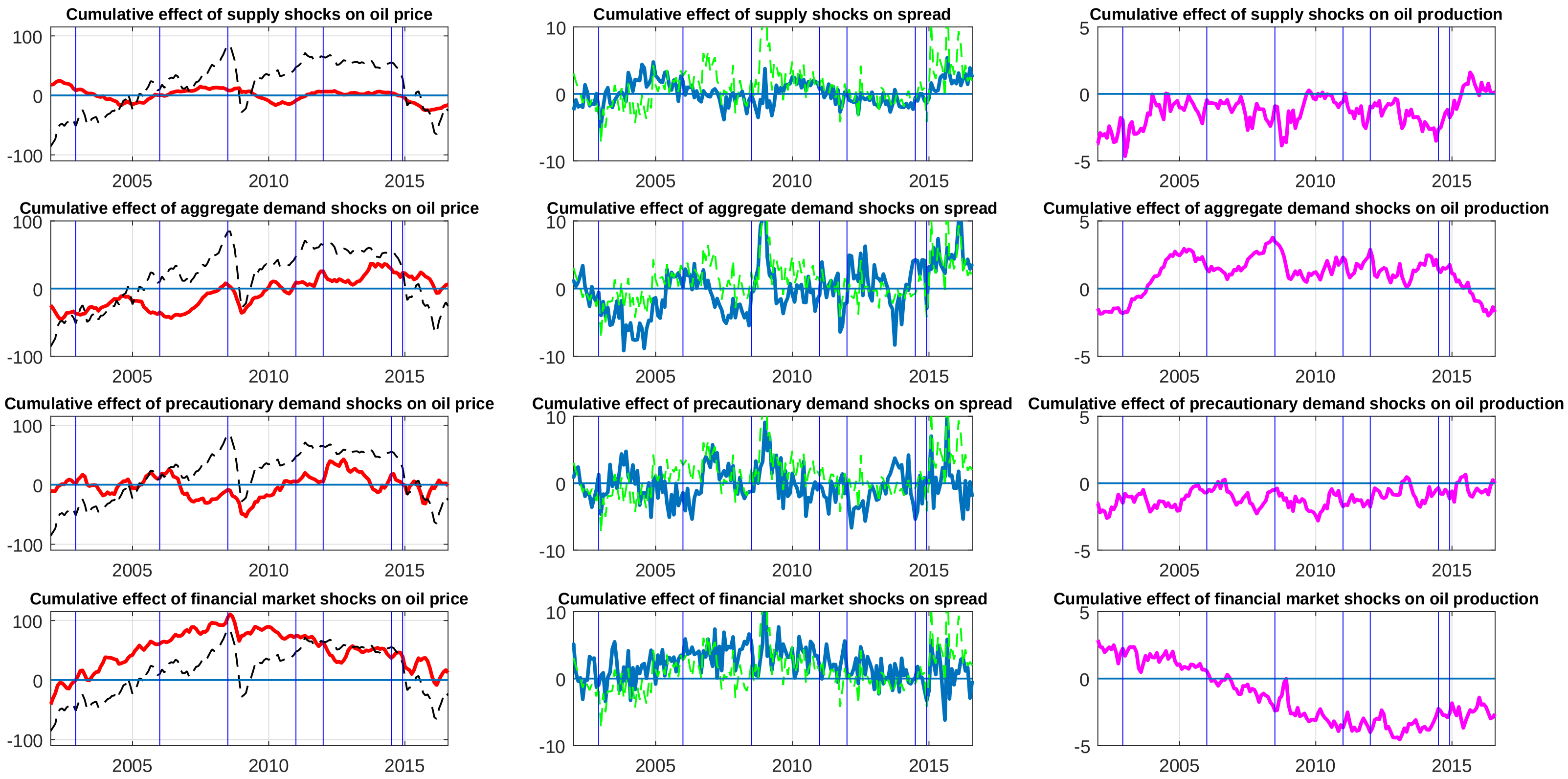
Traditional oil market VAR models include a global proxy for crude oil inventories to capture forward-looking expectations (hence, speculative actions) of oil traders; see among the others Kilian and Murphy (2014); Kilian and Lee (2014); Lombardi and Robays (2011) and Baumeister and Hamilton (2017). Therefore the speculative demand for crude oil reflects a rise in the demand for storage for precautionary purposes or more in general for future consumption. For this investigation we use the definition of oil price speculation as discussed in Fattouh et al. (2013) because in principle both commercial and non-commercial firms [23] could influence the path of the convenience yield.

The authors state that "anyone buying crude oil not for current consumption but for future use" can be considered as a speculator from the economic point of view. The case discussed in Kilian and Murphy (2014) refers to a situation where the inventories' build-up is explained by an increase in the demand for storage. This causes an instantaneous reduction in the oil futures-spot spread which is mainly driven by a rise in the convenience yield. Another possibility is that the accumulation of crude oil inventories causes a contemporaneous increase in the oil futures-spot spread which is mainly explained by a decline in the convenience yield. Therefore the existence of speculative pressure can be identified from changes in the oil futures-spot spread in response to unanticipated financial market shocks. In the last part of this subsection we discuss the cumulative effect of each shock on the real price of oil, oil futures-spot spread and the global oil production. Figure 3 plots the historical decomposition of the above mentioned three endogenous variables.

