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Modelling the Global Price of Oil: Is there any Role for the Oil Futures-spot Spread?

Daniele Valenti

Economic Theory

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Modelling the Global Price of Oil: Is there any Role for the Oil Futures-spot Spread?

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Summary

In this work, we propose an analysis of the global market for crude oil based on a revised version of the Structural Vector Autoregressive (SVAR) model introduced by Kilian and Murphy (2014). On 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 new shock 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 rises in the price of oil during the period 2003-2008.

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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Modelling the global price of oil: is there any role for the oil futures-spot spread?

Daniele Valenti*

Abstract

In this work, we propose an analysis of the global market for crude oil based on a revised version of the Structural Vector Autoregressive (SVAR) model introduced by Kilian and Murphy (2014). On 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 new shock 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 rises in the price of oil during the period 2003-2008.

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1 Introduction

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 market.

As reported by the Energy Information Administration (EIA), in 2016 the total crude oil consumption amounted to 35 billion barrels of oil, and the average annual West Texas Intermediate (WTI) spot price ¹ was about 43 dollars. Therefore the overall oil market size reached 1.5 trillion dollars. Due to the growing flow of money into the crude oil markets, 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.

Given the large number of participants in the international market ² for crude oil, it is widely accepted that the global price of oil ³ is being determined by worldwide supply-and-demand. Thus, a common practice among researchers is to consider the endogeneity of the price of oil with respect to the economy, as discussed in Kilian and Lutkepohl (2016). The first analysis to take up this feature is a study by Kilian (2009). The author introduces a Structural Vector Autoregressive (SVAR) model for the global market for crude oil, which represents a novelty in terms of methodology and results. The SVAR model of interest includes monthly past data on three aggregate variables: the global oil

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

²The 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.

³We consider the US refiners' imported acquisition cost (RAC) as a proxy for the spot price in the global market for crude oil. This is available from the web-site of the U.S. department of Energy Information Administration (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.

production, a specific measure for real economic activity and the real price of crude oil. 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 study 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 discussed in Kilian (2009). Second, the studies show that unanticipated shocks to demand for crude oil are the most important drivers in explaining the fluctuation in the price of oil. Third, the implied structural models do not include a measure used to capture the forward-looking behaviour of oil traders and thus make the VAR model of the global market for crude oil invalid. Kilian and Murphy (2014) addresses the issue of identifying the forward looking component by adding to the set of endogenous variables discussed in Kilian (2009) a proxy for global crude oil inventories. The authors explicitly identify a speculative demand component which is reflected in changes of the level of crude oil inventories above the ground. The following model does not provide empirical evidence that the speculative demand have contributed to explain the rise in the 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) perform a Factor Augmented VAR model (FAVAR) in order to exploit all information retrieved by a large dataset. They find evidence that financialization of commodity markets ⁴ have played an important role in the rise of oil prices during the period 2004-2008. Notwithstanding, the main driver to capture the largest fraction of oil price fluctuations remains the oil consumption demand driven by economic activity.

A work by Lombardi and Robays (2011) includes data on the oil futures prices to iden-

⁴In 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.

tify 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.⁵ 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 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 market 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 unavailable. In this context the aggregation of world crude oil inventories is a big challenge. 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

⁵The oil futures-spot spread is defined as the difference between the impulse responses of the futures and spot prices of crude oil.

the US petroleum stocks.⁶

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 the most accurate proxy for global crude oil inventories does 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 continue release as opposed to a proxy for global crude oil inventories. Second, the oil futures-spot spread is simple to derive and represents a reliable 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 analysis⁷. 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.

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

⁶Data 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.

⁷ 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.

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 data and methodology. Section 3 discusses the empirical results and section 4 concludes.

2 Data and methodology

2.1 Data

The following study consists of four monthly aggregate variables based on time-series data that covers the period 1983:3-2016:9.

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 based on the US refiners' imported acquisition cost of crude oil which is deflated by the US consumer price index. Following Kilian and Murphy (2014) we specify the price of oil in log deviation from its simple mean.

