On the Sources and Consequences of Oil Price Shocks: The Role of Storage[*]

Deren Unalmis[†] Ibrahim Unalmis[‡] D. Filiz Unsal[§]

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Abstract

Kilian (2009, AER) focuses on three main sources of oil price fluctuations: oil supply shocks, global aggregate demand shocks and precautionary or speculative demand shocks. He empirically documents the distinct effects of these shocks on the global economy. Using an estimated DSGE model for the U.S. economy, we show that similar results can be obtained. Incorporating (speculative) competitive oil storage to the model enables us to formally analyze the impact of a storage demand shock, and also to assess how the effects of various demand and supply shocks change in the presence of oil storage facility. We find that productivity shocks are the most important drivers of oil price fluctuations during 1982-2007, but the storage demand shock has played a role as well. Moreover, 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 suggest a change in the composition of shocks, which can help explain the resilience of macroeconomic environment to oil price hikes in 2000s. Finally, speculative storage is shown to have a mitigating or amplifying role depending on the nature of the shock.

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

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[†] 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, Istiklal Caddesi No.10, 06100-Ulus Ankara, Turkey. Email: Ibrahim.Unalmis@tcmb.gov.tr

[§] Research Department, International Monetary Fund, 700 19th Stret, N.W. Washington, D.C. 20431, USA. E-mail:dunsal@imf.org.

1 Introduction

The belief that the stagflation in the 1970s had been brought by the increase in the real price of oil motivated a large body of research as to why oil price shocks have such a dramatic impact on the economy. Hamilton (1983) argues that most U.S. postwar recessions are caused by oil price increases. Bernanke et al. (1997) challenge this view, arguing that postwar recessions were brought by endogenous tightening of monetary policy to accelerating inflation induced by oil price increases, rather than by the oil price increases per se. On the other hand, Kilian and Lewis (2011) find no credible evidence that monetary policy responses to oil price shocks caused large aggregate fluctuations in those years. According to Barsky and Kilian (2002), stagflation in 1970s had deeper roots. They argue that worldwide shifts in monetary policy regimes at the beginning of 1970s, which were not related to the oil market, were the main source of the stagflation. They indicate that the rise in global liquidity drove the general price levels upwards, in response to which monetary policy makers raised interest rates. When these coincided with the oil supply shock, stagflation was inevitable. In addition to the ones discussed above, many studies in the literature examine the role of monetary policy and inflation dynamics in the wake of an oil price shock.[1]

The last oil price run up, observed between the end of 2002 and the mid 2008, has brought a shift in the focus in the literature. In contrast to what happed in 1970s, inflation remained low and growth has been high and stable around the world in 2000s. Consequently, reasons behind the resilience of the world economy to sustained oil price increases attracted great attention from academics, analysts and politicians. A notable study in this line of research is Blanchard and Gali (2010), who argue that oil price shocks have recently had less impact on the U.S. economy because of more flexible labor markets and lower oil intensity in production.

Recently more attention has been paid to the origins of oil price shocks. Frankel (2008) argues that low interest rates set by the Federal Reserve were the main drivers of the rising commodity prices in the 1970s, and again in

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[1] Some notable examples are Leduc and Sill (2004), Carlstrom and Fuerst (2006), Herrera and Pesavento (2009), Nakov and Pescatori (2010).

2000s. This is because low interest rates weaken the value of the U.S. Dollar, reduce the cost of holding inventories and curbs incentive to extract resources today. Supporters of this view argue that some Asian countries which implicitly peg their currency to the U.S. dollar forced by the Federal Reserve policies to keep interest rates low. This resulted in overheating in these economies and led to excess demand for oil and other commodities. However, Erceg et al. (2011) test this view using a multi-country SIGMA model but find no evidence to support it.

One important finding of the literature focusing on the sources of oil price fluctuations is that the macroeconomic impact of oil price fluctuations varies depending considerably on the origin of the shock. Among the most influential studies that examine various sources of oil price changes and their distinct effects, Kilian (2009a) argues that there are three main sources of oil price fluctuations: shocks to the production of crude oil ("oil supply shocks"), shocks to the global demand for all industrial commodities including crude oil ("aggregate demand shocks"), and shocks to precautionary or speculative demand for crude oil that reflects shifts in expectations about future oil supply shortfalls.[2] Using a structural VAR model, Kilian (2009a) shows that the recent commodity price increases were driven by repeated positive shocks to the demand for industrial commodities, including crude oil. Kilian (2009a) and Kilian and Hicks (2009) documented that oil price increases during 2000s were mainly caused by the fast economic growth in emerging Asia, such as China and India, where much of the unexpected demand for industrial commodities has occurred.

Relatedly, there has been increased interest in exploring the role of expectations in oil price fluctuations. Due to the forward-looking nature of the price of oil, expectations of an oil supply shortfall can lead to a precautionary demand for oil. Kilian (2008a, 2009a), Kilian and Murphy (2010), and Kilian (2010) documented that expectations driven demand shocks are important determinants of oil price fluctuations in certain periods. Kilian and Murphy

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[2] Guerrieri (2005) is the first paper to study the impact of different sources of oil price changes on economic activity. See also Baumeister and Peersman (2009), Dvir and Rogoff (2009), Kilian and Park (2009), Kilian et al. (2009), Lippi and Nobili (2009), and Unalmis et al. (2009).

(2010) found that there is a significant evidence on expectations driven oil price fluctuations in 1979, 1986 and 1990, but this is not the case for the oil price run-up between 2003-2008.