During the period 2002-2008, panel (2,1) of figure 3 shows that the increase in the real price of oil was mainly triggered by shocks to aggregate demand, most likely driven by global economic growth from OECD countries and emerging Asia. However, the cumulative effect of the aggregate demand shocks decreased between the beginning of 2005 and mid 2006 and rose again until mid-2008. Since 2003 the financial market shocks have

[23] The Commodity Futures Trading Commission (CFTC) provides two macro categories for the oil market players: commercial and non-commercial firms. The former include physical participants such as producers, merchants, processors and end-users that have a direct interest in physical oil production, consumption and trade. The latter are mainly made by financial participants like money managers and hedge funds that are interested in trading futures contracts for investment purposes.

Figure 3: Historical decompositions based on the SVAR model



Note: Black and green dashed lines indicate the observables for real price of oil and oil futures-spot spread, respectively. Solid red line denotes the cumulative effect of each shock on the real price of crude oil. Blue line reflects the cumulative effect of each shock on the oil futures-spot spread. Pink line refers to the cumulative effect of each shock on the worldwide crude oil production. The reference period is 2002:1-2016:7 and vertical lines indicate the major exogenous events in the global market for crude oil: Venezuela crisis in November 2002 followed by the Iraq invasion in early 2003; financialization of commodity markets and great surge of oil price from 2003 until mid 2008; global financial collapse in June 2008; Arab spring between 2011-2012; large drop in oil prices between June and November 2014.

contributed significantly to the oil price increase as shown in panel (4,1).

Interestingly, panel (4,2) shows that both rises in the real price of oil and in the oil futures-spot spread were attributed to positive financial market shocks. The latter are likely to reflect a reduction in the convenience yield driven by speculative purchases of futures contracts. Panel (4,3) shows that post-2006, high levels of oil futures-spot spread were associated with a reduction in the global crude oil production, mainly driven by positive financial market shocks. These results might be representative of economic incentives to take oil off the physical market and increase the worldwide oil stocks. [24]

It is important to highlight that panel (3,1) does not provide empirical evidence that the demand for precautionary inventories drove up the real price of oil during the financialization of commodity markets, consistent with the studies of Kilian and Murphy (2014) and Kilian and Lee (2014).

Moreover the surge of the real price of oil during the first six months of 2008 was primary driven by oil demand shocks. In June 2008 the real price of crude oil fell due to the world financial crisis. The main economic reasons behind this drop were explained by negative shocks to precautionary demand for oil in anticipation of the world recession and negative shocks to aggregate demand. By contrast, since August 2008 both the precautionary and the aggregate demand shocks stimulated the recover of the oil prices.

Panel (1,1) shows that in February 2011 there was a small evidence of an increase in the real price of oil associated with the revolution wave in Arab countries.

Finally, the decline in the global price of oil started in November 2014 was mainly driven by a simultaneous combination of the first-three structural shocks.

On the supply side, the decline in the price of crude oil might be reflected by the large recovery of oil production from Libya, Syria and Iraq combined with the OPEC's announcement on November 2014 to not reduce the level of crude oil production. Moreover, the OPEC's announcement should also explain a large reduction in the precautionary demand for storage causing the real price of oil to decline and the oil futures-spot spread to

[24] A large fraction of the increase in the global crude oil inventories might be explained by an accumulation of crude oil strategic reserves to protect the economy of emerging countries like China and India against short-term energy crisis. In the recent period, India continues developing its strategic petroleum reserve, as pointed out by the EIA: `https://www.eia.gov/todayinenergy/detail.php?id=27132`.

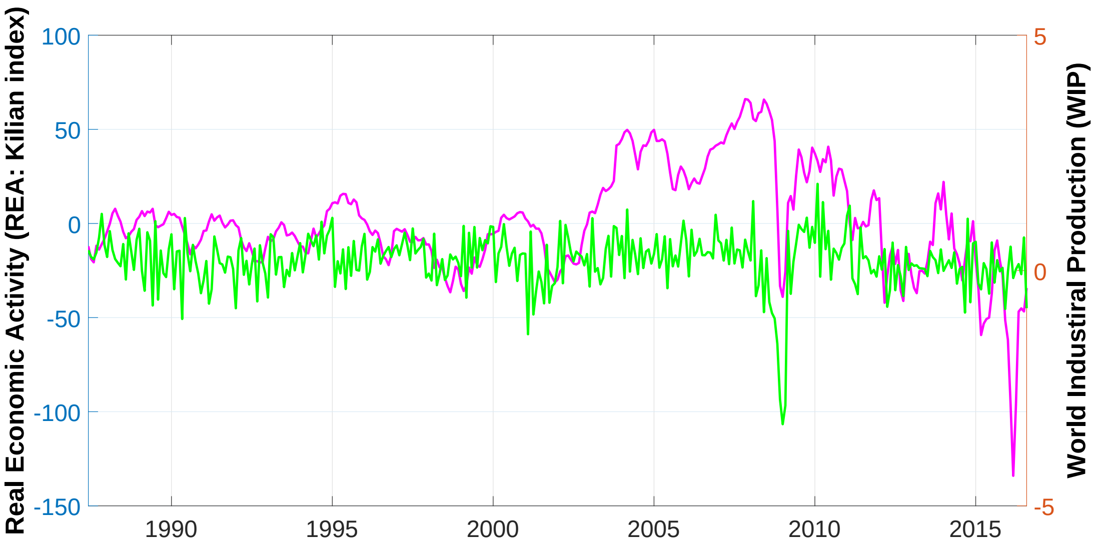
increase, as shown in panels (3,1) and (3,2), respectively. Overall, positive supply shocks and a weak demand for crude oil from OECD and emerging countries caused a reduction in the real price of oil during the recent period.