The macroeconomic indicator adopted for this analysis is the real economic activity index (REA) as proposed by Kilian (2009).⁸

Finally, the oil futures-spot spread is defined as the percent deviation of the futures price⁹ 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.¹⁰ The main reason is that, WTI prices allow us to extend the dataset from

⁸Details about the construction of the index are reported in Kilian (2009). The real economic activity index measures the global demand for industrial commodities and the state of the global economy as pointed out in Baumeister and Kilian (2016). The index is available from the web page of L. Kilian.

⁹A 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 is derived in the same way, by taking the end-of-month value of the daily spot price. Both oil prices are available from Datastream provider.

¹⁰Notice that, the spread between Brent and WTI prices is very small apart the period that coincides with the shale oil US production. This suggests that both prices are driven by the same worldwide economic fundamentals and do not affect the validity of the oil futures-spot spread as global forward-looking indicator.

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 - September 2016) we use prices from Brent futures and spot markets.

2.2 The econometric method

In this section we conduct an empirical study of the global real price of crude oil builds on a revised version of the SVAR model proposed by Kilian and Murphy (2014).

The SVAR model is the following:

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

where α is vector of constant terms ¹¹ and B_0 is a matrix capturing the simultaneous relations among the endogenous variables ¹² 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), 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' lags¹³ 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

¹¹The seasonal dummies have been suppressed for notional convenience.

¹²This 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.

¹³The choice of 24 monthly lags is needed to capture the dynamic of the economic business cycle and to allow the model for proper transmission of the structural shocks.

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.

2.3 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 models.

2.3.1 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 in the SVAR model. The compounded expression of the oil futures-spot spread can be defined as follow:

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

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.¹⁴

In the theory of storage¹⁵ 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.

In order to motivate the sign restrictions on impact responses reported in table 1 and the empirical results presented in section 2 a stylised theoretical model in the spirit of Eastham (1939) is discussed in appendix B.

An unanticipated oil supply disruption represents a shift to the left of the contempo-

¹⁴The 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.

¹⁵As discussed in Pindyck (1994), the 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. For instance 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.

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.

aneous 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.

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).¹⁶

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 not known a priori.

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 a higher 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).

2.3.2 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

¹⁶In Alquist and Kilian (2010) the authors 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.

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.

By arbitrage mechanisms and ignoring the effects of the interest rate ¹⁷ 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 of the marginal convenience yield and/or an increase in cost of storage.

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 physical market 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 accordance with Juvenal and Petrella (2015) ¹⁸. This case reflects a situation in which a shift to the left of the production curve is 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.

2.3.3 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

¹⁷In principle, low real interest rates might cause a simultaneous increase in the demand for storage and a decline of the supply of crude oil. However 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.

¹⁸The authors show a model with a set of sign restrictions and a proxy for crude oil inventory to infer the role of speculation on oil prices. In this case speculation is triggered from the supply side and is considered equivalent to speculation from futures market. The analysis carried out by the authors consists of a different econometric approach compared with our study. In particular we use a SVAR model with time series dataset whereas the authors develop a Factor Augmented VAR model (FAVAR).

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 double the lower bound ²⁰ of the impact price elasticity of oil supply, originally imposed by Kilian and Murphy (2014). Therefore the new value of the short-run price elasticity of oil supply is 0.0516 and is motivated by the following reasons.

First, the short-run oil supply curve should be consistent with all structural shocks.

Kilian and Murphy (2014) impose a lower bound for the supply elasticity ignoring the existence of the residual structural shock. Such approach yields a set of models where the supply curve is inelastic in response to the first two demand shocks but much more elastic in response to residual structural shocks.

In our analysis we rule out this possibility and we impose that the elasticity of oil supply cannot significantly vary across different changes in the global demand for crude oil.

Second, 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. However it is unlikely that the same value could necessarily hold after twenty years.

Third, other theoretical and empirical models, such as Baumeister and Hamilton (2017) and Knittel and Pindyck (2016) discuss the possibility that some oil producer countries like Saudi Arabia and others states within the OPEC cartel could react rapidly to market changes by increasing their production of crude oil.

At this step, we end up with a very small 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 the possibility that the

¹⁹The 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.

²⁰The 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 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).

response of the real economic activity to financial market shocks are larger than aggregate demand shocks.

In the end, for each SVAR model we identify three separate shocks to the demand for crude oil with the corresponding specific measures of short-run price supply elasticity. Notice that 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.

