WP/12/270

IMF Working Paper

On the Sources and Consequences of Oil Price Shocks: the Role of Storage

Deren Unalmis, Ibrahim Unalmis, and D. Filiz Unsal

INTERNATIONAL MONETARY FUND

 WP/12/270

IMF Working Paper

Research Department

On the Sources and Consequences of Oil Price Shocks: the Role of Storage

Prepared by Deren Unalmis+, Ibrahim Unalmis±, D. Filiz Unsal§

Authorized for distribution by Steve Phillips

November 2012

Abstract

Building on recent work on the role of speculation and inventories in oil markets, we embed a competitive oil storage model within a DSGE model of the U.S. economy. This enables us to formally analyze the impact of a (speculative) storage demand shock and to assess how the effects of various demand and supply shocks change in the presence of oil storage facility. We find that business-cycle driven oil demand shocks are the most important drivers of U.S. oil price fluctuations during 1982-2007. Disregarding the storage facility in the model causes a considerable upward bias in the estimated role of oil supply shocks in driving oil price fluctuations. Our results also confirm that a change in the composition of shocks helps explain the resilience of the macroeconomic environment to the oil price surge after 2003. Finally, speculative storage is shown to have a mitigating or amplifying role depending on the nature of the shock.

JEL Classification: C68, E12, Q43

Keywords: oil storage, oil price fluctuations, oil demand and oil supply shocks speculative oil demand, sticky-price DSGE model

*We are grateful to the editor Pierre-Olivier Gourinchas, two anonymous referees of the IMF Economic Review, Harun Alp, Nese Erbil, Refet Gurkaynak, Hande Kucuk, Andrea Pescatori, Steven Phillips and Rafael Portillo for valuable contributions, comments and suggestions. We also thank the participants at the conference on "Policy Responses to Commodity Price Movements"; particularly Oliver Blanchard, Tommaso Monacelli, and Roland Straub for insightful discussions and comments. The views expressed in this paper are solely the responsibility of the authors and should not be interpreted as reflecting the views of the Central Bank of the Republic of Turkey and the International Monetary Fund.

+Research and Monetary Policy Department, Central Bank of the Republic of Turkey, Istiklal Caddesi No.10, 06100-Ulus Ankara, Turkey. Email: Deren.Unalmis@tcmb.gov.tr.

±Communications and Foreign Relations Department, Central Bank of the Republic of Turkey, Istklal Caddesi No100, 06100-Ulus Ankara, Turkey. Email: Ibrahim.Unalmis@tcmb.gov.tr.

§Research Department, International Monetary Fund, 700 19th Street, N.W. Washington, D.C. 20431, USA. Email: dunsal@imf.org.

Contents

Page

1 Introduction

Recently, there has been increased interest in exploring the role of market expectations for oil price fluctuations. Due to the forward-looking nature of the real price of oil, expectations of an oil supply shortfall can create precautionary or speculative demand for oil, which in turn is reflected in the real price of oil. Alquist and Kilian (2010) and Kilian and Murphy (2010) document that expectations-driven demand shocks have been an important determinant of global oil price fluctuations during certain episodes. Kilian and Murphy (2010) in particular, using structural vector autoregressions, found significant evidence of expectations-driven oil price fluctuations in 1979, 1986 and 1990, and 2002, but not during the oil price run-up between 2003 and 2008. This work has highlighted the role played by crude oil inventories in transmitting shifts in expectations to the real price of oil via shifts in the speculative demand for storage (also see Dvir and Rogoff 2009; Hamilton 2009; Fattouh, Kilian and Mahadeva 2012).

In markets for storable commodities such as oil, dynamics of (speculative) storage can be an important factor in influencing the short-run dynamics of the real price. In this paper, we incorporate oil storage into a New Keynesian closed economy DSGE model. Our analysis builds on the theory of optimal storage á la Williams and Wright (1982, 1984,1991), and Deaton and Laroque (1992, 1996).[1] We postulate that storage is a way of transferring oil from current to future periods. Oil storage is performed by competitive, risk-neutral storers (speculators) who buy oil from oil producers at the spot price and optimally decide how much to sell or store. In the presence of oil storage, the market-clearing oil price becomes a function of availability (given by new production plus change in oil storage) relative to the total demand, which is endogenously determined. We use this framework to analyze the effects of various structural shocks, namely, an unexpected decrease in U.S. crude oil production, an increase in flow demand for oil and a speculative storage demand shock in the U.S.. Our analysis complements the analysis of global oil markets in recent VAR studies such as Kilian (2008, 2009a) and Kilian and

[1] The modern storage theory was pioneered by Williams (1939), Kaldor (1939) and Working (1948).

Murphy (2010).

Speculative oil storage is important to model, first, because it introduces a dynamic link among oil inventories, storers' expectations of the price of oil and the current price of oil. We refer to exogenous disturbances to oil stocks as speculative storage demand shocks. Such shocks could be interpreted as precautionary demand shocks.[2] In our model, when there is a positive storage demand shock, storage increases, the availability of oil decreases, and the real price of oil goes up. Taking advantage of our general equilibrium approach also, and building up on the insights provided by Kilian (2008, 2009a), we highlight differences in the transmission channels of several demand and supply shocks (both oil market specific shocks such as the speculative demand shock or business cycle driven shocks such as productivity shocks) in oil markets. Second, incorporating oil storage also allows us to assess how the impact of other shocks to the economy changes when oil storage is taken into consideration. In particular, the presense of storage generates another monetary policy transmission channel that works through the impact of interest rate changes on the storage behavior. We show that storage may amplify or mitigate the shock's impact depending on the origin of the shock, in contrast to its mitigating role in standard storage literature. This feature is consistent with the empirical evidence presented in Kilian and Murphy (2010) and the theoretical analysis in Dvir and Rogoff (2009).

We estimate the model for the U.S. economy with Bayesian techniques for the period 1982-2007.[3] Having obtained estimates for the parameters of the model and for the exogenous shock processes, we analyze the transmission mechanisms of the shocks and their contribution to oil price changes. Our main results are: (i) productivity shocks were the most important drivers of oil price

[2] The speculative storage shock in our setup could be interpreted as a reduced form way of modeling the precautionary shock in Alquist and Kilian (2010). In Alquist and Kilian (2010), the precautionary demand shock is modeled as an exogenous shock to uncertainty regarding the future production of oil, which in effect increases the demand for storage. In our case, we take a more direct approach, and allow an exogenous shock to oil storage demand. This oil-specific demand shock by construction captures fluctuations in precautionary demand for oil driven by uncertainty about future oil shortfalls. See also Kilian (2009a) and Kilian and Park (2009).

[3] We estimate the model also for the 2000-2007 period in which the macroeconomic resilience to the oil price hikes has been seen unprecedented. During this period, inflation remained low and growth has been high and stable around the world despite high oil prices, unlike what happened in the previous episodes of oil price surges.

changes, (ii) ignoring storage facility in the model causes a considerable upward bias in the estimated contribution of oil supply shocks to oil price fluctuations, (iii) the variance decomposition carried out for the more recent subsample shows that total factor productivity shock contributed more, and oil supply and storage demand shocks contributed less to the oil price volatility which can in part explain the resilience of macroeconomic environment to the oil price hikes in 2000s, and finally (iv) the presence of speculative storers mitigates or intensifies the fluctuations in oil prices depending on the source of the shock.

The paper proceeds as follows. In Section 2, the structure of the model is laid out. Section 3 discusses the data, the econometric methodology to estimate the parameters and shocks of the model, and discuss the results and present impulse-responses for the shocks. We leave Section 4 for concluding remarks.

2 The Model

The model shares its basic features with many recent New Keynesian DSGE models, including the benchmark models of Clarida, Gali and Gertler (2001) and Gali (2002). We enrich the model by allowing for features such as external habit formation in consumption, inflation indexation and investment adjustment costs. Following Bodenstein, Erceg and Guerrieri (2011) we include oil in both consumption and production.

The most novel feature of our model is that we incorporate oil storage into our model, based on a canonical competitive commodity storage model a la Williams and Wright (1982, 1984, 1991) and Deaton and Laroque (1992, 1996). This enables us to formally consider the impact of a storage demand shock, which is empirically shown to play an important role in driving oil price dynamics in the existing literature. Another advantage of introducing oil storage to the model is to assess how the impact of other shocks change in the presence of speculative storers. More specifically, the classic mitigating effect of storage may not hold in a dynamic general equilibrium setting.

The model economy is populated by households, firms, a government, a monetary authority and oil storers. Households receive utility from consumption, provide labor to the production firms, hold the capital stock and rent it to firms in a perfectly competitive rental market. The households also own the firms in the economy, and therefore receive profits from these firms. Oil is consumed directly and also used as an input in production. Production firms produce a differentiated core consumption good using capital, labor, and oil as inputs. These firms set prices in a staggered fashion, and hence prices are sticky. Households consume the core consumption goods after combining it with oil. Oil production is assumed to follow an exogenous process.[4]

The activity of the risk-neutral, profit-maximizing, competitive oil storer firms (speculators) is to carry forward oil as above-ground oil inventories from one period to the next. They buy oil from the producers and optimally decide how much to sell or store through an intertemporal arbitrage condition. Conditional on the current information, whenever expected appreciation (depreciation) in the price of oil exceeds the marginal cost of storage, speculators increase (decrease) their stockholding until the equilibrium in the oil market is restored.[5]

In what follows, small letters denote percentage deviations of the respective variables from their steady-state levels. We briefly sketch the model here, while the details of the model and all the log-linearized equations are provided in the Appendix.

2.1 Households

The economy is populated by a continuum of households indexed by $j \in [0, 1]$. A representative household is infinitely-lived and seeks to maximize the ex-

[4]Kilian (2009a) makes the case that due to adjustment costs and uncertainty about the future oil demand, oil producing countries will not revise their production level in response to demand shocks within the same month. Obviously, the oil supply might give an endogenous response to oil demand in longer horizons. In this paper, for the sake of simplicity, we take oil supply as exogenous in a quarterly model. However, future research should relax this assumption. There are various papers which account for endogenous oil production. For example, Backus and Crucini (2000) model oil supply partially endogenously, in a neoclassical setup, by assuming that OPEC supply is exogenous. See also Nakov and Pescatori (2010), which also distinguish between OPEC and non-OPEC supply, but supply is determined endogenously in both.

[5]In its current form, the model features a closed economy. Hence, it abstracts from the open economy channels of the transmission of oil price shocks. An obvious extension in the future would be to embed our model of storage within a model of the global economy. Bodenstein and Guerreri (2011) incorporate an open economy dimension and discuss the effects of various domestic and foreign oil demand and supply shocks on oil price fluctuations. However, their model excludes speculative storage.

pected present value of the period utility given by:

$$E_0 \sum_{t=0}^{\infty} \beta^t \left(\frac{(C_t(j) - H_t)^{1-\sigma}}{1-\sigma} - \frac{N_t(j)^{1+\varphi}}{1+\varphi} \right) \quad (1)$$

where $H_t = hC_{t-1}$ captures external habit formation for the optimizing household with $h \in [0, 1]$, β is the discount factor, σ is the inverse of the intertemporal elasticity of substitution of consumption, φ is the inverse of the intertemporal elasticity of hours, $C_t(j)$ denotes consumption and $N_t(j)$ denotes hours of work. Note that the habit stock refers to the aggregate habit consumption rather than the individual habit consumption. Aggregate consumption is:

$$C_t = \left(\int_0^1 C_t(j)^{\frac{\varepsilon-1}{\varepsilon}} dj \right)^{\frac{\varepsilon}{\varepsilon-1}} \quad (2)$$

where ε denotes the elasticity of substitution between varieties. $C_t(j)$ is a CES aggregate of oil (fuel) consumption $O_{C,t}(j)$ and non-oil (non-fuel) core consumption $Z_t(j)$:

$$C_t(j) = \left[(1 - w_{oc})^{\frac{1}{\rho_c}} Z_t(j)^{\frac{\rho_c - 1}{\rho_c}} + w_{oc}{}^{\frac{1}{\rho_c}} O_{c,t}(j)^{\frac{\rho_c - 1}{\rho_c}} \right]^{\rho_c/(\rho_c - 1)} \quad (3)$$

where ρ_c is the intratemporal elasticity of substitution between oil and non-oil consumption and $0 < w_{oc} < 1$ indicates the expenditure share of the core goods in the consumption basket of households.