4.4 Robustness Checks

The first robustness check relies on the work of Baumeister and Hamilton (2017), who uses the world industrial production index [25] as a proxy for global real output.

Figure 4 depicts two alternative proxies for the worldwide economic activity: the real

Figure 4: Global real economic activity measures



Note: Pink and green lines denote the real economic activity indicator (REA: Kilian's index) and the world industrial production (WIP) index, respectively. Since 2006, the WIP have included additional data for the non-OECD countries like, China, India, Brazil, Russia, South Africa and Indonesia.

economic activity index derived from the cost of international shipping and the world industrial production for OECD and non-OECD countries. As confirmed by the qualitative comparison shown in figure 4, the two main differences of these measures coincide with the sharp increase of the Kilian's index between 2003 and mid 2008 and its decline in the beginning of 2016 compared to the world industrial production index.

During 2016, the drop of the Kilian's index is bigger than the value assumed during the

[25] An updated version of the WIP has been proposed by Baumeister and Hamilton (2017) and it can be downloaded from the following link: `https://sites.google.com/site/cjsbaumeister/research`

financial crisis, casting doubts on the accuracy if this indicator. A study of Kilian and Zhou (2017) shows that 60% of this drop can be explained by the global economic slowdown and the remaining fraction is related to idiosyncratic shocks in the market for iron ore. As a second robustness check, we consider the Brent spot price as a proxy for the global price of crude oil.

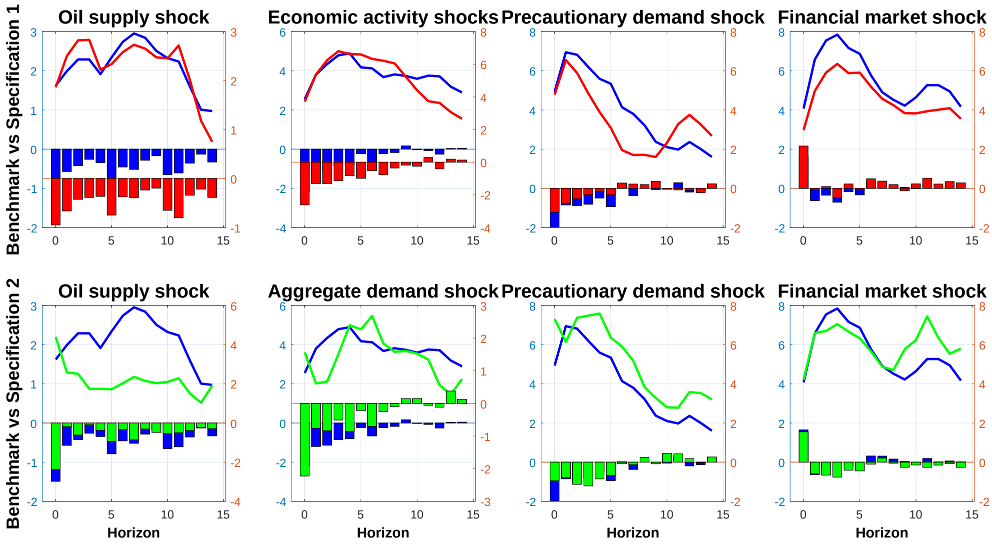
The debate on which type of proxy for global real output should be included in VAR modelling is still an open question. That's interesting to check is whether the empirical results provided by model 1 are robust to changes in the variables of global business cycle and real price of crude oil. Therefore we estimate two alternative candidates of the benchmark SVAR model. The first specification includes the same variables except for the real economic activity index proposed by Kilian (2009). Thus, the Kilian's index is replaced with an updated measure of world industrial production as a proxy for global economic activity. As regards the second specification, the Brent spot price is preferred than RACi, using the same variables included in the benchmark model.

In section 4.1 we have shown that, unexpected increases in the real price of oil driven by negative oil supply shocks and positive shocks to aggregate and precautionary demand are associated with a drop in the oil futures-spot spread, on impact. On the other hand, positive financial market shocks cause an instantaneous increase in both the real price of oil and the oil futures-spot spread.

Figure 5 plots the price and spread responses to one-standard deviation structural shocks. Three basic features emerge.

First, all impact responses are grounded on the economic theory. Second, the row upper-panel of figure 5 shows that a positive economic activity shock causes a smaller but much more persistent increase in the price of oil for the benchmark model than specification 1. As opposed, a positive financial market shock is associated with a larger increase in the price of oil implied by the benchmark model, with a peak after 4 months. Notice that, the effects of an oil supply disruption and a positive precautionary demand shock on the global price of crude oil are quite similar in both models. Moreover, the impulse response of the oil-futures spot spread to each structural shock remains robust to changes in the economic activity measures.

Figure 5: Structural impulse responses for robustness check



Note: Red and green solid lines denote the RACi and Brent oil spot prices response estimates implied by specifications 1 and 2, respectively. Blue line refers to the RACi response based on the benchmark model, as discussed in section 3. Analogous explanation is for the impulse responses of oil futures-spot spread, which are represented by bar charts.