The recent proliferation of research on the oil price movements, however, has missed an adequate reference to the role played by oil inventories (notable exceptions are Alquist and Kilian, 2010 and Kilian and Murphy, 2010) in creating expectations driven oil price fluctuations. In markets for storable commodities such as oil, dynamics of (speculative) storage can be an important factor in influencing the short run dynamics of price as established by theory of optimal storage á la Williams and Wright (1982, 1984,1991), and Deaton and Laroque (1992, 1994).[3] In this paper, we propose a novel way of incorporating oil storage into a DSGE model. We assume 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 shocks studied in Kilian (2009a) and Kilian and Murphy (2010); namely, a decrease in the crude oil production, an increase in aggregate demand for commodities and the speculative storage demand shock. Our paper enriches the related literature in three dimensions. First, (speculative) oil storage introduces a dynamic link among oil inventories, storers' expectations of oil price and the spot price. We refer exogenous disturbances to oil stocks as storage demand shocks.[4] In our set-up, when there is a positive storage demand shock, storage increases, availability of oil decreases, and the price of oil goes up. Second, incorporat-

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

[4] Kilian (2009a) and Kilian and Park (2009) argue that oil price movements that can not be explained by either shocks to supply or demand should be considered as precautionary demand shocks. The endogenous response of oil storage in our model is also separate from the direct effects of the shocks, but it responds to the expected mean price, rather than its expected volatility as in precautionary demand case. Kilian and Murphy (2010) highlight that precautionary demand shocks represent only an example of a speculative demand shock. See Alquist and Kilian (2010) for a formal study of precautionary demand shocks.

ing 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, 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.[5] As we explore later, this feature may help to account for increased volatility of oil price in certain periods, and is consistent with the empirical evidence presented in Kilian and Murphy (2010). Third, building up on the insights provided by Kilian (2009a), we show that origins of oil price fluctuations matter for the transmission of these fluctuations to the rest of the economy and their attendant consequences. Taking advantage of the general equilibrium approach, we highlight different transmission channels of several different oil price shocks.

We further take the model to data and estimate the model for the U.S. economy with Bayesian techniques for the period 1982-2007.[6] 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 changes, but storage demand shocks played a role as well, (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

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[5] Dvir and Rogoff (2009) is an exception. They show that under persistent growth shocks, storage could increase the volatility in commodity prices.

[6] We estimate the model also for the 2000-2007 period in which the macroeconomic resilience to the oil price hikes has been seen unprecedented, as discussed before.

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 (1999) 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 Medina and Soto (2005), An and Kang (2010) and Bodenstein et al. (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, 1994). 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 supply is assumed to follow an exogenous process.[7]

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[7] 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 produc-

The activity of the risk-neutral, profit-maximizing, competitive oil storer firms (speculators) is to carry forward oil as out-of-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.

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 expected present value of the period utility given by:

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

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:

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

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 $Z_t(j)$:

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tion. 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.

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

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:

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

Oil demand and non-oil consumption are given by:

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

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

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 $I_t(j)$. $D_{t+1}(j)$ 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:

$$\begin{aligned} & P_tC_t(j) + P_tI_t(j) + E\left\{Q_{t,t+1}D_{t+1}(j)\right\} \\ \leq\ & D_t(j) + W_tN_t(j) + R_t^K K_t(j) + \Pi_t(j) + T_t(j) \end{aligned} \tag{7}$$

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. Let $R_t = 1/E_t(Q_{t,t+1})$ 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

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

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:

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

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:

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

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:

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

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

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:

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

The CPI inflation 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:

$$r_t = \phi_r r_{t-1} + (1-\phi_r)\phi_\pi \pi_t + (1-\phi_r)\phi_x y_t \tag{18}$$

where $\phi_r \in [0,1]$ is interest rate smoothing parameter,π_t and y_t are (log-linearized) 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:

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

2.5 Storage and Oil Market Equilibrium

2.5.1 Oil Storage

Oil storage takes the form of holding out of ground oil inventories. There is a continuum of competitive oil storers, *competitive speculators*, indexed by $z \in [0,1]$ 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" z from storing $S_t(z)$ is the difference between revenue in period $t+1$ and the cost of purchasing $S_t(z)$ in the spot market in period t while covering the storage costs. Oil storers seek to maximize their expected profit which is:

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

where $\Upsilon(S_t(z)) = \kappa + \frac{\Psi}{2}S_t(z)$ 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).[8] We denote $(1-a)$ as the "waste".

As each storer share the same rational expectations with other storers, there is no need for storer specific index z. 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.[9] 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 form storage equal to the marginal costs.

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 $\Theta = \frac{a\beta}{\Psi \overline{S}}$ and the storage demand shock (sd_t) is assumed to follow a

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[8] 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 Gibson and Schwartz (1990). More recently, Alquist and Kilian (2010) also adopt this modelling device.

[9] 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.

stationary stochastic process. According to Equation (25), the 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 i.i.d. shocks.[10] The process for the (log) oil supply ($o_{s,t}$) is defined by a stationary AR(1) process. 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:

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

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 oil prices drive up. In fact, using the cost minimization condition for firms 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.[11] First, the dynamics of the model are obtained by taking a log-linear approximation of equilibrium conditions around the steady state.[12] 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 can not be directly simulated, we use Monte Carlo Markov Chain methods which approximate the generation of random variables from

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[10] 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.

[11] 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.

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

the posterior distribution, after finding the parameters that maximize the posterior density using an optimization routine.[13]

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 eliminate the non-linearites caused by the zero lower bound on the federal funds rate, as in Gali et al. (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 num-

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

ber 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 et al. (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 et al. (2011). We assume that some, but very small part, of the oil is wasted during the storage process, hence we set $1 - a = 0.01$.[14] The steady state ratio of total oil stocks to the quarterly oil supply is calculated using U.S. data as 0.61.[15]

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.[16]

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

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[14] 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.

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

[16] 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 model without 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.

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 et al. (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.[17]

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

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[17] 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.