Let $P_{o,t}$ and $P_{z,t}$ denote the prices of oil and non-oil consumption goods, respectively. The consumer price index (CPI) P_t can be written as:

$$P_t = \left[(1 - w_{oc}) P_{z,t}^{1-\rho_c} + w_{oc} P_{o,t}^{1-\rho_c} \right]^{1/1-\rho_c} \quad (4)$$

Demand functions for oil consumption and non-oil consumption are given by:

$$O_{c,t}(j) = w_{oc} \left[\frac{P_{o,t}}{P_t} \right]^{-\rho_c} C_t(j) \quad (5)$$

$$Z_t(j) = (1 - w_{oc}) \left[\frac{P_{z,t}}{P_t} \right]^{-\rho_c} C_t(j) \quad (6)$$

The household enters period t with portfolio $D_t(j)$ that pays out one unit of currency in a particular state, earns wage income by hiring labor, earns rental income from hiring capital and receives profits (dividends) $\Pi_t(j)$ from monopolistic firms. $W_t(j)$ is the nominal wage, $R_t^K(j)$ represents rate of return on capital, $K_t(j)$ is the beginning of t capital stock, and $T_t(j)$ is a composite of lump-sum transfers and/or taxes. In each period, the household purchases consumption goods $C_t(j)$ and investment goods $I_t(j)$. We assume that investment goods are composed of only non-oil goods. $D_{t+1}(j)$ is the expected nominal pay-off in period $t+1$ of the portfolio held at the end of period t, including the shares in firms. Hence, the representative household's budget constraint in period t is:

$$\begin{aligned} & P_t C_t(j) + P_{z,t} I_t(j) + E_t \left\{ Q_{t,t+1} D_{t+1}(j) \right\} \\ \leq \; & D_t(j) + W_t N_t(j) + R_t^K K_t(j) + \Pi_t(j) + T_t(j) \end{aligned} \tag{7}$$

and the capital accumulation equation is:

$$K_{t+1}(j) = (1-\delta) K_t(j) + \Phi \left(\frac{I_t(j)}{K_t(j)} \right) K_t(j) \tag{8}$$

where $Q_{t,t+1}$ is the stochastic discount factor for the one period ahead nominal payoff. Considering the Ricardian nature of our model, it is analytically convenient to assume that $T_t(j)$ is set in each period so that the government budget is balanced.

In Equation (8), δ is the depreciation rate, and the term $\Phi \left(\frac{I_t(j)}{K_t(j)} \right) K_t(j)$ captures capital adjustment costs where we assume that the steady state values of Φ, its first derivative and its second derivative are $\Phi_{ss} = \delta$, $\Phi'_{ss} = 1$, $\Phi''_{ss} = \xi < 0$, respectively, with $\delta\xi = -1$. The representative household, therefore, maximizes the utility (1) subject to (7) and (8).

Under the assumption of complete asset markets, households entertain perfect risk-sharing, and consumption is equal across households. Therefore, there is no need for index j. $R_t = 1/E_t(Q_{t,t+1})$ is the risk-free nominal interest rate. The equilibrium conditions for households are given by:

$$\beta E_t \left[\left(\frac{C_{t+1} - H_{t+1}}{C_t - H_t} \right)^{-\sigma} \frac{P_t}{P_{t+1}} \right] = \frac{1}{R_t}, \tag{9}$$

$$(C_t - H_t)^{\sigma} N_t^{\varphi} = \frac{W_t}{P_t}, \tag{10}$$

and

$$P_{z,t}\Lambda_t = \beta E_t \left\{ \left(\frac{C_{t+1} - H_{t+1}}{C_t - H_t} \right)^{-\sigma} \frac{P_t}{P_{t+1}} \left(R^K_{t+1} + P_{z,t+1}\Lambda_{t+1}\widetilde{\Phi} \right) \right\}. \qquad (11)$$

where $\widetilde{\Phi} = (1-\delta) + \Phi\left(\frac{I_{t+1}}{K_{t+1}}\right) - \Phi'\left(\frac{I_{t+1}}{K_{t+1}}\right)\frac{I_{t+1}}{K_{t+1}}$ and $\Lambda_t = 1/\Phi'\left(\frac{I_{t+1}}{K_{t+1}}\right)$ is the shadow price of capital.

2.2 Firms and Production

There is a continuum of monopolistically competitive firms which produce a differentiated core (non-oil) good indexed by $i \in [0,1]$ with identical production functions:

$$Y_{z,t}(i) = A_{1t}\left[(1-w_{oy})^{\frac{1}{\rho_y}} V_t(i)^{(\rho_y-1)/\rho_y} + w_{oy}{}^{\frac{1}{\rho_y}} O_{y,t}(i)^{(\rho_y-1)/\rho_y}\right]^{\rho_y/(\rho_y-1)} \qquad (12)$$

where $O_{y,t}(i)$ is the amount of oil used in production by firm i, ρ_y is the elasticity of substitution between oil and value added inputs, $0 < w_{oy} < 1$ indicates the share of the oil in production and A_{1t} represents a stationary total factor productivity shock in the goods sector that is common to all firms. Each producer utilizes labor and capital to produce a value added input $V_t(i)$ which is characterized in CES form:

$$V_t(i) = \left[(1-w_{ny})^{\frac{1}{\rho_v}} K_t(i)^{(\rho_v-1)/\rho_v} + w_{ny}{}^{\frac{1}{\rho_v}} (A_{2t}N_t(i))^{(\rho_v-1)/\rho_v}\right]^{\rho_v/(\rho_v-1)} \qquad (13)$$

where ρ_v is the elasticity of substitution between capital and labor inputs, $0 < w_{ny} < 1$ indicates the share of labor in production and A_{2t} represents a stationary labor productivity shock that is common to all firms.

Assuming that firms take the price of each input as given, cost minimization of the firm implies:

$$\begin{aligned} \frac{P_{o,t}O_{y,t}(i)^{1/\rho_y}}{w_{oy}{}^{1/\rho_y}} &= \frac{W_t N_t(i)^{1/\rho_v}}{A_{2t}^{(\rho_v-1)/\rho_v}(1-w_{oy})^{1/\rho_y} w_{ny}^{1/\rho_v} V_t^{(1/\rho_v-1/\rho_y)}} \\ &= \frac{R^K_t K_t(i)^{1/\rho_v}}{(1-w_{oy})^{1/\rho_y}(1-w_{ny})^{1/\rho_v} V_t^{(1/\rho_v-1/\rho_y)}} \qquad (14) \end{aligned}$$

which holds for each firm i. $P_{o,t}$, the price of oil is in fact determined endogenously in our model, as will be explored later. The nominal marginal cost of production is constant and the same across all firms, given by:

$$MC_t^n = \frac{1}{A_{1t}}\left[(1-w_{oy})V_{c,t}^{1-\rho_y} + w_{oy}P_{o,t}^{1-\rho_y}\right]^{1/(1-\rho_y)}. \tag{15}$$

where $V_{c,t} = \left((1-w_{ny})\left(R_t^K\right)^{1-\rho_v} + w_{ny}\left(\frac{W_t}{A_{2t}}\right)^{1-\rho_v}\right)^{\frac{1}{1-\rho_v}}$.

We assume that firms set prices according to Calvo (1983) framework, in which only a randomly selected fraction $(1-\theta)$ of the firms can adjust their prices optimally in each period. We also assume a partial indexation scheme where ς captures the degree of inflation indexation in the economy. Hence, firm's optimal price setting strategy implies the following marginal cost-based (log-linearized) Phillips curve:

$$\pi_{z,t} = \frac{\beta}{1+\beta\varsigma}E_t\left\{\pi_{z,t+1}\right\} + \frac{\varsigma}{1+\beta\varsigma}\pi_{z,t-1} + \frac{(1-\theta)(1-\beta\theta)}{\theta(1+\beta\varsigma)}mc_t \tag{16}$$

where $\pi_{z,t} = p_{z,t} - p_{z,t-1}$ is the non-oil CPI inflation between $t-1$ and t. The CPI inflation ($\pi_t = p_t - p_{t-1}$) is given by:

$$\pi_t = (1-w_{oc})\pi_{z,t} + w_{oc}\pi_{o,t} \tag{17}$$

where $\pi_{o,t} = p_{o,t} - p_{o,t-1}$ is the oil price inflation.

2.3 Monetary and Fiscal Policy

The monetary policy reaction function is assumed to be a simple Taylor rule:

$$r_t = \phi_r r_{t-1} + (1-\phi_r)\phi_\pi \pi_t + (1-\phi_r)\phi_y y_{z,t} \tag{18}$$

where $\phi_r \in [0,1]$ is the interest rate smoothing parameter, ϕ_π and ϕ_y denote the monetary policy responses to consumer price inflation and output.

Government spending index can be written as:

$$G_t = \left(\int_0^1 G_t(j)^{(\varepsilon-1)/\varepsilon}dj\right)^{\varepsilon/(\varepsilon-1)} \tag{19}$$

We assume that government consumes only non-oil goods. Government follows a balanced budget in each period and finances its expenditures by lump-sum taxation:

$$P_{z,t}G_t = T_t \tag{20}$$

Expenditure minimization leads to the following government demand function:

$$G_t(j) = \left(\frac{P_{z,t}(j)}{P_{z,t}}\right)^{-\varepsilon} G_t \tag{21}$$

We assume a stationary AR (1) process for the government spending (G_t).

2.4 Goods Market Equilibrium

The equilibrium condition in the goods market requires that the production of core goods satisfies:

$$Y_{z,t}(i) = G_t(i) + I_t(i) + Z_t(i). \tag{22}$$

2.5 Storage and Oil Market Equilibrium

2.5.1 Oil Storage

Oil storage takes the form of holding above-ground oil inventories. There is a continuum of competitive oil storers, *competitive speculators*, indexed by $l \in [0, 1]$ who are able to buy and sell on the spot market and are able to store oil. In line with the literature, we assume that there are no barriers to enter to the storage sector and storers are risk neutral. They form rational expectations about the returns to their activities.

The profits earned by a representative "storer" l from storing $S_t(l)$ is the difference between revenue in period $t+1$ and the cost of purchasing $S_t(l)$ in the spot market in period t while covering the storage costs. Oil storers seek to maximize their expected profit which is:

$$\frac{aE_t(P_{o,t+1})S_t(l)}{R_t} - P_{o,t}S_t(l)(1 + \Upsilon(S_t(l))) \tag{23}$$

where $\Upsilon(S_t(l)) = \kappa + \frac{\Psi}{2}S_t(l)$ is the (physical) cost of storing one unit of oil with $\kappa < 0$ (reflecting convenience yield) and $\Psi > 0$ (where the cost is increasing with the amount of oil).[6] We denote $(1-a)$ as the "waste", where $a \in [0, 1]$.