Overall, the results obtained from the first specification exhibit striking qualitative similarities with the responses of oil price and the oil futures-spot spread implied by the benchmark model.

Third, row bottom-panel of figure 5 suggests that the type of global price of crude oil matters for drawing conclusions in modelling oil price shocks. If the Brent series was the proxy for global price of oil then the implied impulse response functions would not be as clear as they were when the price of imported crude oil was included in the set of endogenous variables.

The response of Brent spot price to an oil supply disruption exhibits a fast decline in the first three months as opposed to the benchmark model. A similar picture emerges in case of a positive aggregate demand shocks.

These results suggest that the shape of the impulse response of Brent and RACi to oil supply shocks and aggregate demand shocks are different. In contrast, the price responses to precautionary demand and financial market shocks are not affected by the types of oil prices.

Despite a widespread beliefs that Brent price represent the international benchmark [26] of the spot price of oil, the empirical evidence shown in figure 5 does not find sufficient support of it. For this reason, we conclude that RACi still continues to be the best proxy for the price of crude oil in the global market.

5 Conclusions

There are two main important features in modelling the global price of crude oil. First, the selection of a proper set of endogenous variables. Second, the choice of the identification scheme that is applied to identify the structural shocks.

To our knowledge, we propose a model that differs for both aspects from those specifications proposed in the previous literature.

Most studies show SVAR models that include a physical proxy for crude oil inventories to describe the forward-looking behaviours of the oil traders.

In this analysis instead, we replace a physical proxy for global oil stocks with a financial measure of forward-looking expectations: the oil futures-spot spread. The latter is considered a proxy for the convenience yield but expressed with an opposite sign.

We show that the main benefits of using the oil futures-spot spread is to establish a direct link between physical and financial markets within the context of SVAR model. This allows to derive the real time market value of crude oil inventories held anywhere on Earth. The other relevant contribution of this model consists of the economic interpretation of the residual structural shock. This can be viewed as an additional source of explanation which is able to capture the effects of oil price speculation and other forms of financial incentives that are implemented to keep crude oil off the physical market, causing the real price of oil to rise. We also show that the oil price speculation that are identified by oil market VAR models a' la Kilian and Murphy are conceptually different from the financial market shock discussed in this analysis. While both shocks are designed to capture an instantaneous increase in the amount of oil stocks for future consumption, the

[26] Oil experts, Central Banks, and media consider Brent spot price as a reliable proxy for the global price of oil. The main reason is that it represents a reference price for North-west Europe, all West African, Mediterranean and recently for some South-east Asia crude oil.

main difference stemming from the value of holding oil inventories. In the first case, the inventories' build-up is explained by an increase in the demand for storage. This causes an instantaneous reduction in the oil futures-spot spread which is mainly driven by a rise in the convenience yield. In the second case, the accumulation of crude oil inventories causes an increase in the oil futures-spot spread which is mainly explained by a decline of the convenience yield. We find evidence that financial market shocks have played an important role in explaining the rises in the price of oil during the period 2003-2008.

References

Alquist, R. and Kilian, L. (2010). What do we learn from the price of crude oil futures? *Journal of Applied Econometrics*, 25:539–573.

Baumeister, C. and Hamilton, J. D. (2017). Structural interpretation of vector autoregressions with incomplete identification: Revisiting the role of oil supply and demand shocks. Working paper series.

Baumeister, C. and Peersman, G. (2013). The role of time varying price elasticities in accounting for volatility changes in the crude oil market. *Journal of Applied Econometrics*, 28:1087–1109.

Caldara, D., Fuentes-Albero, C., Gilchrist, S., and Zakrajek, E. (2016). The macroeconomic impact of financial and uncertainty shocks. *European Economic Review*, 88:185–207.

Eastham, J. K. (1939). Commodity stocks and prices. *Review of Economic Studies*, 6:100–110.

Fama, E. and French, K. (1987). Commodity futures prices: some evidence on forecast power, premiums and the theory of storage. *Journal of Business*, 60:55–73.

Fattouh, B., Kilian, L., and Mahadeva, L. (2013). The role of speculation in oil markets: what have we learned so far? *The Energy Journal*, 34:7–33.

Frankel, J. A. and Rose, A. K. (2010). Determinants of agricultural and mineral commodity prices. In Renee Fry (CAMA), C. J. R. and (RBA), C. K., editors, *Inflation in an Era of Relative Price Shocks*, pages 9–51.

Gorton, G. B., Hayashi, F., and Rouwenhorst, K. G. (2013). The Fundamentals of Commodity Futures Returns. *Review of Finance*, 17:35–105.

Hausman, J. A. and Newey, W. K. (1995). Nonparametric estimation of exact consumers surplus and deadweight loss. *Econometrica*, 63:1445–1476.

Juvenal, L. and Petrella, I. (2015). Speculation in the oil market. *Journal of Applied Econometrics*, 30:621–649.

Kilian, L. (2009). Not all oil price shocks are alike: disentangling demand and supply shocks in the crude oil market. *American Economic Review*, 99:1053–1069.

Kilian, L. and Lee, T. K. (2014). Quantifying the speculative component in the real price of oil: the role of global oil inventories. *Journal of International Money and Finance*, 42:71–87.

Kilian, L. and Lutkepohl, H. (2016). *Structural vector autoregressive analysis*.