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 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 shocks 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. 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 oil storage growth volatility, 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 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 emprical 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 as it will be explained later in the impulse response analysis. We also find that in 2000s the role of oil supply shocks decreased, further confirming results of Kilian (2009a). The role of the storage demand shock 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.[18] 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

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[18] As explained in Footnote 4, our emprical results on the role of speculative demand shock are not directly comparable with Kilian (2009a)'s results on the role of precautionary demand shock.

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 productivity shocks, the oil supply shock and the storage demand shock. In total, 86 percent of the total variation in the real oil price is explained by these four shocks in the short run and 98 percent is explained by these shocks in the long run. Therefore, we focus on three causes of oil price increases: a positive oil demand shock (either through an increase in TFP or an increase in labor productivity), a negative oil supply shock, and a storage demand shock. In the impulse responses plotted in Figures 1-4, the bold line is the mean response and the bands around this line represent the 90 percent confidence intervals.

Total Factor Productivity Shock and Labor Productivity Shock 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 oil demand and hence an increase in the real oil price. Due to more productive factors of production, rising oil prices lead to substitution between oil and other factors of production. Hence, oil usage in production declines. However, oil usage in consumption increases because of the positive income effect. At the same time, higher technology implies lower marginal cost of production which leads to lower prices. As a result, an increase in output growth is accompanied by lower consumer price inflation, but higher oil prices.

One of the striking results in this experiment is the positive response of the storage demand to a TFP shock. This response is mainly due to expectations about higher future oil prices. The effect of the storage demand on the economy is not outlined here, since this issue will be analyzed in detail in the next section.

Figure 2 reports the impulse responses in case of a positive one standard deviation of the labor productivity shock. The initial increase in the real price of oil is less than in the case of a TFP shock. However, the initial increase in output is similar in both cases. Therefore, income effect dominates here. An increase in labor efficiency leads to higher oil demand due to higher production. Hence, in contrast to the TFP shock, oil used in production increases and oil storage decreases. The need for more oil in production leads to lower oil usage in consumption. Similar to the case above, output, consumption and investment increase and interest rate and inflation decrease. Labor productivity shock leads to more persistent effects on the real price of oil and other variables.

This exercise reveals an important result: 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.

Oil Supply Shock We present the responses to a negative one standard deviation shock to the oil supply which leads to a jump in the real oil price. Figure 3 shows the results. A decline in the oil availability decreases both the oil used in production and the oil used in consumption, since the decrease in the oil storage is not enough to compensate for the decline in the oil supply. Compared to the productivity shocks, the effects of the oil supply shock on the other macroeconomic variables are relatively smaller in magnitude. An increase in the oil price pushes up the CPI above the steady state level due to the rising marginal cost of production.

Storage Demand Shock We model storage demand shock as an exogenous change in the storage demand of the competitive storers. As these speculators increase their storage demand, the total oil availability decreases. This brings an increase in the price of oil, as shown in Figure 4. The rest of the transmission of the shock to the economy works in a similar manner as in the oil supply shock, but the interaction of storage with the interest rate (opportunity cost of storage) in the economy is different under two scenarios. Moreover, the persistency of the storage demand shock is less than the oil supply shock.

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 oil storage in the transmission of oil price shocks. The results are presented in Figures 5-7. The presence of oil storage makes the real price of oil more sensitive to a TFP shock (Figure 5). The reason is that, oil storage creates an additional demand for oil leading to even higher oil price increases compared to the case without storage. Under this scenario, an increase in oil storage amplifies the responses of all variables to a TFP shock. After a labor productivity shock, the presence of speculative storers makes output, consumption, investment, oil in production and oil in consumption less volatile, but makes the real price of oil, the interest rate and inflation more volatile (Figure 6). In case of an oil supply shock, however, the availability of oil storage makes the responses of the output, consumption, investment and real price of oil notably smaller compared to the case with no storage (Figure 7).

This is 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 led to a surge of studies in the literature that examine the causes and effects of oil price shocks. However, in context of the recent theoretical models that examine the issue, the role of (speculative) oil storage on the oil price movements has been generally neglected. In other words, effects of oil price changes are mostly investigated by assuming that oil supply is always equal to the oil demand. We show that incorporating (speculative) oil storage into a general equilibrium framework introduces a dynamic link among oil inventories, storers' expectations of oil price and the spot price. This set up also allows us to study the impact of a storage demand shock, which decreases availability of oil in place, and therefore increases the oil price.

Using our framework, we investigate the origins and macroeconomic consequences of several shocks which cause oil price fluctuations. Namely, we consider a total productivity shock, a labor productivity shock, a government spending shock, a monetary policy shock, an oil supply shock and a storage demand shock. To offer more quantitative answers to the issues addressed in the paper, we estimate the model for the U.S. economy with Bayesian methods, and identify the relative role played by these shocks in deriving oil price fluctuations for the period 1982-2007 as well as a recent subsample: 2000-2007.

Our estimates indicate that despite total factor productivity shocks and labor productivity shocks are the most important drivers of changes in oil prices, storage demand shock has also played a role. Importantly, when storage facility is omitted, the estimated contribution of oil supply shocks to oil price fluctuations amplifies considerably, in particular for 2000s. This indicates that studies that do not consider storage demand shocks could estimate the role played by oil supply shocks with a sizeable upward bias.

Another important finding is that in 2000s, the contribution of productivity shocks in driving oil price fluctuations 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 smooths or intensifies the fluctuations in oil prices 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).

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 H. Kang, 2011. Oil Shocks in a DSGE Model for the Korean Economy, Chapter in NBER book on Commodity Prices and Markets, Volume 20 (2011), Takatoshi Ito and Andrew K. Rose, editors, 295-321.