[6] The existence of convenience yield is a common assumption in commodity storage literature. The non-exhaustive list includes Brennan (1991), Fama and French (1988), and

As each storer shares the same rational expectations with other storers, there is no need for storer specific index l. In line with the existing literature on commodity storage, there is a non-negativity constraint on aggregate storage; $S_t \geqslant 0$— it is impossible to borrow stocks from the future.[7] For this price-taker storer, the F.O.C. with respect to S_t, given the constraint, yields:

$$aE_t[P_{o,t+1}] = R_t P_{o,t}(1 + \kappa + \Psi S_t) \tag{24}$$

Equation (24) is the decision rule for competitive storers: profit maximizing competitive storage, if positive, will set the expected marginal revenue from storage equal to the marginal cost.

The log-linearized version of the storage demand equation is:

$$s_t = \Theta(E_t\{\widehat{p_{o,t+1}}\} - \widehat{p_{o,t}} - (r_t - \pi_{t+1})) + sd_t \tag{25}$$

where $\Theta = \frac{a\beta}{\Psi \bar{S}} > 0$, and $\widehat{p_{o,t}} = p_{o,t} - p_t$ is the real price of oil. On the right hand side of Equation (25), we add an exogenous storage demand (sd_t), in order to capture the exogenous disturbances to oil stocks. The storage demand shock is assumed to follow a stationary stochastic process. According to Equation (25), storage demand is driven by the expected real price of oil, the current real price of oil, the real interest rate and an exogenous storage demand.

2.5.2 Oil Market Equilibrium

We assume that at each point in time there is a world oil endowment ($O_{s,t}$) which is subject to exogenous shocks defined by a stationary AR(1) process.[8] Given storage, the total quantity demanded by households and firms is equal to the new production, plus old inventories net of depreciation, minus new inventories:

Gibson and Schwartz (1990). More recently, Alquist and Kilian (2010) also adopt this modeling device.

[7] The level of storage is always positive in our framework as the steady state level is positive and sufficiently high and *deviations* of storage from its steady state are sufficiently small (within the neighborhood of the steady state). Incorporating non-linearities associated with storage technology is beyond the scope of this paper. Although conceptually appealing, this would make solution and estimation of the model considerably more complicated without providing any additional insight for the issues we focus here.

[8] For the sake of simplicity, we assume that the profits from selling and storing oil are distributed evenly among the consumers and are included in the lump-sum transfers in the budget constraints of households.

$$O_{c,t} + O_{y,t} = O_{s,t} + aS_{t-1} - S_t \tag{26}$$

Holding everything else constant, an increase in the expected price of oil raises oil storage through Equation (24), which in turn creates excess demand for oil through Equation (26), and drives oil prices up. In fact, using the cost minimization conditions for firms and households together with Equation (26), and the storage demand in Equation (24), one can derive the real price of oil.

3 Estimation

We estimate the model using standard Bayesian methods.[9] First, the dynamics of the model are obtained by taking a log-linear approximation of equilibrium conditions around the steady state.[10] Second, the solution of the model is expressed in state-space form. Given this representation, we compute the likelihood function recursively using the Kalman filter, which is then combined with the prior distributions to form the posterior densities of the parameters. Because the latter cannot be directly simulated, we use Monte Carlo Markov Chain methods which approximate the generation of random variables from the posterior distribution, after finding the parameters that maximize the posterior density using an optimization routine.[11]

3.1 Data

In the estimation process, we use quarterly output growth, investment growth, CPI inflation, interest rate, real price of oil and oil storage growth for the U.S. Our sample period covers 1982Q1 to 2007Q4. The U.S. monetary policy approach markedly changed in 1982, and the Federal Reserve moved away from targeting monetary aggregates. Moreover, in an influential paper Lubik and Schorfheide (2004) show that pre-Volcker period is not consistent with the determinacy in New Keynesian models. Our selection of 1982 as the starting year reflects these considerations. We end our sample period in 2007Q4 to

[9] See Lubik and Schorfheide (2006) and An and Schorfheide (2007) for details of the methodology and its advantages over other methods in estimating DSGE models.

[10] See Appendix for the full set of linearized equilibrium conditions of the model.

[11] The estimation is done using Dynare 4.2.4. The posteriors are based on 250,000 draws of the Metropolis-Hastings algorithm.

eliminate the non-linearities caused by the zero lower bound on the federal funds rate, as in Gali, Smets and Wouters (2011).

Real GDP, private fixed investment, GDP deflator, civilian non-institutional population (persons 16 years of age and older), consumer price index and federal funds rate are taken from the Federal Reserve Bank of St. Louis's database (FRED). Additionally, we collect West Texas Intermediate (WTI) crude oil price and U.S. ending stocks of crude oil from the U.S. Energy Information Agency (EIA). In order to calibrate the steady state ratio of total oil stocks to the quarterly oil supply, we need the oil supply series for the U.S. This series is calculated by adding the quarterly U.S. field production of crude oil to the quarterly U.S. net imports of crude oil using the data collected from EIA.

Nominal investment is deflated by the GDP deflator. Output, investment and storage are expressed in per capita terms. Quarterly output, investment, CPI and storage series are first detrended using a Hodrick-Prescott filter (with a smoothing parameter 1600) and then log-differenced. Spot price of WTI is deflated using the U.S. CPI series.

3.2 Calibrated Parameters

We estimate certain parameters while imposing dogmatic priors on others at their calibrated values to match the U.S. data. In particular, there are a number of parameters which have observable steady state values based on their long-run averages and great ratios, but for which the set of observable variables that we use does not provide information to estimate them. Calibrated parameter values are reported in Table 1. We set $\beta = 0.99$, implying a riskless annual return of approximately 4% in the steady state. The depreciation rate (δ) is set to 0.025. We set the shares of investment spending and government spending in output as $I_y = 0.2$ and $G_y = 0.18$ respectively, which are consistent with the ones used in many other studies for the U.S. We set the share of labor in value added production as $\omega_{ny} = 0.66$, based on the U.S. data reported in Ríos-Rull and Santaeulàlia-Llopis (2010) and Raurich, Sala and Sorollae (2012). The share of oil in consumption (ω_{cy}) and production (ω_{cy}) are taken as 0.023 and 0.028 respectively, as in Bodenstein, Erceg and Guerrieri (2011). We assume that some, but very small part, of the oil is wasted during the storage process, hence we set $1-a=0.01$.[12] The steady state ratio of total oil stocks to the quarterly oil supply is calculated using U.S. data as 0.61.[13]

3.3 Prior Distributions and Estimation Results

We estimate 12 structural parameters, 6 AR(1) coefficients and 6 shock standard deviations. In Table 2, we present prior distributions, the posterior means and 90 percent credible set of the estimated parameters and exogenous shocks. Table 2 reports the estimation results both for the benchmark model (with storage) and for a version of the benchmark model without storage.[14]

First, we comment on the parameters that relate to the oil storage and the use of oil in consumption and production in the model. In the baseline case, we set the prior mean of convenience yield (κ) as -0.03 with a standard deviation of 0.1. This implies that convenience yield can be between -0.2 and 0.2 in the 90 percent confidence interval. This prior selection reflects our loose knowledge about this coefficient. Posterior mean indicates that convenience yield is indeed negative, confirming our presumption. The prior means for the elasticities of substitution between oil and non-oil goods in consumption (ρ_c), between oil and non-oil inputs in production (ρ_y), and between capital and labor (ρ_v) are set using the calibrated parameters in Bodenstein, Erceg and Guerrieri (2011) for the U.S. as 0.4 and 0.4 a,d 0.5 respectively. For our sample period, posterior means for ρ_c and ρ_y are found as 0.66 and 0.55. We find that the posterior mean for ρ_v is somewhat low, with a value of 0.05.[15]

Second, we comment on the coefficients regarding nominal rigidities. We choose beta prior distributions for Calvo probability (θ) and the inflation in-

[12] Parameter ψ is a function of a, κ and some steady state ratios (see Appendix for details). Hence, we do not need to calibrate or estimate ψ.

[13] In order to calculate this steady state ratio, we use the data for 1973-2011, which is the longest period available.

[14] For the model without storage, we exclude one of the observables (oil storage) and one of the shocks (speculative demand) from the estimation. In the absence of oil storage, oil supply directly equals the total oil usage (oil in consumption plus oil in production), and hence the model excludes parameters a and κ. The prior distributions are the same for the models with and without storage.

[15] There is no clear consensus regarding the value of ρ_v. As reported by Chirinko (2008), the estimated elasticities in the literature generally vary within the range from 0.15 to 0.75. Our low estimate for ρ_v could reflect the difficulty of estimating this relationship with aggregate data.

dexation parameter (ς) with a mean of 0.5 and standard deviation of 0.15. These set of priors are within the range of values often set in the existing literature for the U.S. economy such as Sahuc and Smets (2008) and Nakov and Pescatori (2010). The posterior means for both θ and ς are lower than the prior means, with 0.38 and 0.32 respectively. Calvo probabilities are slightly lower than Sahuc and Smets (2008), but are close to Nakov and Pescatori (2010) using a more recent data set.

Next, we look at the parameters related to preferences. Consumption utility parameter (σ) has a normal prior distribution with mean 1 as in Sahuc and Smets (2008). For the inverse Frisch labor supply elasticity (φ), we opt for a gamma distribution with mean 1 and standard deviation of 0.25 as in Nakov and Pescatori (2010). For both σ and φ, the estimated values are slightly lower than the prior means. We also find a small degree of habit formation (posterior mean of 0.27) in line with Lubik and Schorfheide (2006), but in contrast to Sahuc and Smets (2008).

The means of prior distributions for the monetary policy block of the parameters follow Nakov and Pescatori (2010). The prior mean of interest rate smoothing parameter (ϕ_r) is set at 0.6, with a standard deviation of 0.1. For the prior distributions of inflation and output gap responses in the monetary policy rule, we choose gamma distribution with a mean 1.5 and 0.5 respectively. The estimated mean of the inflation coefficient is somewhat higher (3.3), but almost identical to the estimated mean in Nakov and Pescatori (2010).

Finally, the standard deviations of all exogenous shocks are assumed to follow an inverse-gamma distribution with a mean of 2. The persistence of AR(1) processes are assumed to be beta distributed with mean 0.5 and standard deviation 0.2. The posterior means for the AR(1) coefficients for total factor productivity, labor productivity and storage demand shocks suggest highly autocorrelated shocks. However, analysis of shock processes requires a more in depth analysis which is taken up in the next section.

3.3.1 Variance Decomposition

Before moving onto the impulse response analysis, we first check the relative importance of each shock in explaining variations in the real price of oil and oil storage. Table 3 reports variance decompositions for the benchmark model and the model without storage. For the whole sample period, the volatility in the real price of oil is mainly driven by the total factor productivity in the short term and labor productivity in the longer term. In the long term (horizon of 50 quarters), labor productivity explains around 87 percent of the variation in the oil price.[16] Oil supply and storage demand shocks are also important drivers of short-term fluctuations in oil price. Together, they represent about 26 percent of the oil price variation in one year. Government spending and monetary policy shocks are relatively less important in explaining oil price volatility. Volatility of oil storage growth is mainly explained by the oil supply shock both in the long and the short run— 77-78 percent of the variation is explained by this shock. Storage demand shock is the second most important driver of the volatility in oil storage growth, explaining around 11-13 percent of the total variation.