As a result, we select the model with the lowest standard deviation of the impact price elasticities of oil supply. This condition is consistent with the economic assumption that the oil supply curve does not significantly change in response to unexpected demand shocks.

3 Empirical results

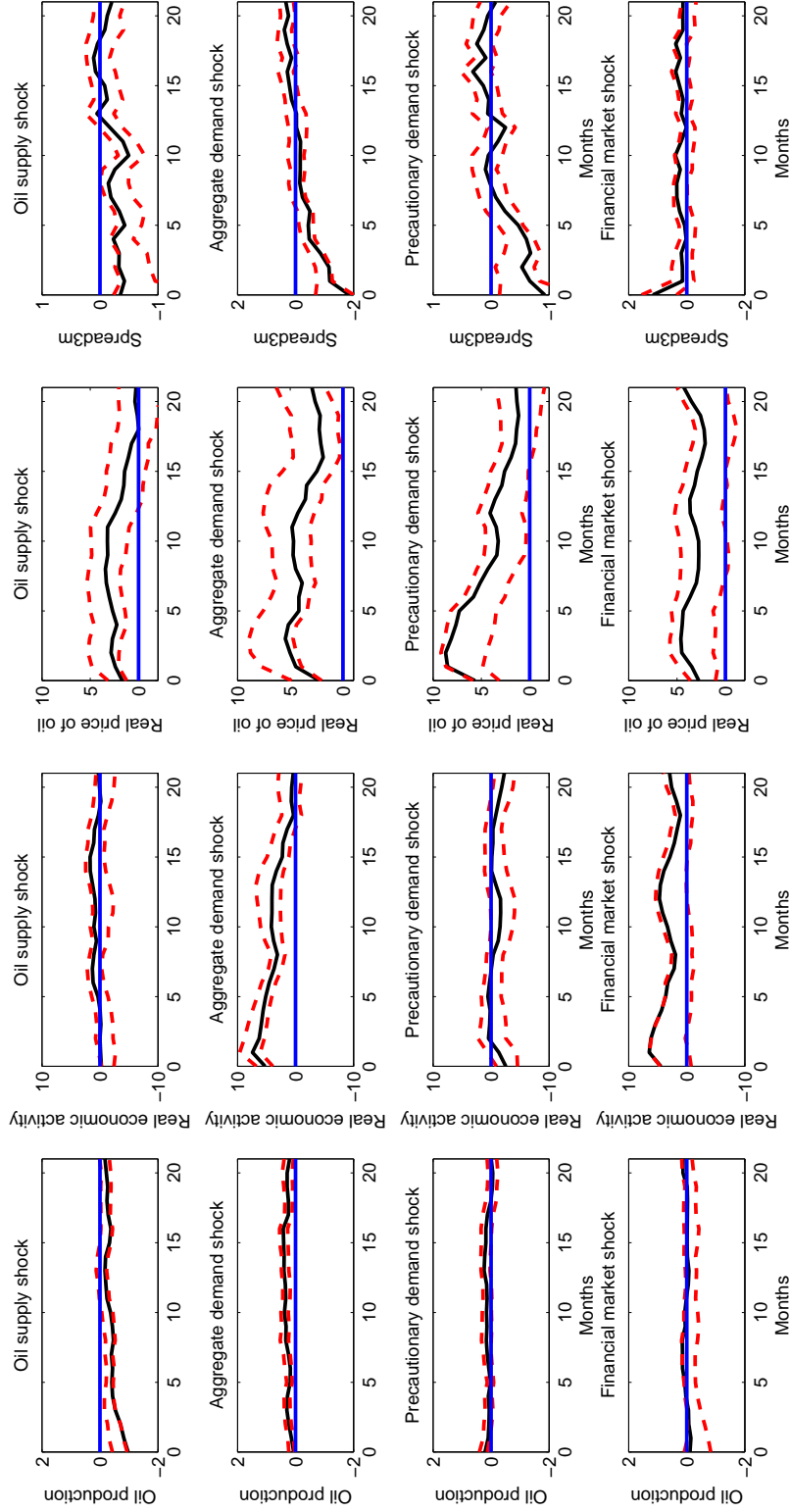
3.1 Impulse response analysis

In this section we proceed to the analysis of the dynamic responses of the endogenous variables to each structural shock. Figure 1 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.