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

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

[5] Barsky, R. B. and L. Kilian, 2002. Do We Really Know that Oil Caused the Great Stagflation? A Monetary Alternative, in: *NBER Macroeconomics Annual 2001*, B.S. Bernanke and K. Rogoff (eds.), MIT Press: Cambridge, MA, 137-183.

[6] Baumeister, C., and G. Peersman, 2008. Time-Varying Effects of Oil Supply Shocks on the U.S. Economy, mimeo, Ghent University.

[7] Baumeister, C., and G. Peersman, 2009. Sources of the Volatility Puzzle in the Crude Oil Market, mimeo, Ghent University.

[8] Bernanke, B. S., M. Gertler, and M. Watson, 1997. Systematic Monetary Policy and the Effects of Oil Price Shocks, *Brookings Papers on Economic Activity*, 1, 91-142.

[9] Blanchard, O. J. and J. Gali, 2010. The Macroeconomic Effects of Oil Price Shocks: Why are the 2000s so Different from the 1970s? In J. Galí and M. Gertler (eds.), *International Dimensions of Monetary Policy.* University of Chicago Press.

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

[11] 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.

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

[13] Carlstrom, C.T., and T.S. Fuerst, 2006. Oil Prices, Monetary Policy, and Counterfactual Experiments, *Journal of Money, Credit and Banking*, 38, 1945-1958.

[14] 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.

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

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

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

[18] Erceg, C., L. Guerrieri and S.B. Kamin, 2011. Did Easy Money in the Dollar Bloc Fuel the Oil Price Run-Up?, *International Journal of Central Banking*, 7/1, 131-160.

[19] Frankel, J., 2008. An Explanation for Soaring Commodity Prices, Available at http://www.voxeu.org.

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

[21] Gali, J., J. D. Lopez-Salido, and L. J. Valles, 2007. Understanding the Effects of Government Spending on Consumption, *Journal of the European Economic Association*, Vol. 5(1), 227-270.

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

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

[24] Guerrieri, L., 2005. "The Effects of Oil Shocks on the Global Economy." Unpublished manuscript, Federal Reserve Board, 2005.

[25] Hamilton, J. D., 1983. Oil and the Macroeconomy Since World War II, *Journal of Political Economy*, 91(2), 228–248.

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

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

[28] Kilian, L., 2008a. Exogenous Oil Supply Shocks: How Big Are They and How Much Do They Matter for the U.S. Economy?, *Review of Economics and Statistics,* 90(2), 216-240.

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

[30] 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.

[31] 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.

[32] Kilian, L., 2010. Oil Price Shocks, Monetary Policy and Stagflation, RBA Annual Conference Volume, in: Renee Fry&Callum Jones&Christopher Kent (eds), Inflation in an Era of Relative Price Shocks, Reserve Bank of Australia.

[33] Kilian, L. and B. Hicks, 2009. Did Unexpectedly Strong Economic Growth Cause the Oil Price Shock of 2003-2008, *CEPR Discussion Paper*, No. 7265.

[34] Kilian, L., and L.T. Lewis, 2011. Does the Fed Respond to Oil Price Shocks?, *The Economic Journal,* 121 (555), 1047-1072.

[35] 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.

[36] 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.

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

[38] Leduc, S. and K. Sill, 2004. A Quantitative Analysis of Oil-Price Shocks, Systematic Monetary Policy, and Economic Downturns, *Journal of Monetary Economics,* 51, 781-808.

[39] Lippi, F. and A. Nobili, 2009. Oil and the Macroeconomy: A Quantitative Structural Analysis, Temi di discussione (Economic working papers) 704, Bank of Italy, Economic Research Department.

[40] 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.

[41] 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.

[42] Medina, J.P. and C. Soto, 2005. Oil Shocks and Monetary Policy in an Estimated DSGE Model for a Small Open Economy, Central Bank of Chile Working Paper, No.353.

[43] Nakov, A. and A. Pescatori, 2010. Oil and the Great Moderation. *The Economic Journal,* 120: 131–156.

[44] 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.

[45] Raurich, X. Sala, H. 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.

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

[47] 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.

[48] Scheinkaman, J.A. and L. Weiss, 1983. A Simple Competitive Model with Production and Storage, *Review of Economic Studies*, 50(3), 427-441.

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

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

[51] 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.

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

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

Appendix: Equilibrium Conditions

Household's maximization of (1) subject to (7) and (8) yields the following (log-linearized) optimality conditions:

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

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

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

where $\rho=-\log\beta$, $\log R_t=\log(1+r_t)\approx r_t$ is the nominal interest rate and $\pi_{t+1}=p_{t+1}-p_t$ is the (log) 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 $R^K_tK_t+W_tN_t+P_{o,t}O_{y,t}$ subject to (12). Log-linearized F.O.C.s are as follows:

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

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

where $\widehat{r}^k_t=r^k_t-p_{z,t}$ is the real rental rate of capital, $\widehat{w}_t=w_t-p_t$ is the real wage, and $pr_{z,t}=p_{z,t}-p_t$ 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 $z_t = c_t - w_{oc}\rho_c(pr_{z,t} - \widehat{p_{o,t}})$, $G_y = \overline{G}/\overline{Y}_z$ and $I_y = \overline{I}/\overline{Y}_z$ are the steady state shares of government spending and investment in output[19].

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:

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

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

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

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[19] Letters with a bar above indicate the steady state levels.