When the impact of competitive storage is ignored as it is the case in the existing literature, the relative importance of oil supply shocks is estimated much higher compared to the baseline case. The estimated role of oil supply shocks more than double from about 15 percent to about 36 percent in the short run, and from 3 percent to 11 percent in the long run when there is no storage technology in the model. It should be noted that the upward bias in the role played by oil supply shocks are above and beyond the impact of storage demand shock under the first scenario. For the period 2000-2007, omitting storage in the model causes even more amplification (from about 6 percent to about 24 percent) of the role of oil supply shocks in driving oil price volatility. Notably, this is the case even though storage demand shocks are not a very

[16] Bodenstein and Guerreri (2011) reach different outcomes than ours in their historical decomposition exercise. This is mostly brought by important differences in the model setups. By incorporating an open economy dimension, they are able to account for both U.S. specific and foreign shocks. Besides, different from us, they also analyze the effects of oil efficiency shocks and their model excludes speculative oil storage. In particular, they find that oil efficiency shocks and foreign productivity shocks were the key drivers of fluctuations in oil prices between 1984-2008 and 2003-2008 respectively. In our variance decomposition exercise, productivity shocks explain the majority of the oil price fluctuations. This could be partly brought by the absence of the foreign dimension in the model such that the productivity shocks might be capturing the effects of this missing channel (foreign demand). Note, however, that the decomposition is more balanced in shorter horizons. Notice also that, the presence of storage technology in the model elevates the estimated contribution of productivity shocks at every horizon.

important factor during that period.

There has been a lot of discussion about whether the causes of the oil price increases in 2000s are different from the ones in earlier periods. In order to shed some light on this issue, we estimate the model also for the 2000Q1-2007Q4 period and analyze the changes in the relative importance of shocks in explaining oil price movements when compared to the full estimation period (1982Q1-2007Q4). In the more recent period, the role of the total factor productivity in driving the short-term fluctuations in the real price of oil is significantly higher by about 20 percent, although the importance of the labor productivity is slightly lower. More specifically, the total effect of the two productivity shocks in driving short-term oil price volatility is around 76 percent, which was around 61 percent in the full sample period. The labor productivity is still the main driver of the variations in the real price of oil in the long-run.

The finding that the role of the productivity shocks in explaining the oil price volatility increased in 2000s is in line with the empirical evidence presented in Kilian (2009a). This finding has crucial implications as to why macroeconomic environment was much more resilient to the changes in oil prices at the beginning of the century. In particular, in the face of a productivity shock, output remains high and inflation decreases as shown in the impulse response analysis later in Section 3.3.2. We also find that in 2000s the role of oil supply shocks decreased, further confirming results of Kilian (2009a). The role of speculative storage demand shocks were considerably lower in the more recent periods. Together with oil supply shocks, they explain less than 10 percent of the total oil price volatility in the short run. The effect of the government spending shock decreased as well in 2000s, while the monetary shock has almost two times higher role in driving fluctuations in the oil price. The variation in the oil storage growth is still mainly driven by the oil supply shock, although the importance is now lower compared to the whole sample. The role of the storage demand shock is lower as well. In this sample period, the total factor productivity became an important driver of the volatility of the oil storage growth, whose effect in the total variation is around 18 percent. The roles of both government spending and monetary policy shocks in driving the volatility of oil storage growth are higher in 2000s, compared to the whole sample.

3.3.2 Impulse Response Analysis

The analysis of the variance decomposition presented above shows that the oil price fluctuations in our sample are mostly driven by the two productivity shocks, the oil supply shock and the storage demand shock. In total, 86 percent of the variation in the real price of oil is explained by these four shocks in the short run and 98 percent is explained by these shocks in the long run. Therefore, in the impulse response analysis, we focus on: a positive oil demand shock (either through an increase in TFP or an increase in labor productivity), a negative oil supply shock, and a positive speculative demand shock. In Figures 1-4, the bold line is the mean impulse response and the bands around this line represent the 90 percent confidence interval.

Total Factor and Labor Productivity Shocks Responses of selected variables to a positive one standard deviation TFP shock are shown in Figure 1. Under a TFP shock, positive output growth leads to higher demand for all inputs in production. The increase in the real price of oil is higher than the increases in the prices of other factors of production as oil supply is fixed by assumption. Hence, firms substitute other inputs for oil, and oil in production falls. As factors become more productive, marginal cost of production declines, bringing lower consumer prices. The monetary authority responds to the lower CPI inflation by reducing the interest rate. Under this scenario, the decline in the nominal interest rate is higher than the decline in the expected CPI inflation, causing a lower real interest rate. The lower real interest rate leads to increases in oil consumption and speculative oil storage. Higher storage demand decreases available oil supply and pushes the real price of oil further up. Overall, following a TFP shock, an increase in output growth is accompanied by lower consumer price inflation, but higher oil prices.

Figure 2 reports the impulse responses in case of a positive one standard deviation labor productivity shock. The shock to labor-specific productivity causes output, consumption and investment to rise, similar to the case under a TFP shock. In case of a TFP shock, the productivity of all factors of production increase. However, when there is an increase in the productivity of labor only, the substitution between labor and other factors of production is expected to become more intensive. As our estimation results posit a low degree of substitution between capital and labor ($\rho_v = 0.05$), in the face of a labor productivity shock, firms need to hire more capital and oil in order to produce more. As a result, capital and oil in production increase, and the declines in the marginal cost and hence in the CPI inflation are much lower compared to the case of a TFP shock. The initial response of the nominal interest rate is even positive since the decline in inflation is relatively muted and the comparably larger movement in output prevents the monetary authority to reduce the nominal interest rate. Hence, the real interest rate rises, causing a decline in oil in consumption and speculative storage, which mitigates some of the increases in the real price of oil.

These exercises reveal two important results. First, higher oil prices do not necessarily lead to a conventional higher inflation-lower output scenario. Instead, the positive effects of productivity increases on the inflation and output growth compensate the negative effects of the higher oil prices. Given that most of the variation in oil prices in 2000s come from productivity shocks as explained above, it is not surprising that in the U.S. oil price increases during that period were not accompanied by a major recession. Second, and perhaps more interestingly, the presence of storage generates a new monetary policy transmission channel, which works through the impact of changes in real interest rates on storage, and hence on oil prices. On the one hand, monetary policy responds to changes in inflation and output, which are affected by the oil price movements. On the other hand, monetary policy actions have a role to play in determining changes in oil prices when speculative storage is taken into account. We take up this issue again in Section 3.3.3 where we compare the responses of the model with and without storage.

Oil Supply Shock Figure 3 presents the responses to a negative one standard deviation shock to the oil supply which leads to a jump in the real oil price. As the decrease in oil storage is not sufficient to compensate for the decline in the oil supply, oil price increases on impact after the shock. The rise in oil price brings a decline in the oil used in both production and consumption as output contracts. An increase in the oil price pushes the CPI above the steady state level due to the rising marginal cost of production. Nevertheless, compared to the productivity shocks, the effects of the oil supply shock on the other macroeconomic variables are relatively smaller in magnitude due to the small share of oil in production (2.8 percent) and consumption (2.3 percent).

Note that the decline in oil storage under a negative supply shock is brought by both the expected negative change in the real price of oil and the rising opportunity cost, i.e. the real interest rate. Therefore, when the oil supply shock hits the economy, it becomes more profitable for competitive storers to sell the oil.

Oil Storage Demand Shock We model oil storage demand shock as an exogenous change in the storage demand of the storers. This might happen because of precautionary motives. As the storage demand increases, the total oil availability decreases which is immediately reflected in the real price of oil (Figure 4). The rest of the transmission of the shock to the economy works in a similar manner as in the negative oil supply shock.[17]

3.3.3 Comparison: The impulse responses with and without storage

We compare the impulse responses for the models with and without oil storage demand to assess the importance of taking into account the presence of oil storage in determining the impacts of different oil price shocks.[18] The results are presented in Figures 5-7.

When we take the oil storage into account, the real price of oil becomes more sensitive to a TFP shock (Figure 5). In response to a TFP shock, oil storage increases as opportunity cost of storing oil (expected real interest rate) declines. This creates an additional oil demand, leading to about 50 percent more increase in the oil price compared to the case without storage. Indeed, under this scenario, the responses of all variables are amplified.

[17] Note that, as in the case of a negative oil supply shock, the endogenous component of the storage demand decreases, which causes a hump shape in the response of the total oil storage.

[18] In order to make the comparison, we estimate the models with and without storage separately. This allows us to reveal the effects of ignoring oil storage when studying the cause and consequences of oil price changes. Notice that there are two factors that cause the impulse responses differ under the cases with and without storage. One comes from differences in estimated parameters, the other from the direct effect of taking or not taking into account storage.

After a labor productivity shock, similar to a TFP shock, when storage is taken into account, the response of the real price of oil is higher (Figure 6). This is partially brought by the fact that the estimated ρ_c differs under cases of with or without storage. Higher estimated ρ_c (1.16 compared to 0.66) in the absence of storage implies more substitution between non-oil goods and oil consumption relative to the case under storage, which pushes the real price of oil upwards. When storage is taken into account, the responses of output, consumption, investment, interest rate and CPI inflation become less volatile.

In case of an oil supply shock, the availability of oil storage makes the responses of output, consumption, investment and real price of oil notably smaller in magnitude compared to the case with no storage (Figure 7). With storage, some of the decline in oil supply is offset by the decrease in oil storage demand. This limits the decline in oil in production and consumption, and leads to less increase in the real price of oil. As a result, when there is an oil supply shock, the storage technology is particularly effective in mitigating the impact of the shock by changing the oil availability.

Our findings are in sharp contrast with the standard mitigating role of storage in the existing competitive storage literature. In a general equilibrium setting, our findings indicate that amplifying or mitigating role of the competitive storage depends on the source of the shock, in line with the empirical evidence presented in Kilian and Murphy (2010) and Alquist and Kilian (2010).

4 Conclusion

The dramatic rise in oil prices between 2003 and 2008 has prompted several new studies that examine the causes and effects of oil price shocks (see, e.g., Kilian 2009a,b; Kilian, Rebucci and Spatafora 2009; Unalmis, Unalmis, and Unsal 2009; Nakov and Pescatori 2010; Bodenstein, Erceg and Guerrieri 2011; Lippi and Nobili 2012; Kilian and Hicks 2012; Kilian and Murphy 2012). This paper focused on the role of speculative oil storage for oil price movements in the U.S., building on work by Alquist and Kilian (2010), Dvir and Rogoff (2009) and Kilian and Murphy (2010), in particular. In contrast to these earlier studies we incorporated a model of speculative oil storage into a dynamic general equilibrium framework. This allowed us to study the dynamic link between oil inventories, monetary policy responses, storers' expectations of the price of oil and the spot price.

Using this model, we investigated the origins and macroeconomic consequences of several U.S. shocks that are associated with oil price fluctuations, including a total factor productivity shock, a labor productivity shock, a government spending shock, a monetary policy shock, an oil supply shock and a storage demand shock. To quantify the model responses we estimated the model on U.S. data. We identified the relative importance of these shocks for the real price of oil during 1982-2007 as well as for the subsample of 2000-2007. Our estimates suggest that oil demand shocks in the form of total factor productivity shocks and labor productivity shocks are overall the most important drivers of changes in oil prices. When the storage feature is omitted from the model, the estimated contribution of oil supply shocks to oil price fluctuations is amplified considerably, in particular after 2000. Hence, studies that do not consider storage demand shocks are likely to overestimate the role played by oil supply shocks.