Figure 1: Structural impulse responses based on the SVAR model



Note: Figure 1 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 200 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.

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. 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

3.2 Forecast error variance decomposition

Table 2 shows the percentage of the forecast error variance decomposition (FEVD) ²² of the endogenous variables implied by model 1. In the short run the variation of the real price of crude oil is mainly driven by precautionary demand shocks, accounting for up to 63% of price variability. The aggregate demand shock represents the second driver

²¹It 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.

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

Table 2: Forecast error variance decomposition

| Variables/Shocks | Horizon | S | AD | PD | FM |
|-------------------------|-------------|--------------|--------------|--------------|--------------|
| Oil production | h=3 months | 91.2% | 1.7% | 5.4% | 1.8% |
| | h=6 months | 89.0% | 2.9% | 5.7% | 2.4% |
| | h=12 months | 85.9% | 4.1% | 6.0% | 3.9% |
| Real economic activity | h=3 months | 0.0% | 53.1% | 3.7% | 43.2% |
| | h=6 months | 0.1% | 55.9% | 2.3% | 41.8% |
| | h=12 months | 1.2% | 56.4% | 2.9% | 39.6% |
| Real price of crude oil | h=3 months | 5.8% | 17.5% | 62.7% | 14.0% |
| | h=6 months | 5.9% | 20.1% | 57.8% | 16.2% |
| | h=12 months | 10.3% | 25.2% | 48.5% | 16.0% |
| Oil futures-spot spread | h=3 months | 4.3% | 64.5% | 16.6% | 14.6% |
| | h=6 months | 6.2% | 60.2% | 21.7% | 11.9% |
| | h=12 months | 10.0% | 55.9% | 19.8% | 14.3% |

Note: Table 2 shows the percentage of the forecast error variance decomposition of the endogenous variables based on the SVAR model.

explaining up to 25% of oil price fluctuations.

Interestingly, shocks to the aggregate demand explain up to 64% of oil futures-spot spread fluctuations whereas financial market shock contributes up to 15%.

In turn, oil supply shocks explain 10% of the fluctuations in oil futures-spot spread whereas the precautionary demand shocks explain up to 22% of the futures-spot spread movements. These results imply that, on average, shocks to aggregate demand are relevant to explain the fluctuation in the oil futures spot spread.

3.3 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. This is coherent with the concept of speculation discussed in Fattouh et al. (2013). 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 of 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 of 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. For this investigation we use the definition of oil price speculation ²³ as discussed in Fattouh et al. (2013) because in principle both commercial and non-commercial firms could influence the path of the convenience yield.

In the last part of this section we discuss the cumulative effect of each shock implied by the SVAR model of interest.

First row panel of figure 2 plots the actual values of the real price of oil, the oil futures-spot spread and the global oil production. The rest of the figure illustrates the historical decomposition of the above mentioned three endogenous variables.

During the period 2002-2008, panel (3,1) of figure 2 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.