Kilian, L. and Murphy, D. P. (2012). Why agnostic sign restrictions are not enough: understanding the dynamics of oil market VAR models. *Journal of the European Economic Association*, 10:1166–1188.

Kilian, L. and Murphy, D. P. (2014). The role of inventories and speculative trading in the global market for crude oil. *Journal of Applied Econometrics*, 29:454–478.

Kilian, L. and Vigfusson, R. J. (2011). Nonlinearities In The Oil PriceOutput Relationship. *Macroeconomic Dynamics*, 15:337–363.

Kilian, L. and Zhou, X. (2017). Modeling Fluctuations in the Global Demand for Commodities. CESifo Working Paper Series 6749, CESifo Group Munich.

Knittel, C. R. and Pindyck, R. S. (2016). The simple economics of commodity price speculation. *American Economic Journal: Macroeconomics*, 8:85–110.

Lombardi, M. J. and Robays, I. V. (2011). Do financial investors destabilize the oil price? Working paper series 1346, European Central Bank.

Lutkepohl, H. and Netsunajev, A. (2014). Disentangling demand and supply shocks in the crude oil market: how to check sign restrictions in structural VARs. *Journal of Applied Econometrics*, 29:479–496.

Pindyck, R. S. (1994). Inventories and the short-run dynamics of commodity prices. *Journal of Economics*, 25:141–159.

Rubio-Ramirez, J. F., Waggoner, D. F., and Zha, T. (2010). Structural Vector Autoregressions: Theory of Identification and Algorithms for Inference. *Review of Economic Studies*, 77:665–696.

Smith, J. L. (2009). World oil: market or mayhem? *Journal of Economic Perspectives*, 23:145–164.

Sockin, M. and Xiong, W. (2015). Informational frictions and commodity markets. *The Journal of Finance*, 70:2063–2098.

Appendix A Identification strategy

Consider the generic representation of the reduced-form VAR model, with n endogenous variables and p lags:

$$y_t = \Theta_1 y_{t-1} + \Theta_2 y_{t-2} + \cdots + \Theta_p y_{t-p} + u_t \qquad t = 1, 2, \ldots, T \tag{3}$$

where y_t is a $n \times 1$ vector of endogenous variables, $\Theta_1, \Theta_2, \ldots, \Theta_p$ are p matrices of dimension $n \times n$ and u_t is a vector of non-autocorrelated reduced-form innovations following a multivariate normal distribution $u_t \sim \mathcal{N}(0, \Sigma_u)$.

Σ_u is a $n \times n$ symmetric positive definite matrix in which the error terms of individual equations can be simultaneously correlated. Since the reduced-form innovations display contemporaneous correlation it is difficult to provide an economic interpretation of the impulse responses function of the elements of the vector u_t.

On the other hand, v_t denotes a $n \times 1$ vector of mutually uncorrelated structural errors term with the following variance covariance structure: $E_t(v_t v_t') = \Sigma_v$, where Σ_v is normalized such that $\Sigma_v = I_n$. Notice that, I_n represents an identity matrix of order n. The fact that, Σ_v is a diagonal matrix implies that the structural shocks can be economically interpreted in terms of shifts in demand and supply.

The structural disturbances can be obtained as follow: $u_t = \tilde{B} v_t$, where $\tilde{B}$ is a $n \times n$ matrix, such that $\tilde{B} \equiv B_0^{-1}$. In other words, $\tilde{B}$ coincides with the impact multiplier matrix and it captures the contemporaneous relations among the endogenous variables of the VAR model.

For the construction of the impulse responses function we need to identify the elements of the impact multiplier matrix $\tilde{B}$ by exploiting the algorithm discussed in Rubio-Ramirez et al. (2010). This is based on a set of sign restrictions that are directly imposed on the impulse response functions. The latter are constructed from consistent estimates of the reduced-form slope parameters. Therefore the set of impact multiplier matrix can be defined as the product between B and any orthogonal square matrix D.

The matrix B is lower triangular (with all zeros above the main diagonal) such that $BB' = \Sigma_u$. In other words, B represents the Cholesky factorization of Σ_u, such that

$B = P\Lambda^{0.5}$, where Λ is a $n \times n$ diagonal matrix in which the elements λ_i's are the eigenvalues of Σ_u and the columns of the matrix P are the corresponding eigenvectors. Thus, the variance covariance matrix of the reduced-form VAR innovation can be also expressed as $\Sigma_u = P\Lambda P'$.

The $n \times n$ matrix D is also referred to as the rotation matrix and is such that $D'D = DD' = I_n$, where I_n is an identity matrix of order n. The algorithm proposed by Rubio-Ramirez et al. (2010) consists of two stages and it can be implemented as follow.

The first step is based on the construction of the QR decomposition of a $n \times n$ matrix X such that $X = QR$ where Q is an orthogonal matrix and R is upper triangular matrix with the elements on the main diagonal normalized to be positive. This step must be done in a repeated sampling by drawing the matrix X from a independent standard normal distribution.

The second step defines $D = X'$ and it involves the construction of the set of admissible impulse responses function by using the following orthogonalization $\tilde{B} = BD$. If all the impulse response estimates satisfy the sign restrictions we retain $\tilde{B}$, otherwise we discard it and we go back to the first stage.