Another important finding is that after 2000, the contribution of productivity shocks to the variance of the real price of oil is higher by about 15 percent in the short run, when compared to the whole sample. On the other hand, the contributions of the oil supply shock and the storage demand shock is lower by more than half, compared to the full estimation period. This finding sheds some light on the resilience of the macroeconomic environment to oil price increases at the beginning of the century.

Finally, taking advantage of our general equilibrium model, we show that the presence of speculative oil storers may smooth or intensify the oil price fluctuations depending on the source of the shock. This is in contrast with the classic storage literature which emphasizes the mitigating role of the speculative storage, but in line with the empirical evidence presented in Kilian and Murphy (2010) and Alquist and Kilian (2010).

In the interest of keeping the model tractable, we abstracted from the open economy channels of the transmission of oil price shocks and indeed from the role of foreign shocks and focused on the U.S. oil market. An obvious extension would be to embed our model of storage within a model of the global economy.

References

[1] Alquist, R. and L. Kilian, 2010. What Do We Learn From the Price of Crude Oil Futures?, *Journal of Applied Econometrics*, 25(4), 539-573.

[2] An, S. and F. Schorfheide, 2007. Bayesian Analysis of DSGE Models, *Econometric Reviews*, 26(2-4), 113-172.

[3] Backus, D. K. and M. J. Crucini, 2000. Oil Prices and the Terms of Trade, *Journal of International Economics*, 50,185-213.

[4] Bodenstein, M., C.J. Erceg and L. Guerrieri, 2011. Oil Shocks and External Adjustment, *Journal of International Economics*, 83(2), 168-184.

[5] Bodenstein, M. and L. Guerrieri, 2011. Oil Efficiency, Demand, and Prices: a Tale of Ups and Downs, International Finance Discussion Papers No.1031, Board of Governors of the Federal Reserve System.

[6] Brennan, M. J. 1991. The Price of Convenience and the Valuation of Commodity Contingent Claims. Stochastic Models and Option Values. (Eds.) Lund, D. and Øksendal, B., Amsterdam: North-Holland. 135–57.

[7] Calvo, G., 1983. Staggered Prices in a Utility-Maximizing framework, *Journal of Monetary Economics*, 12, 383–98.

[8] Clarida, R., J. Gali, and M. Gertler, 2001. Optimal Monetary Policy in Open vs Closed Economies: An Integrated Approach, *American Economic Review*, 91(2), 248-252.

[9] Chirinko R. S., 2008. σ : The Long and Short of It, *Journal of Macroeconomics*, Vol. 30, Issue 2, 671-686.

[10] Deaton, A. and G. Laroque, 1992. On the Behavior of Commodity Prices, *Review of Economic Studies*, 59(1), 1-23.

[11] Deaton, A. and G. Laroque, 1996, Competitive Storage and Commodity Price Dynamics, *Journal of Political Economy*, 104(5), 896–923.

[12] Dvir, E. and K.S. Rogoff, 2009. The Three Epochs of Oil, Boston College Working Paper in Economics, No. 706.

[13] Fama, E. F., and K. R. French, 1988. Permanent and Temporary Components of Stock Prices, *Journal of Political Economy,* 96, 246-273.

[14] Fattough, B., L. Kilian and L. Mahadeva, 2012. The Role of Speculation in Oil Markets: What Have We Learned So Far? mimeo, University of Michigan.

[15] Gali, J., 2002. New Perspectives on Monetary Policy, Inflation, and the Business Cycle, NBER Working Paper No.8767.

[16] Gali, J., F. Smets and R. Wouters, 2011. Unemployment in an Estimated New Keynesian Model, NBER Chapter in: NBER Macroeconomics Annual 2011, 26.

[17] Gibson, R., and Schwartz, E.S., 1990. Stochastic Convenience Yield and the Pricing of Oil Contingent Claims, *Journal of Finance*, 45(3), 959-976.

[18] Hamilton, J. D., 2009. Causes and Consequences of the Oil Shock of 2007-2008, NBER Working Paper No.150002.

[19] Herrera, A.M., and E. Pesavento, 2009. Oil Price Shocks, Systematic Monetary Policy, and the 'Great Moderation', *Macroeconomic Dynamics*, 13, 107-137.

[20] Kaldor, N., 1939. Speculation and Economic Stability, *Review of Economic Studies*, 7, 1–27.

[21] Kilian, L., 2008. The Economic Effects of Energy Price Shocks, *Journal of Economic Literature*, 46(4), 871-909.

[22] Kilian, L., 2009a. Not All Price Shocks are Alike: Disentangling Demand and Supply Shocks in the Crude Oil Market, *American Economic Review*, 99(3), 1053–69.

[23] Kilian, L., 2009b. Comment on 'Causes and Consequences of the Oil Shock of 2007-08' by James D. Hamilton, *Brookings Papers on Economic Activity*, 1 (Spring), 267-278.

[24] Kilian, L. and B. Hicks, 2012. Did Unexpectedly Strong Economic Growth Cause the Oil Price Shock of 2003-2008?, forthcoming: *Journal of Forecasting.*

[25] Kilian, L. and D.P. Murphy, 2010. The Role of Inventories and Speculative Trading in the Global Market for Crude Oil, CEPR Discussion Paper, No. 7753.

[26] Kilian, L. and D.P. Murphy, 2012. Why Agonistic Sign Restrictions Are Not Enough: Understanding the Dynamics of Oil Market VAR Models, forthcoming: *Journal of the European Economic Association.*

[27] Kilian, L. and C. Park, 2009. The Impact of Oil Price Shocks on the U.S. Stock Market, *International Economic Review*, 50(4), 1267-1287.

[28] Kilian, L., A. Rebucci, and N. Spatafora, 2009. Oil Shocks and External Balances, *Journal of International Economics,* 77(2). 181-194.

[29] Lippi, F. and A. Nobili, 2012. Oil and the Macroeconomy: A Quantitative Structural Analysis, forthcoming: *Journal of the European Economic Association.*

[30] Lubik, T. A., and F. Schorfheide, 2004. Testing for Indeterminacy: An Application to U.S. Monetary Policy, *The American Economic Review,* Vol. 94, No 1, 190-217.

[31] Lubik, T. A., and F. Schorfheide, 2006. A Bayesian Look at New Open Economy Macroeconomics, in Mark, G. and K. Rogoff (eds.), NBER Macroeconomics Annual 2005, Cambridge: The MIT Press, pp. 313–366.

[32] Nakov, A., and A. Pescatori, 2010. Monetary Policy Trade-Offs with a Dominant Oil Supplier, *Journal of Money, Credit, and Banking*, 42(1), 1-32.

[33] Raurich, X., H. Sala and V. Sorollae, 2012. Factor Shares, the Price Markup, and the Elasticity of Substitution between Capital and Labor, *Journal of Macroeconomics,* Vol. 34, Issue 1, 181-198.

[34] Ríos-Rull, J. V. and R. Santaeulàlia-Llopis, 2010. Redistributive Shocks and Productivity Shocks, *Journal of Monetary Economics,* Vol. 57, Issue 8, 931-948.

[35] Sahuc J-G. and F. Smets, 2008. Differences in the Interest Rate Policy at the ECB and the Fed: An Investigation with a Medium Scale DSGE Model, *Journal of Money, Credit, and Banking*, Vol. 40, No. 2-3.

[36] Unalmis, D., I. Unalmis and D.F. Unsal, 2009. On the Sources of Oil Price Fluctuations, IMF Working Paper, No.9285.

[37] Williams, J.B. ,1936. Speculation and the Carryover, *Quarterly Journal of Economics*, 50, 436–55.

[38] Williams, J.C. and B. Wright, 1982. The Roles of Public and Private Storage in Managing Oil Import Disruptions, *Bell Journal of Economics*, 13(2), 341-353.

[39] Williams, J.C. and B. Wright, 1984. The Welfare Effects of the Introduction of Storage, *Quarterly Journal of Economics*, 99(1), 169-92.

[40] Williams, J.C. and B. Wright, 1991. Storage and Commodity Markets, Cambridge University Press.

[41] Working H., 1948. Theory of the inverse carrying charge in futures markets. *Journal of Farm Economics*, 30, 1-28.

Appendix: Equilibrium Conditions

In what follows, small letters denote percentage deviations of the respective variables from their steady-state levels. Household's maximization of (1) subject to (7) and (8) yields the following (log-linearized) optimality conditions:

$$\begin{aligned}\beta\delta\xi E_t\{i_{t+1}-k_{t+1}\} &= \delta\xi(i_t-k_t)-\frac{\sigma}{1-h}E_t\{\Delta c_{t+1}\}+\frac{\sigma h}{1-h}\Delta c_t+E_t\{\pi_{z,t+1}\} \\ &\quad -E_t\{\pi_{t+1}\}+(1-\beta(1-\delta))E_t\{\widehat{r}^K_{t+1}\} \qquad (27)\end{aligned}$$

$$(\frac{\sigma}{1-h})c_t-\frac{\sigma h}{1-h}c_{t-1}+\varphi n_t=\widehat{w}_t \qquad (28)$$

$$E_t\{\Delta c_{t+1}\}=h(\Delta c_t)+(\frac{1-h}{\sigma})(r_t-E_t\{\pi_{t+1}\}) \qquad (29)$$

where $\widehat{r}^K_t = r^K_t - p_{z,t}$ is the real rental rate of capital, $\widehat{w}_t = w_t - p_t$ is the real wage, $\log R_t = \log(1+r_t) \approx r_t$ is the nominal interest rate, $\pi_{z,t+1} = p_{z,t+1} - p_{z,t}$ is the non-oil CPI inflation between t and $t+1$, and $\pi_{t+1} = p_{t+1} - p_t$ is the CPI inflation between t and $t+1$. Law of motion for capital in log-linearized form is as follows:

$$k_{t+1}=\delta i_t+(1-\delta)k_t \qquad (30)$$

Oil used in consumption (Equation 5) is log-linearized as:

$$o_{c,t}=-\rho_c\widehat{p_{o,t}}+c_t \qquad (31)$$

where $\widehat{p_{o,t}} = p_{o,t} - p_t$ is the real price of oil.

Firms will minimize $R^K_t K_t + W_t N_t + P_{o,t}O_{y,t}$ subject to (12). Log-linearized F.O.C.s are as follows:

$$\widehat{w}_t+(1/\rho_v)n_t+((1-\rho_v)/\rho_v)a_{2t}=\widehat{r}^K_t+(1/\rho_v)k_t+pr_{z,t} \qquad (32)$$

$$\begin{aligned}o_{y,t} &= y_t-a_{1t}+\rho_y(1-w_{oy})w_{ny}(\widehat{w}_t-a_{2t})+\rho_y(1-w_{oy})(1-w_{ny})\widehat{r}^K_t \\ &\quad -\rho_y(1-w_{oy})\widehat{p_{o,t}}+\rho_y(1-w_{oy})(1-w_{ny})pr_{z,t} \qquad (33)\end{aligned}$$

where $pr_{z,t} = p_{z,t} - p_t$ is the relative price. Equation (33) presents the determinants of the oil used in production.