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

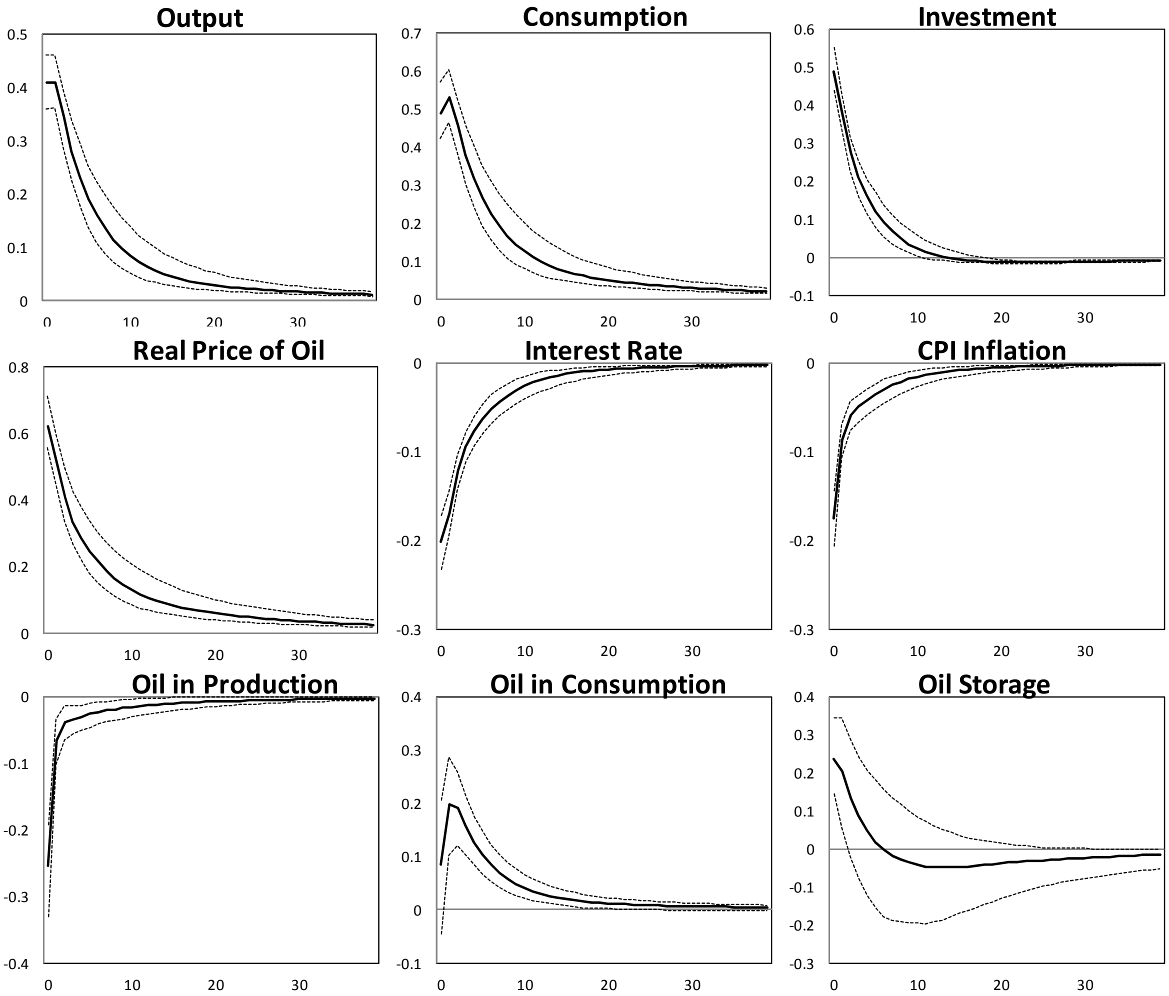

Figure 2. Impulse responses to a one standard deviation positive labor productivity shock