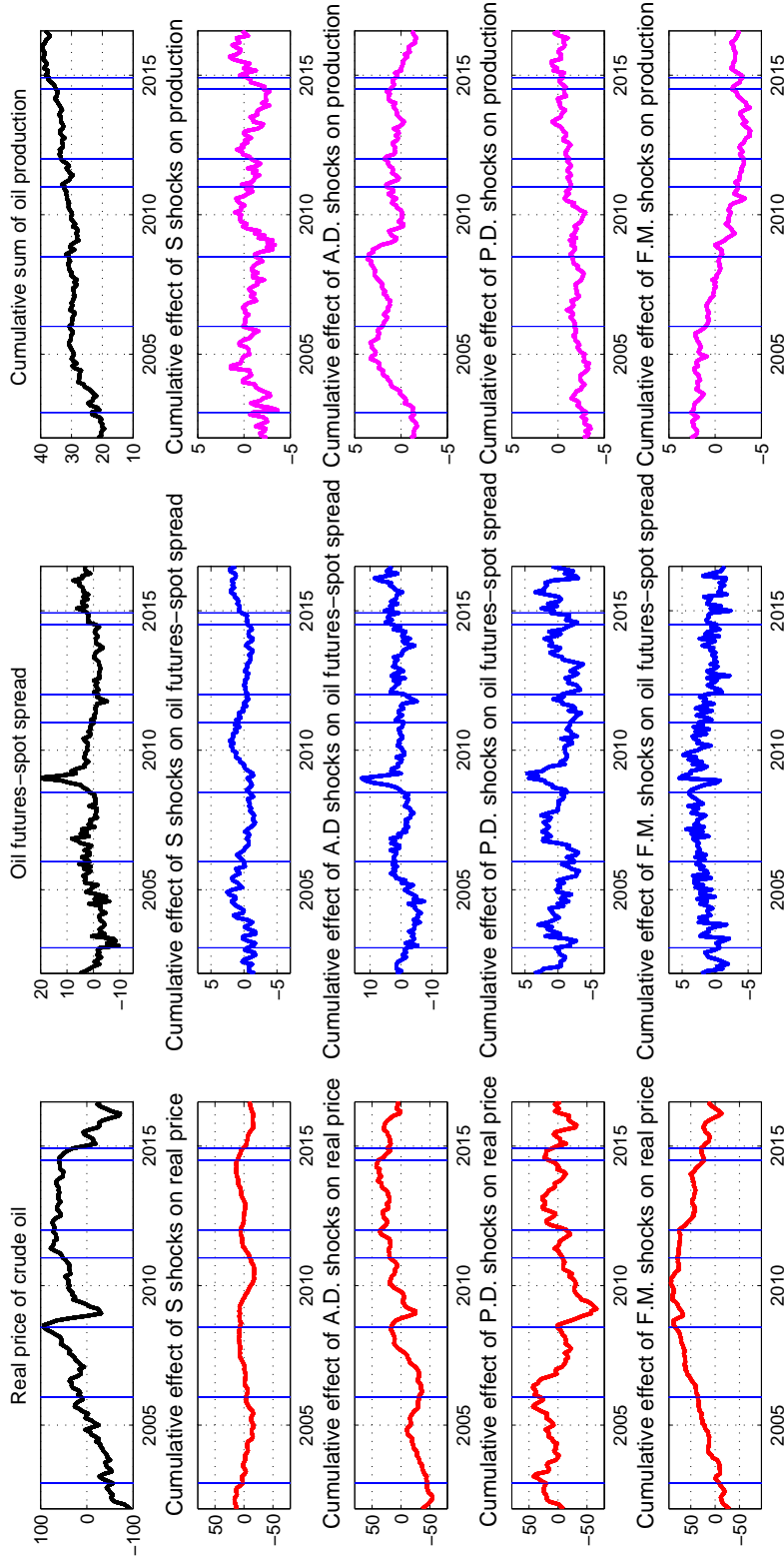
Since 2003 the financial market shocks have contributed significantly to the oil price increase as shown in panel (5,1).

Interestingly, panel (5,2) shows that the increase in the real price of oil was followed by a rise in the oil futures-spot spread. The latter is likely to reflect a reduction in the convenience yield driven by speculative purchase of futures contracts. This represented the financial incentives to take oil off the physical market and increase the worldwide oil stocks.

Panel (5,3) shows that post-2006, high levels of oil futures-spot spread might be explained by a reduction of the global crude oil production in response to positive financial market

²³According to Frankel and Rose (2010) speculation consists of a purchase (or sale) of oil-assets in anticipation of a capital gain at the time of resale.

Figure 2: Historical decompositions based on the SVAR model



Note: Solid black lines indicate the observables for real price of oil, oil futures-spot spread and global oil production. 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 2000:1-2016:9 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.

shocks. This result might suggest an accumulation of the global crude oil inventories below the ground. It is important to highlight that panel (4,1) does not provide a clear empirical evidence that the demand for precautionary inventories drove up the real price of oil during the financialization of commodity markets in accordance with Kilian and Murphy (2014) and Kilian and Lee (2014).

In the beginning of 2008 the surge of the real price of oil was mainly driven by pure psychological shortages triggered by fears about expected oil supply shortfalls as shown in panel (4,1).

In June 2008 the real price of crude oil fell due to the world financial crisis. The reasons behind this drop were mainly explained by negative shocks to precautionary demand for oil in anticipation of the world recession and negative shocks to aggregate demand.