The (log-linearized) real marginal cost ($mc_t = mc_t^n - p_{z,t}$) that is faced by the firms is:

$$
\begin{aligned}
mc_t &= -a_{1t} + (1 - w_{oy})(1 - w_{ny})\widehat{r}_t^k + (1 - w_{oy})w_{ny}(\widehat{w}_t - a_{2t}) \\
&\quad + w_{oy}\widehat{p_{o,t}} - ((1 - w_{oy})w_{ny} + w_{oy})pr_{z,t}.
\end{aligned} \tag{34}
$$

We assume that firms set prices according to Calvo (1983) framework, in which only a randomly selected fraction $(1 - \theta)$ of the firms can adjust their prices optimally in each period. Thus, θ is the probability that firm i does not change its price in period t. These firms of fraction θ can only adjust the price according to a partial indexation scheme:

$$
P_{z,t+k}(i) = \prod_{s=1}^{k} \Pi_{z,t+s-1}^{\varsigma} P_{z,t}(i) \tag{35}
$$

where $\Pi_{z,t} = P_{z,t}/P_{z,t-1}$. For firms who do not have chances to reoptimize prices, the prices are adjusted according to past inflation of core goods. ς captures the degree of inflation indexation in the economy.

The firm i who has opportunity to reoptimize the price chooses the price ($\widetilde{P}_{z,t}(i)$) so that it maximizes the stream of profits discounted by $Q_{t,t+k}$:

$$
E_t \left\{ \sum_{k=0}^{\infty} \theta^k Q_{t,t+k} (Y_{z,t+k}(i) (\prod_{s=1}^{k} \Pi_{z,t+s-1}^{\varsigma} \widetilde{P}_{z,t}(i) - MC_{t+k}^n) \right\} \tag{36}
$$

subject to the demand function faced by the firm:

$$
Y_{z,t}(i) = \left(\frac{P_{z,t}(i)}{P_{z,t}} \right)^{-\varepsilon} Y_{z,t} \tag{37}
$$

where ε is the elasticity of substitution among the core goods.

Therefore, $\widetilde{P}_{H,t}(i)$ should satisfy the following first order condition:

$$
E_t \left\{ \sum_{k=0}^{\infty} \theta^k Q_{t,t+k} (Y_{z,t+k}(i) (\prod_{s=1}^{k} \pi_{z,t+s-1}^{\varsigma} \widetilde{P}_{z,t}(i) - \frac{\varepsilon}{\varepsilon - 1} MC_{t+k}^n) \right\}. \tag{38}
$$

Hence, the firms' optimal price setting strategy implies the marginal cost-based (log-linearized) Phillips curve:

$$\pi_{z,t} = \frac{\beta}{1+\beta\varsigma} E_t \left\{ \pi_{z,t+1} \right\} + \frac{\varsigma}{1+\beta\varsigma} \pi_{z,t-1} + \frac{(1-\theta)(1-\beta\theta)}{\theta(1+\beta\varsigma)} mc_t. \tag{39}$$

Log-linearization of goods market equilibrium condition around the symmetric steady state gives:

$$y_{z,t} = G_y g_t + I_y i_t + (1 - G_y - I_y) z_t \tag{40}$$

where $z_t = c_t - \rho_c pr_{z,t}$. $G_y = \overline{G}/\overline{Y}_z$ and $I_y = \overline{I}/\overline{Y}_z$ are the steady state shares of government spending and investment in output, where letters with a bar above indicate the steady state levels.

In the oil market, oil supply $(o_{s,t})$ is assumed be exogenous, while oil demand and oil storage are endogenously determined. The (log-linearized) equilibrium conditions are:

$$s_t = \Theta(E_t\{\widehat{p_{o,t+1}}\} - \widehat{p_{o,t}} - E_t\{r_t - \pi_{t+1}\}) + sd_t \tag{41}$$

$$\frac{\overline{O}_y}{\overline{O}_s} o_{y,t} + \frac{\overline{O}_c}{\overline{O}_s} o_{c,t} = o_{s,t} + a\frac{\overline{S}}{\overline{O}_s} s_{t-1} - \frac{\overline{S}}{\overline{O}_s} s_t \tag{42}$$

where $\Theta = \frac{a\beta}{\Psi\overline{S}}$, and the oil supply shock $(o_{s,t})$ and storage demand shock (sd_t) are assumed to follow stationary AR(1) processes.

Notice that at steady state, $\kappa + \psi\overline{S} = a\beta - 1 < 0$, $\frac{\overline{O}_y}{\overline{O}_s} = \left(1 + \frac{(1-G_y-I_y)w_{oc}}{w_{oy}(1-w_{oc})}\right)^{-1} (1 + (a-1)\frac{\overline{S}}{\overline{O}_s})$, and $\frac{\overline{O}_c}{\overline{O}_s} = \frac{(1-G_y-I_y)w_{oc}}{w_{oy}(1-w_{oc})} \frac{\overline{O}_y}{\overline{O}_s}$.

Table 1. Calibrated parameters

$\beta = 0.99$	Discount factor
$\delta = 0.025$	Depreciation rate
$I_y = 0.2$	Share of investment spending in output
$G_y = 0.18$	Share of government spending in output
$\omega_{ny} = 0.66$	Share of labor in value added
$\omega_{oc} = 0.023$	Share of oil in consumption
$\omega_{oy} = 0.028$	Share of oil in production
$S/O_s = 0.61$	Ratio of oil stocks to quarterly oil supply
$1 - a = 0.01$	Oil waste

Table 2. Prior distributions and posterior estimates (sample period: 1982Q1-2007Q4)

					benchmark			no storage		
		prior distribution			posterior distribution			posterior distribution		
		type	mean	st.dev.	mean	5%	95%	mean	5%	95%
standard deviation of the innovations										
ε_{tfp}	total factor prod.	inverse gamma	2	2	0.52	0.45	0.58	0.45	0.39	0.51
ε_{l}	labor productivity	inverse gamma	2	2	2.22	1.53	2.92	2.07	1.55	2.58
ε_{g}	govern. spending	inverse gamma	2	2	2.61	2.15	3.00	3.65	2.73	4.47
ε_{mp}	monetary policy	inverse gamma	2	2	0.66	0.52	0.81	0.52	0.30	0.72
ε_{os}	oil supply	inverse gamma	2	2	1.04	0.92	1.16	0.36	0.30	0.41
ε_{sd}	storage demand	inverse gamma	2	2	4.62	2.80	6.33	-	-	-
persistence of the exogenous processes										
ρ_{tfp}	total factor prod.	beta	0.5	0.2	0.80	0.74	0.87	0.83	0.78	0.88
ρ_{l}	labor productivity	beta	0.5	0.2	0.95	0.91	0.99	0.96	0.93	0.98
ρ_{g}	govern. spending	beta	0.5	0.2	0.64	0.54	0.74	0.83	0.77	0.89
ρ_{mp}	monetary policy	beta	0.5	0.2	0.36	0.29	0.43	0.16	0.06	0.26
ρ_{os}	oil supply	beta	0.5	0.2	0.53	0.42	0.64	0.95	0.91	0.99
ρ_{sd}	storage demand	beta	0.5	0.2	0.94	0.90	0.98	-	-	-
structural parameters										
κ	convenience yield	normal	-0.03	0.05	-0.04	-0.05	-0.03	-	-	-
ρ_{v}	elasticity:capital/labor	gamma	0.5	0.1	0.05	0.03	0.08	0.05	0.03	0.07
ρ_{c}	elasticity:core/oil	gamma	0.4	0.1	0.66	0.40	0.89	1.16	0.93	1.39
ρ_{y}	elasticity:va/oil	gamma	0.4	0.1	0.55	0.37	0.72	0.61	0.52	0.69
θ	Calvo parameter	beta	0.5	0.15	0.38	0.28	0.48	0.26	0.18	0.34
ς	price indexation	beta	0.5	0.15	0.32	0.13	0.49	0.26	0.07	0.44
h	habit persistence	beta	0.6	0.1	0.27	0.15	0.38	0.1	0.03	0.16
σ	inv.el. of int.subst. cons.	normal	1	0.1	0.93	0.76	1.08	1.04	0.91	1.18
φ	inv.el. of labor supply	gamma	1	0.25	0.95	0.58	1.27	0.87	0.47	1.19
ϕ_{π}	response to inflation	gamma	1.5	0.5	3.30	2.78	3.82	3.72	3.01	4.44
ϕ_{y}	response to output	gamma	0.5	0.05	0.37	0.29	0.45	0.24	0.16	0.32
ϕ_{r}	int.rate persistence	beta	0.6	0.1	0.52	0.41	0.62	0.64	0.50	0.79

Table 3. Variance decomposition (sample period: 1982Q1-2007Q4)

		benchmark						no storage				
	quarter	ε_{tfp}	ε_l	ε_g	ε_{mp}	ε_{os}	ε_{sd}	ε_{tfp}	ε_l	ε_g	ε_{mp}	ε_{os}
real price of oil	4	32.49	28.37	9.73	3.48	14.87	11.06	25.25	24.76	11.07	2.89	36.03
	8	24.06	47.15	5.88	2.16	12.74	8.01	18.01	38.69	8.95	1.54	32.82
	12	17.99	60.72	4.12	1.54	9.91	5.73	13.12	50.47	6.95	1.03	28.44
	50	6.02	87.04	1.30	0.49	3.26	1.89	3.50	83.32	2.05	0.25	10.87
storage growth	4	2.27	0.17	6.38	1.78	78.57	10.83	-	-	-	-	-
	8	2.23	0.24	3.19	1.76	77.49	12.10	-	-	-	-	-
	12	2.18	0.27	6.12	1.74	77.80	11.90	-	-	-	-	-
	50	2.11	0.30	6.00	1.70	76.92	12.98	-	-	-	-	-

Table 4. Variance decomposition (sample period: 2000Q1-2007Q4)

		benchmark						no storage				
	quarter	ε_{tfp}	ε_l	ε_g	ε_{mp}	ε_{os}	ε_{sd}	ε_{tfp}	ε_l	ε_g	ε_{mp}	ε_{os}
real price of oil	4	51.73	23.88	4.92	6.29	5.65	3.52	51.91	13.00	9.77	1.83	23.50
	8	39.38	43.29	3.10	6.71	4.92	2.59	44.76	27.18	8.08	1.09	18.89
	12	29.80	57.48	2.20	4.84	3.83	1.85	36.70	41.23	6.48	0.78	14.80
	50	9.49	86.84	0.66	1.45	1.18	0.59	12.49	80.50	2.19	0.23	4.59
storage growth	4	17.65	0.10	12.87	2.66	62.84	3.88	-	-	-	-	-
	8	18.04	0.12	12.67	2.74	62.21	4.22	-	-	-	-	-
	12	17.95	0.14	12.59	2.80	62.34	4.18	-	-	-	-	-
	50	17.74	0.18	12.47	2.81	62.08	4.72	-	-	-	-	-