These two steps are computationally intensive because they are iterated 5 million of times. The estimation of the uncertainty is conducted under Bayesian method specifying Gaussian-inverse Wishart prior distribution for the reduced form parameters and a Haar distribution for the rotation matrix X. Thus, the credible set of the impulse responses function is constructed by applying the algorithm proposed by Rubio-Ramirez et al. (2010) to each draw of the posterior distribution for the parameters of the reduced-form VAR model.

Appendix B A simplified theoretical model

In this section we provide a stylized version of the theoretical commodity storage model in the spirit of Eastham (1939).

Figures 6 and 7 show the main features of the spot and the storage markets for crude oil. In the spot market the inverse demand function for current consumption is denoted by D^{Cons} and it is defined as $P = f(Q^C)$ where Q^C denotes the amount of crude oil demanded for consumption and P indicates the spot price of a barrel of crude oil in the current period. The global oil production is denoted by S.

In the market for storage, the total amount of oil stocks held in all places around the world is denoted by N. We postulate that the oil stocks supply curve is predetermined in the short period while the demand for storage, denoted by $\Psi^D(N)$, is a decreasing and convex function of the level of the inventories. Thus the marginal price of storage (or marginal convenience yield) is denoted by ψ.

The equilibrium in the spot market states that the total demand for crude oil (D^{Total}) equals the sum of the quantity supplied (S) and the oil stocks carried on from the previous period (N_{t-1}), that is: $Q^T = S + N_{t-1}$. Moreover, the total amount of crude oil demanded is also defined as the sum of the current oil stocks held by the market and that quantity used for consumption, that is: $Q^T = Q^C + N$.

This means that the horizontal difference between D^{Total} and D^{Cons} represents the quantity demanded for storage at a specific spot price P in any given period.

Putting together the two definitions of total demand for crude oil we yield with the following expression: $S - Q^C = \Delta N$ where ΔN is defined as $\Delta N = N - N_{t-1}$ and it represents the current oil inventories flow value. In other words, the market clearing condition implies a relationship between the current spot price P and the current change in inventories ΔN.[27]

Figure 6a describes the effect of a negative supply shock in the global market for crude oil. An oil supply disruption represents a shift to the left of the simultaneous oil supply curve from S_0 to S_1 along the total demand for crude oil. As a result the quantity of

[27] An important assumption of the storage model is that oil inventories cannot be negative.

crude oil declines from Q_0^T to Q_1^T and the real price increases from P_0 to P_1.

In the storage market the oil inventories will be draw down in order to smooth consumption with the consequence of a gradual increase in the marginal convenience yield, limiting the rise of the spot price of oil and causing the oil futures-spot spread to decline. Finally the marginal cost of storage will decline because of the reduction in oil inventories.

When the effect of the oil supply disruption vanishes, the supply curve and the real price of oil will go back to the original level and the replenishment of oil inventories will be reflected by a decline in the convenience yield.

Figure 6b illustrates the effect of a positive aggregate demand shock on the spot price of crude oil. This shock causes a shift to the right of the oil demand curve driven by current consumption from D_0^{Cons} to D_1^{Cons} along the oil supply curve. Thus the demand for crude oil increases from D_0^{Total} to D_1^{Total}. In order to mitigate the adverse effect of the shock on the real price of crude oil, the level of inventories will decline from N_0 to N_1. Thus, the increase in the real price of oil is limited up to P_1 and it is followed by a drop of the oil futures-spot spread, on impact.

Figure 7a represents the effect of a positive precautionary demand shock on the real price of oil in the spot market. This shock can be interpreted as an increase in the demand for crude oil that is mainly driven by an upward shift of the demand for oil stocks.

In the storage market, between $t-1$ and t, the benefit of holding an extra barrel of crude oil increases from ψ_A to ψ_B causing a drop of the oil futures-spot spread at time t.

In the spot market, the total demand for crude oil increases from D_{0A}^{Total} to D_{1B}^{Total} motivated by a build-up of crude oil inventories.

On impact, the real price of oil overshoots in response to a positive precautionary demand shock moving from $P_{A(t-1)}$ to $P_{B(t)}$.

Beyond the impact period in the storage market crude oil inventories will be accumulated at lower rate moving from point B to C.

Analogously in the physical market the spot price of crude oil will decline from $P_{B(t)}$ to $P_{C(T)}$ defining a new long-run equilibrium denoted by E_C.

Finally, figure 7b shows the effects of a positive financial market shock. It represents an accumulation of crude oil inventories for reasons not already captured by the previous three structural shocks.

This shock is triggered by higher prices of the oil futures contracts.

For example, an unexpected positive FM shock might be explained by a speculative purchase of oil futures contracts, arbitrage mechanisms used to restore the equilibrium between financial and physical markets, an increase in the global strategic petroleum reserves and other type of incentive to keep oil off the spot markets.

Therefore we can consider two possible cases through which the structural shock in question affects the real price of oil.