Since August 2008 both the precautionary and the aggregate demand shocks stimulated the recovery of the oil prices.

Panel (2,1) 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 recent decline in the price of crude oil can be explained by a simultaneous combination of the first-three structural shocks working in the same direction.

An unexpected increase in the global oil production caused a decline in the real price of oil until January 2016 as shown in panel (2,1).

Between June and November 2016 a positive supply shock and a weak demand for crude oil from OECD and emerging countries caused a reduction of the real price of oil.

On the supply side, the reduction of oil prices 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 increase, as shown in panels (4,1) and (4,2), respectively.

4 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 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 of 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.

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Appendix A Identification strategy

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

$$y_t = \Theta_1 y_{t-1} + \Theta_2 y_{t-2} + \cdots + \Theta_p y_{t-p} + u_t \quad t = 1, 2, \dots, T \quad (3)$$

where y_t is a $n \times 1$ vector of endogenous variables, $\Theta_1, \Theta_2, \dots, \Theta_p$ 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 contrary, v_t denotes a $n \times 1$ vector of SVAR model innovations with the following variance covariance structure: $E_t(v_t v_t') = D$ and $E_t(v_t v_s') = 0$ if $t \neq s$. The fact that, D is $n \times n$ 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 by exploiting the following relationship $u_t = \tilde{B} v_t$, 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 VAR model.

Given the symmetric property of Σ_u , it is possible to find an orthogonal matrix P such that $\Sigma_u = P \Lambda P'$ 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. Moreover, defining $B = P \Lambda^{0.5}$ we get $B B' = \Sigma_u$. Thus, the set of impact multiplier matrix \tilde{B} can be defined as the product between B and any orthogonal rotation matrix

D . 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. 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 3 and 4 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 .²⁴

Figure 3a 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

²⁴An 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 3b 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 4a 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 4b 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.

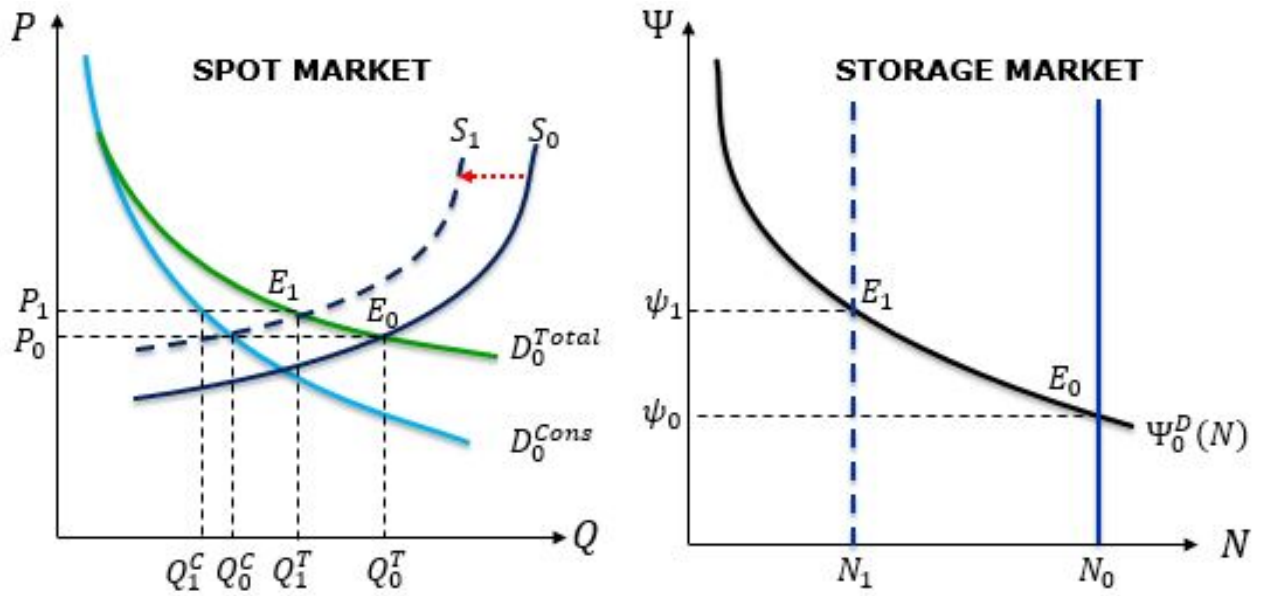
First channel consists of an increase in the total demand for crude oil from D_0^{Total} to D_1^{Total} followed by an simultaneous increase in the spot price of oil from P_0 to P_1 .