Figure 1. Impulse responses to a one standard deviation positive TFP shock

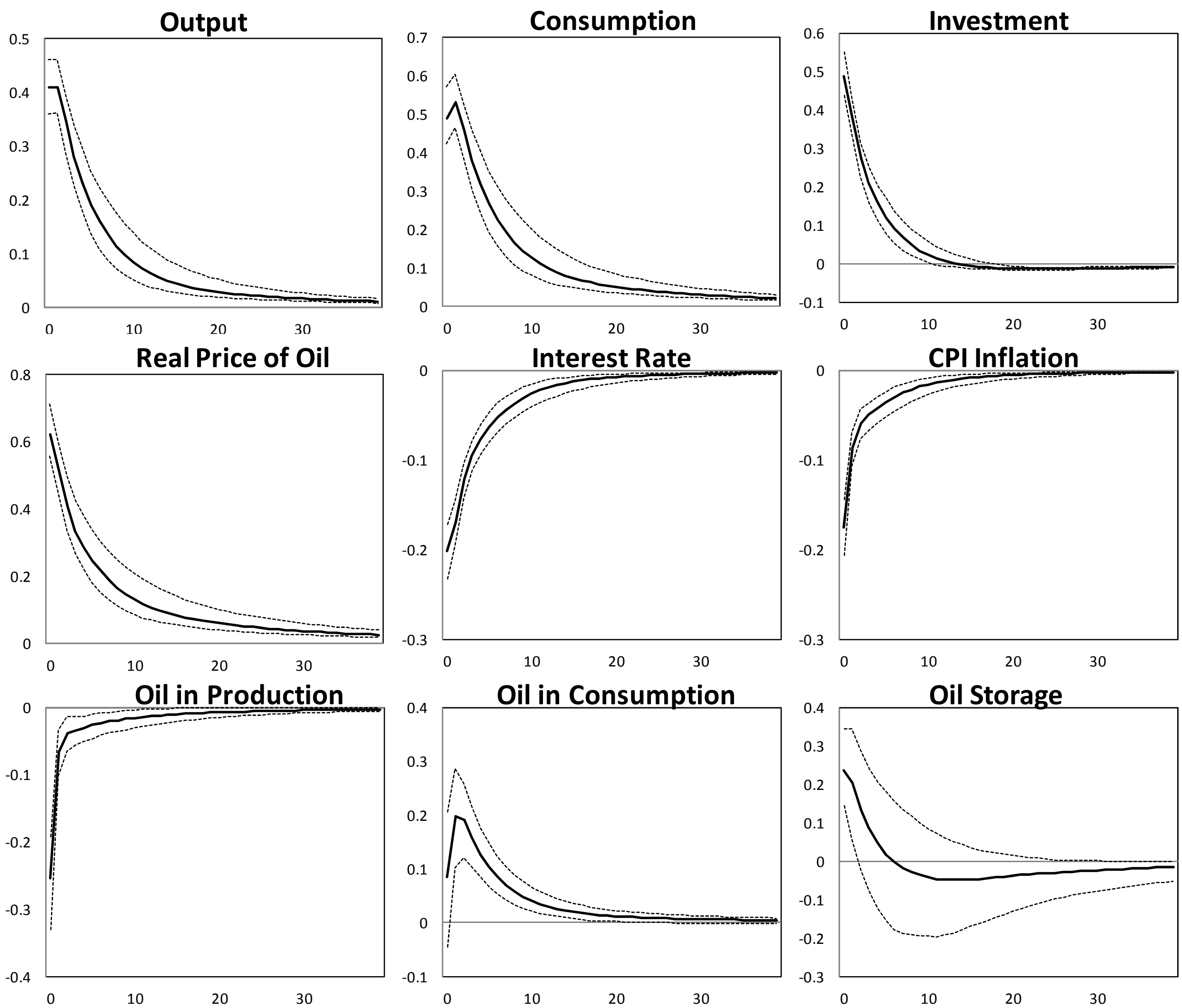

Figure 2. Impulse responses to a one standard deviation positive labor productivity shock

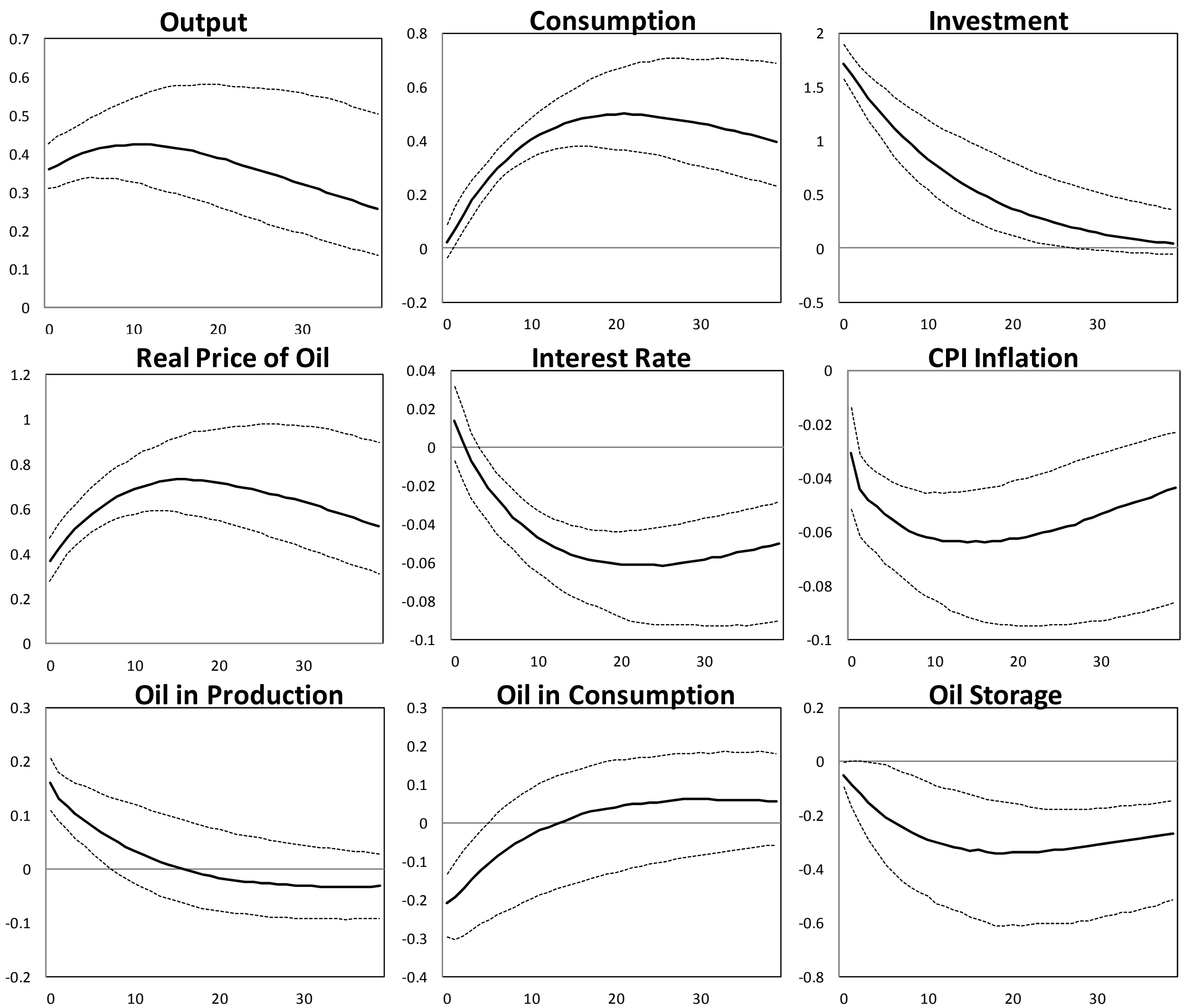

Figure 3. Impulse responses to a one standard deviation negative oil supply shock