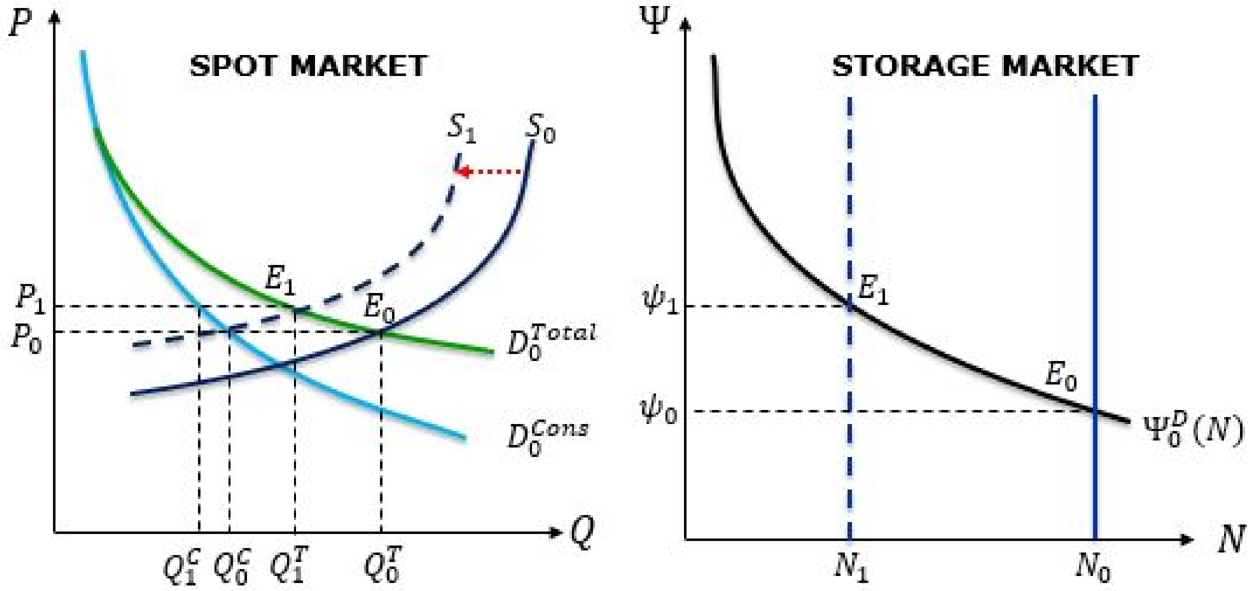
First channel consists of an increase in the total demand for crude oil from D_0^{Total} to D_1^{Total} followed by an simultaneous increase in the spot price of oil from P_0 to P_1.

The inventory accumulation causes a decline in the marginal convenience yield, from ψ_0 to ψ_1 followed by an increase in the storage costs. This causes an instantaneous rise in the oil futures-spot spread.

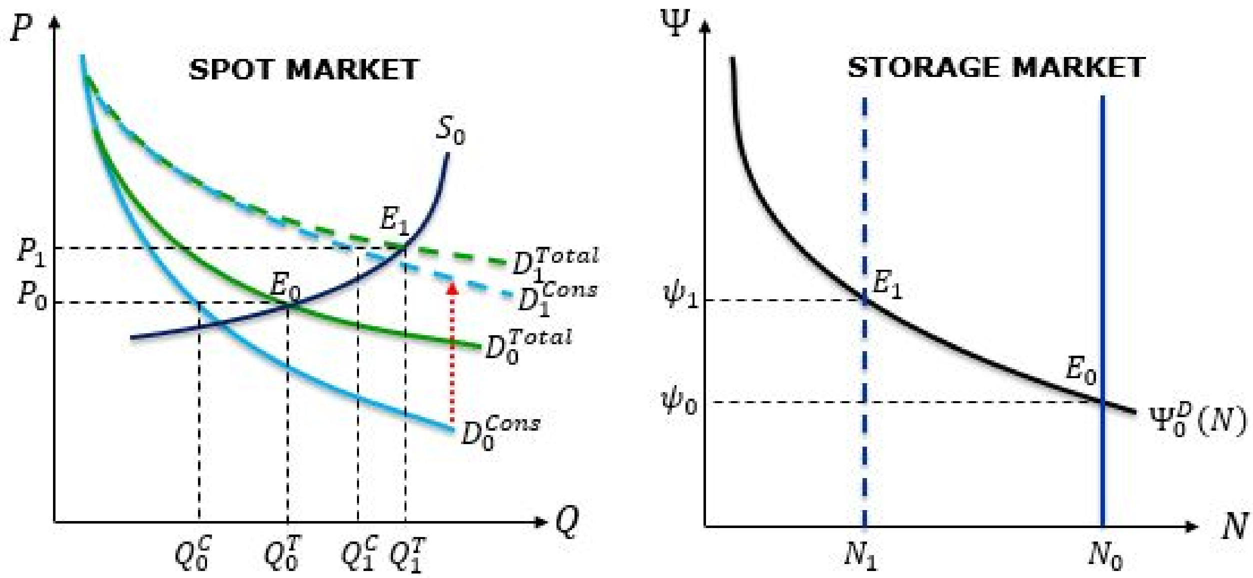
The second channel is given by a shift to the right of the total demand for crude oil followed by an instantaneous shift to the left of the oil supply curve, from S_0 to S_1. This shock drives up the spot price of oil from P_0 to P_2 and the oil futures-spot spread, on impact. This last is motivated by an instantaneous decline of the marginal convenience yield from ψ_0 to ψ_2.

Finally, a reduction of the speculative purchase in the futures market causes a drop of the expected pay-off of holding inventories. This is followed by a massive sell-off of oil stocks causing the spot price of oil to decline and the marginal convenience yield to increase. The latter is reflected by a drop in the oil futures-spot spread.