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.

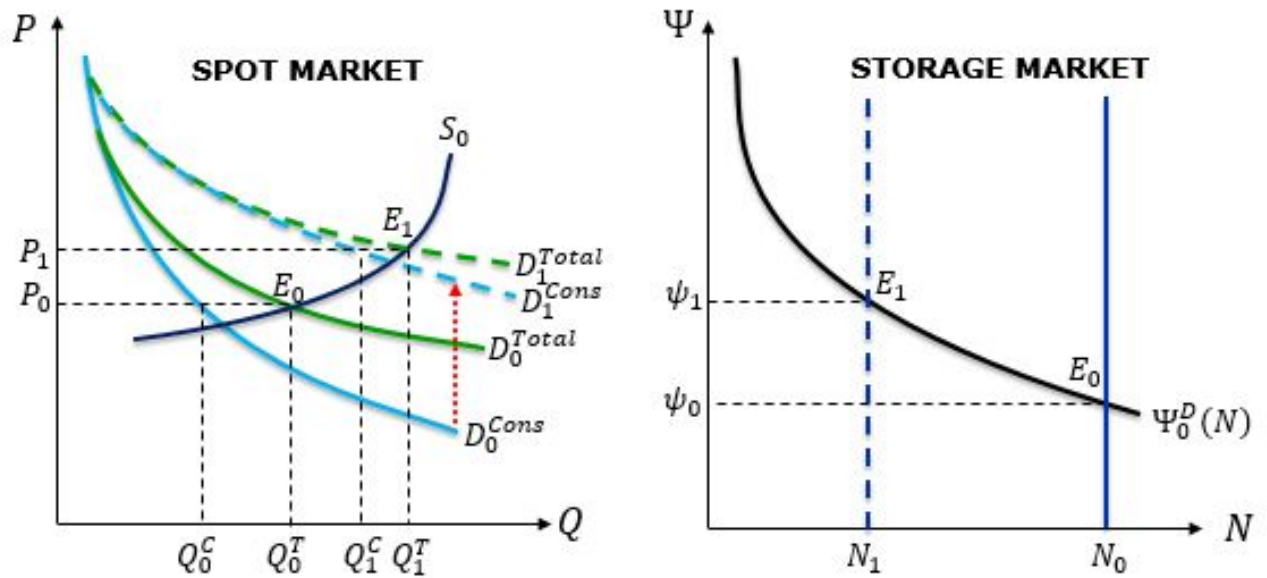
The second channel is given by a shift to the right of the total demand for crude oil followed by an instantaneous shift to the left of the oil supply curve, from S_0 to S_1 . This shock drives up the spot price of oil from P_0 to P_2 and the oil futures-spot spread, on impact. This last is motivated 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 3: A stylized version of the theoretical commodity model (Eastham (1939))