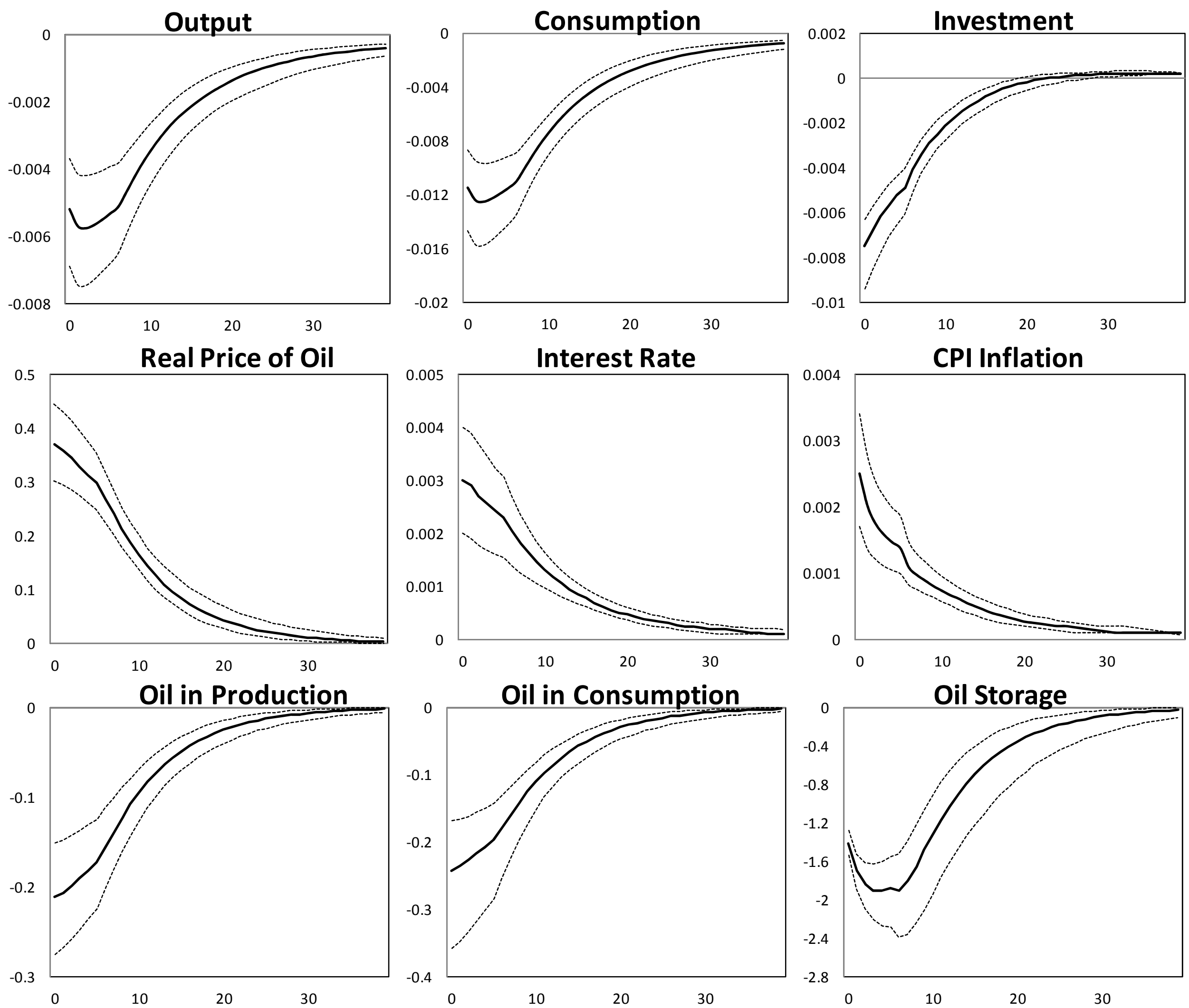

Figure 4. Impulse responses to a one standard deviation storage demand shock

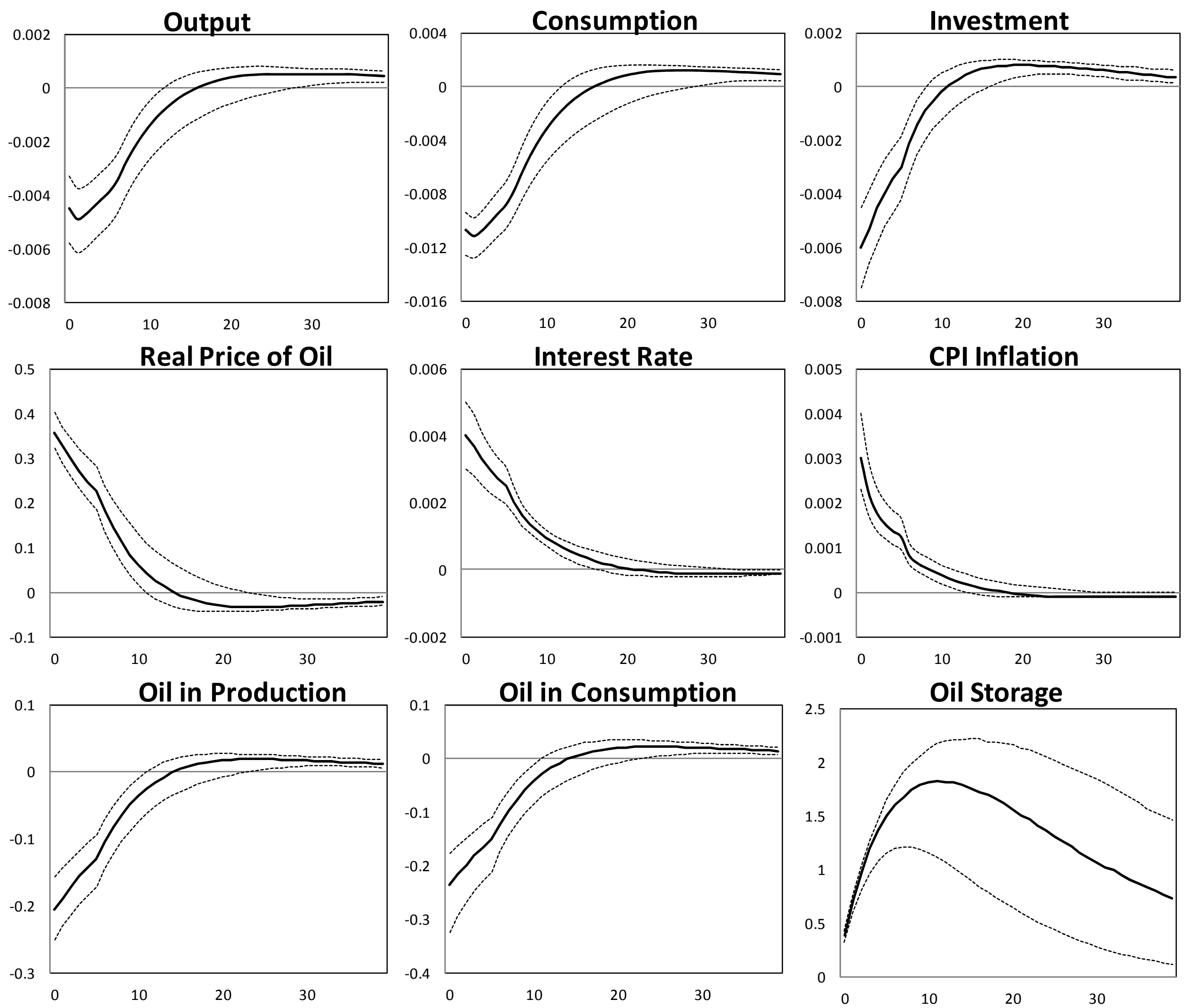

Figure 5. Impulse responses to a one standard deviation positive TFP shock with and without storage

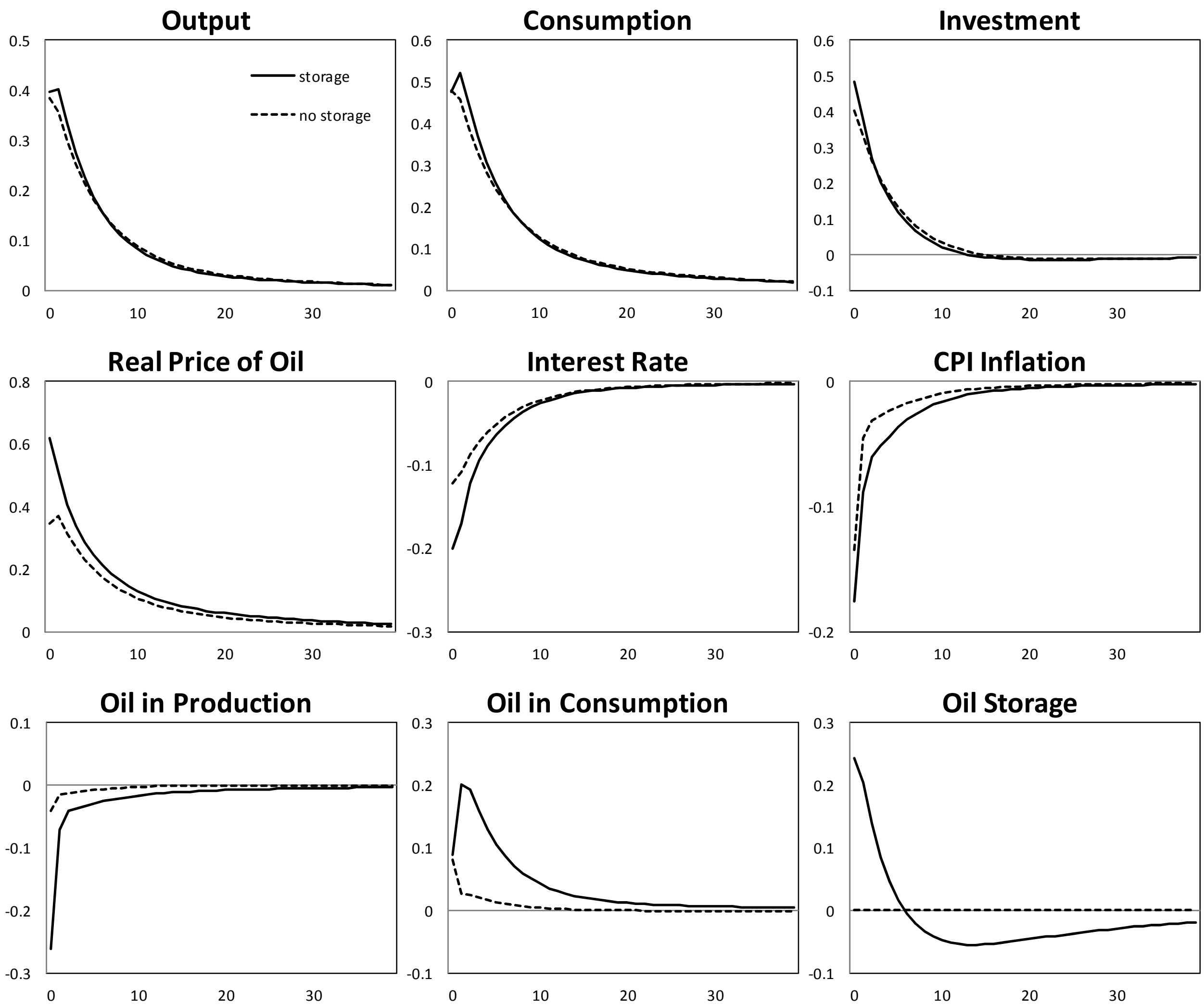

Figure 6. Impulse responses to a one standard deviation positive labor productivity shock with and without storage

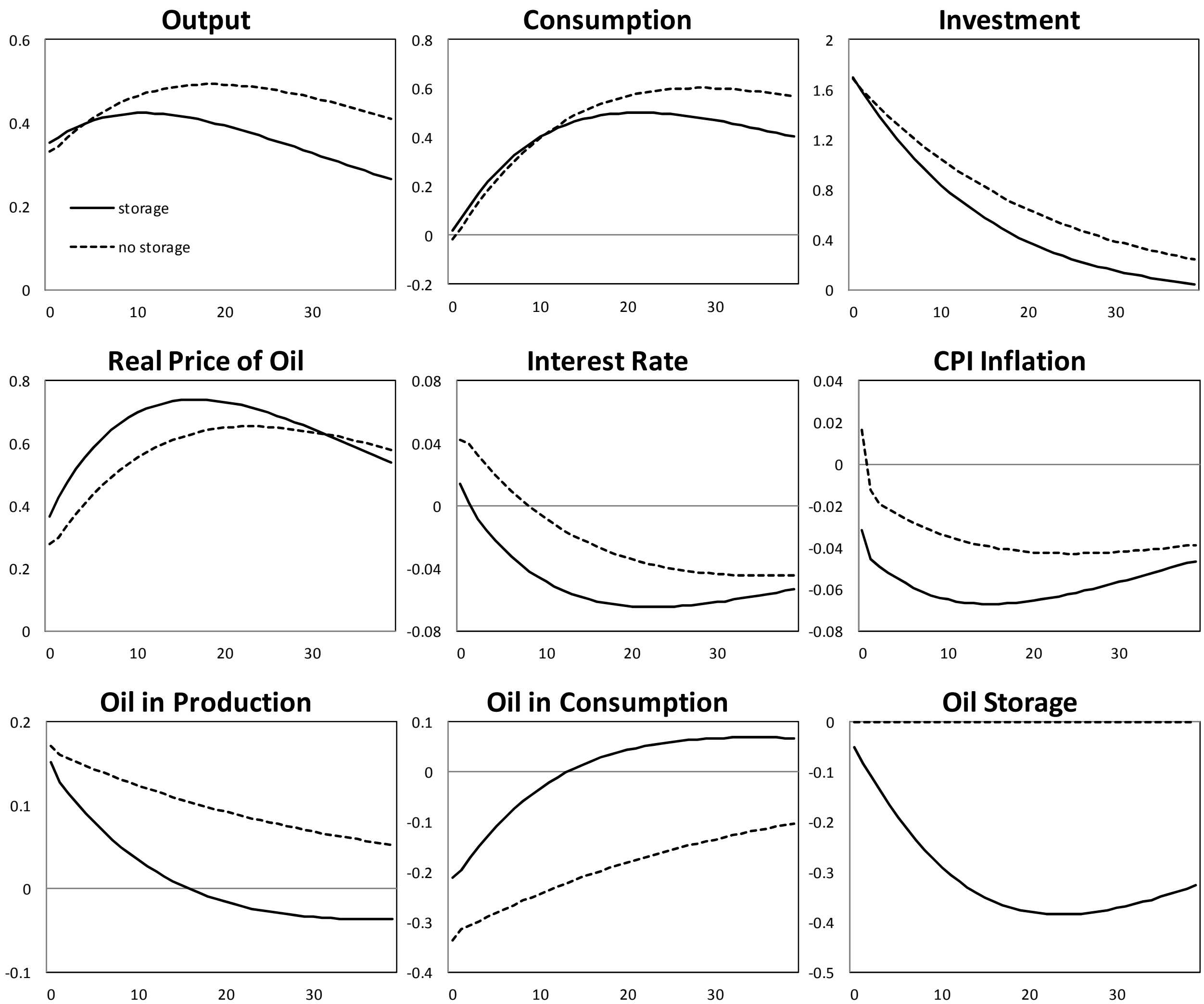

Figure 7. Impulse responses to a one standard deviation negative oil supply shock with and without storage