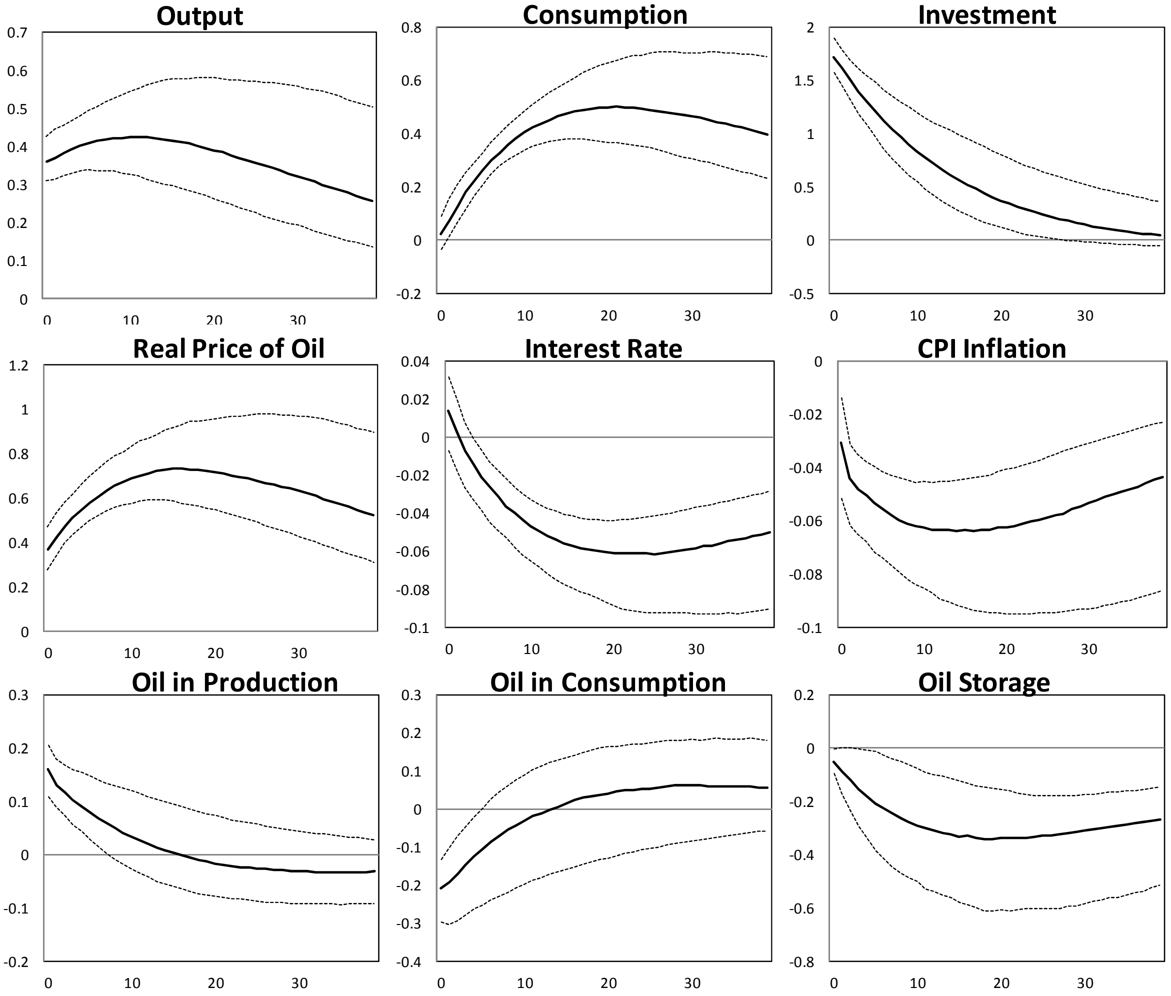

Figure 3. Impulse responses to a one standard deviation negative oil supply shock