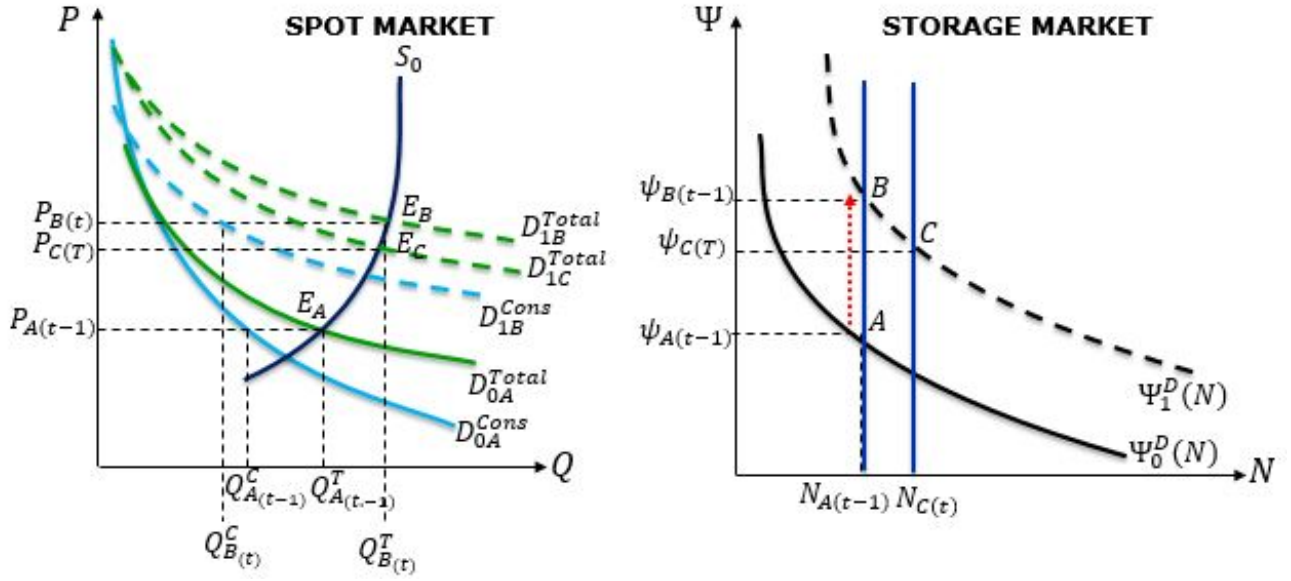


(a) Negative oil supply shock

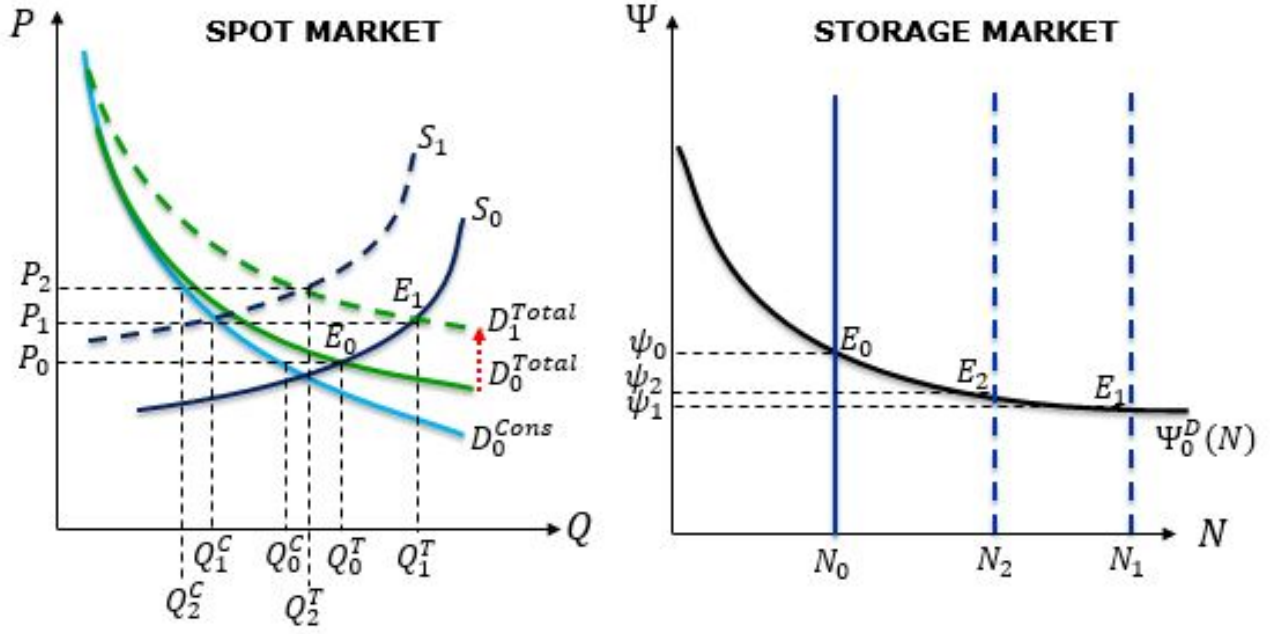


(b) Positive aggregate demand shock

Figure 4: A stylized version of the theoretical commodity model (Eastham (1939))



(a) Positive precautionary demand shock



(b) Positive financial market shock

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