Figure 6: A stylized version of the theoretical commodity model (Eastham (1939))

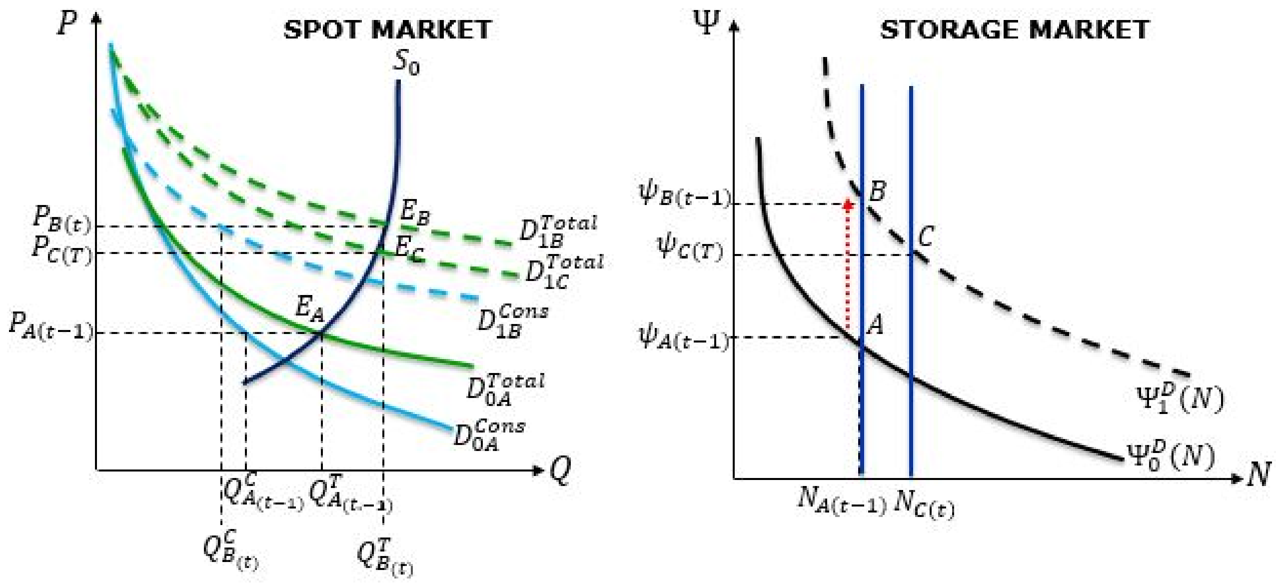


(a) Negative oil supply shock

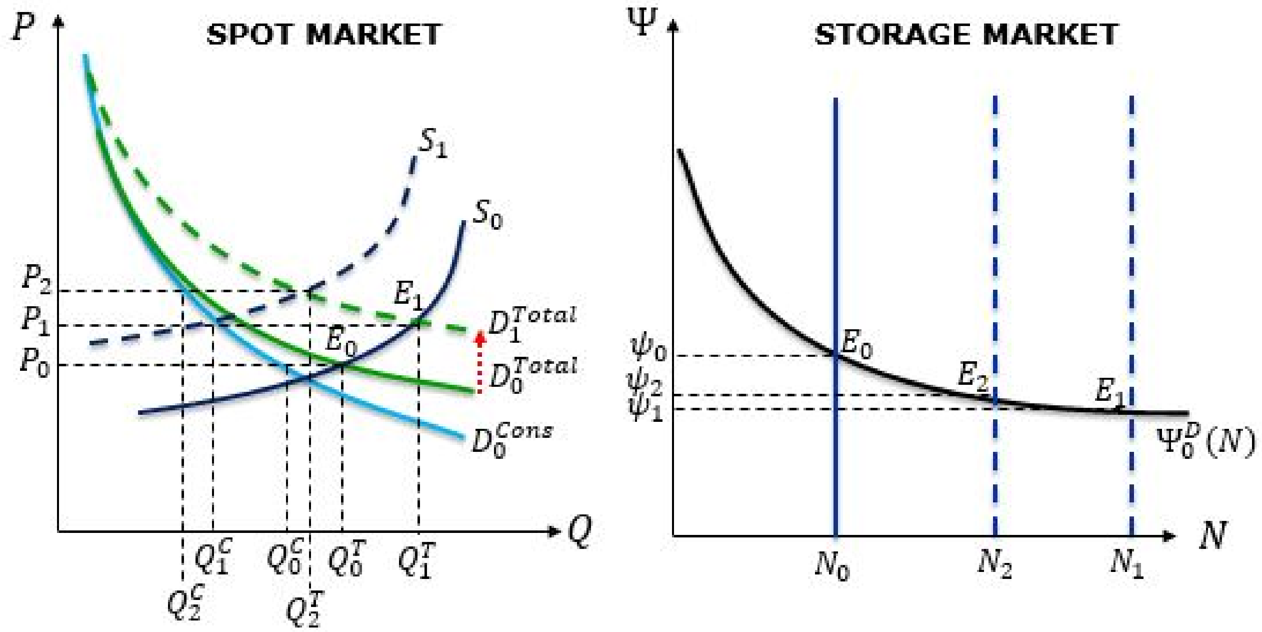


(b) Positive aggregate demand shock

Figure 7: A stylized version of the theoretical commodity model (Eastham (1939))



(a) Positive precautionary demand shock



(b) Positive financial market shock

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