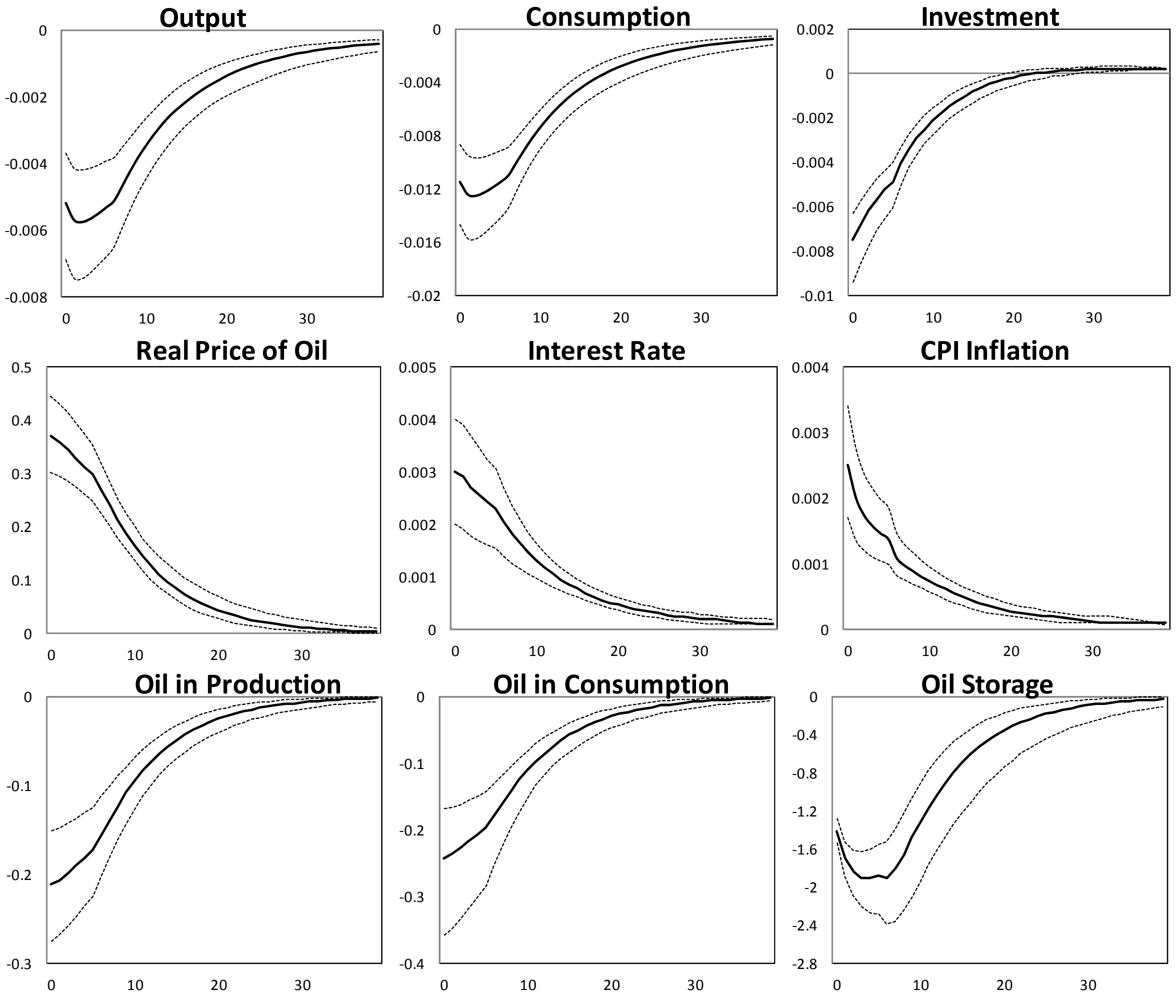

Figure 4. Impulse responses to a one standard deviation storage demand shock

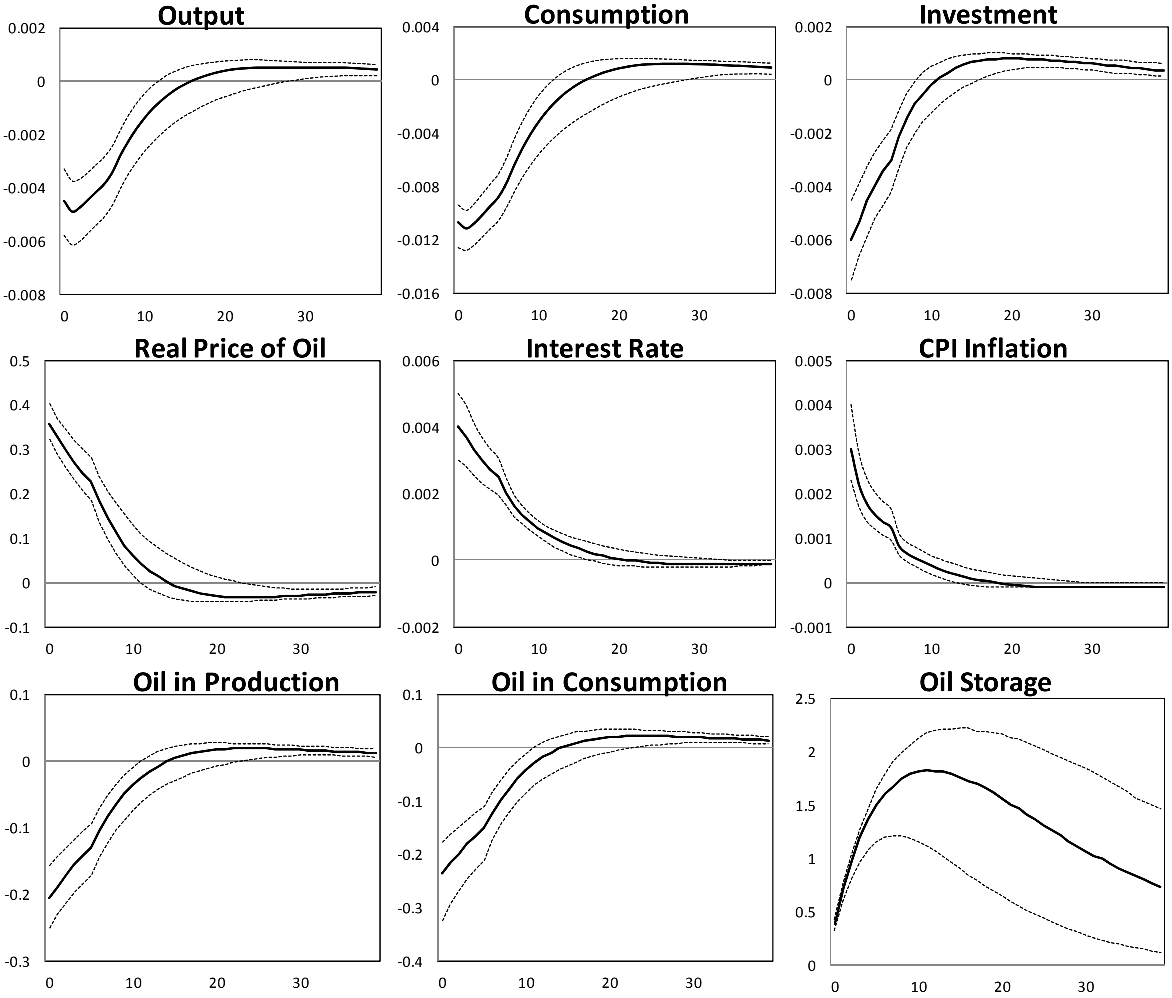

Figure 5. Impulse responses to a one standard deviation positive TFP shock with and without storage

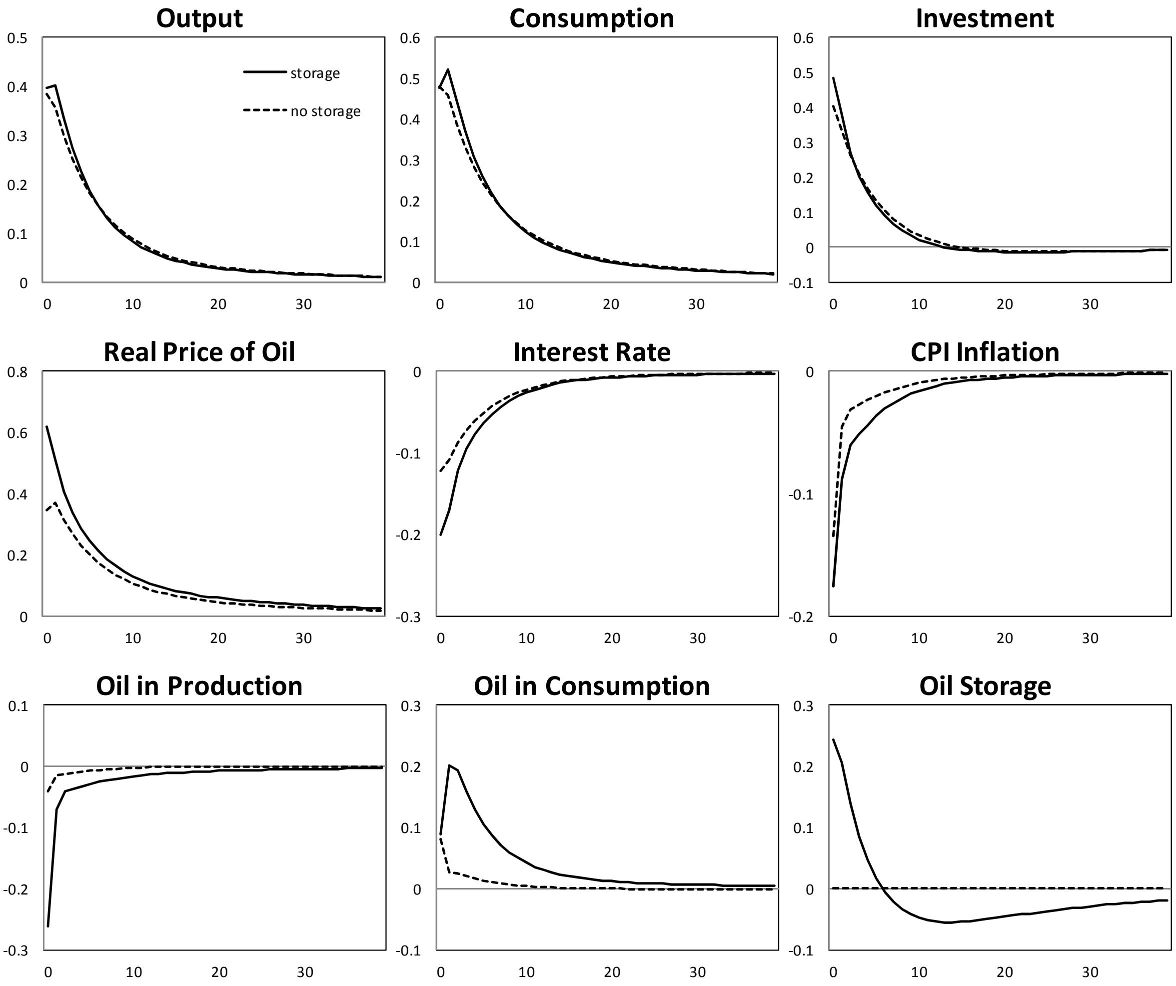

Figure 6. Impulse responses to a one standard deviation positive labor productivity shock with and without storage

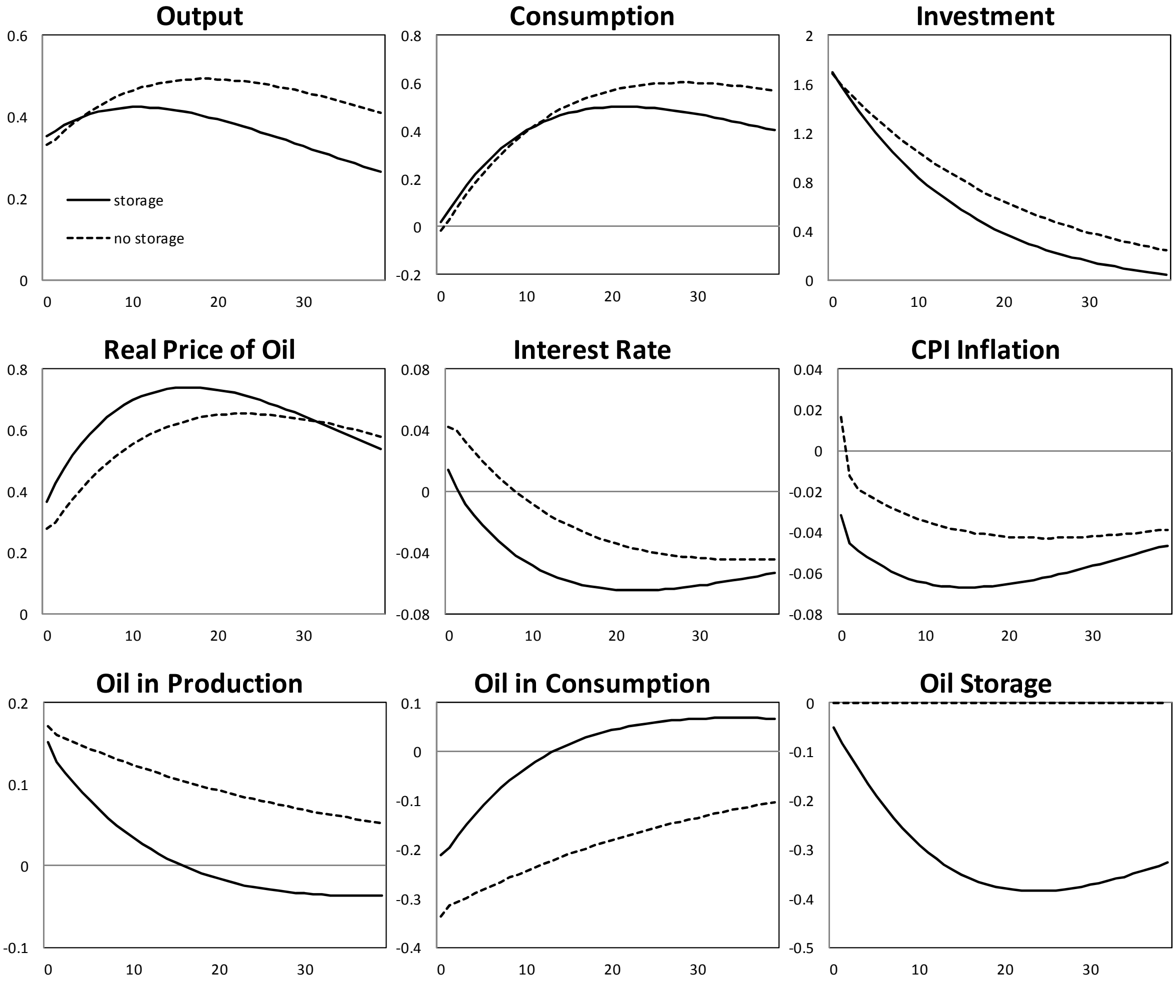

Figure 7. Impulse responses to a one standard deviation negative oil supply shock with and without storage