Oil Price Shocks and Macroeconomy: The Role for Precautionary Demand and Storage

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1 December 2011

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October 12, 2012

Abstract

Traditional literature on energy economics gives a central role to exogenous political events (supply shocks) or to global economic growth (aggregate demand shock) in modeling the oil market. However, more recent literature claims that the increased precautionary demand for oil triggered by increased uncertainty about a future oil supply shortfall is also driving the price of oil. The intuition behind the precautionary demand is that since firms, using oil as an input in their production process, are concerned about the future oil prices, it is reasonable to think that in the case of uncertainty about future oil supply (such as a highly expected war in the Middle East), they will buy futures and/or forward contracts to guarantee a future price and quantity. We find that under baseline Taylor-type interest rate rule, real oil price, inflation and output loss overshoot and go down below steady state at the next period if uncertainties are not realized. However, if the shock is realized, i.e. followed by an actual supply shock, the effect on inflation and output loss is high and persistent.

JEL Codes: E52, E32, D53, Q43

Keywords: oil price shocks, precautionary demand, oil and finance, monetary policy

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I am grateful to Ted Temzelides, Peter Hartley, Borghan Narajabad, Kenneth Medlock and Ron Alquist for their feedback and suggestions. I also thank Ibrahim Ergen, Burcu Cigerli, Bela Szemely, the participants of 4^{th} Energy & Finance Conference, 34^{th} IAEE International Conference and 30^{th} USAEE North American Conference for their useful comments.

1 Introduction

The energy crisis of 1973-1974 coincided with one of the longest post-World War recessions. This gave rise to many studies on the effects of oil price increases on the economy. A large number of studies tried to establish theoretical links and document empirical evidence in support of the idea that oil prices were responsible for the recessions, episodes of inflation, the reduced productivity and declining economic growth. In fact, Figure 1 shows that 9 of the 10 recessions in the United States were preceded by a sharp rise in the price of oil.

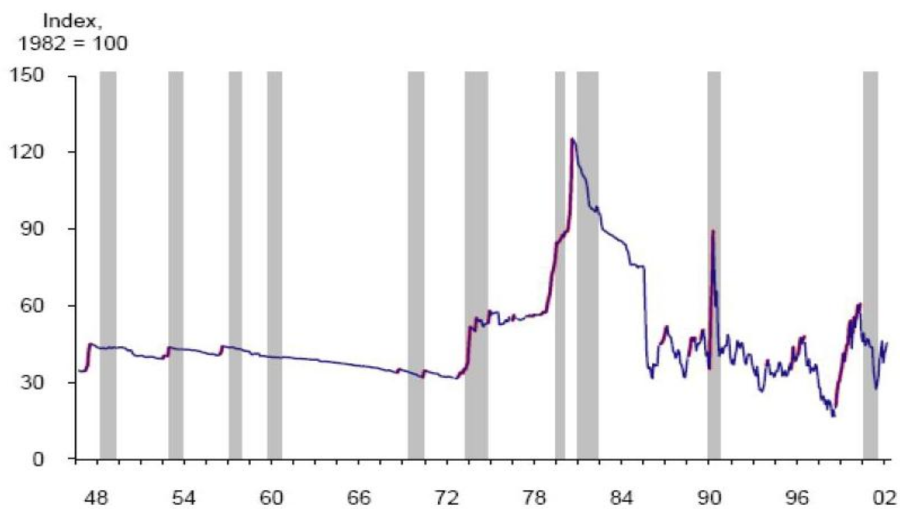

Figure 1: Real oil prices and US recessions

However, closer examination of this influence reveals that the economy does not respond in the same way to oil price movements. To be precise, since the late 1990s, the global economy has experienced two oil shocks of sign and magnitude comparable to those of the 1970s, but, in contrast with the previous episodes, GDP growth and inflation have remained relatively stable in much of the industrialized world. In order to explain this difference, the energy economics literature mainly takes two approaches. The first approach claims that the oil price shocks themselves were never important factors behind those macreconomic downfalls, their effects were rather exaggerated. In other words, according to some researchers (Bernanke et al. (1997), Wei (2003), Dhawan and Kerske (2006)) oil prices themselves are not the creators, but just the marginal contributors to those recessions. A second approach focuses on the nature of these shocks and challenges the notion that at least the major oil movements can be viewed as exogenous with respect to the U.S. economy (Barsky and Kilian (2002), Blanchard and Gali (2007)).

This paper tries to explain the factors behind the change in the nature of oil price shocks and their effects on the economic activity. The traditional literature on energy economics gives a central role to exogenous political events in modeling the oil prices. However, more recent studies (Barsky and Kilian (2002), Kilian (2009), Blanchard and Gali (2007), Campolmi (2007)) take a different stand and provide arguments in favor of reverse causality from macroeconomic variables to oil prices. Besides, all these papers draw attention to differences between oil prices shocks and their macroeconomic implications in 70s and 2000s. The main conclusion of those papers were that oil price shocks were caused by supply disruptions in 70s and aggregate demand shocks in 2000s.

Kilian (2009), on the other hand, constructs a structural VAR model of the global crude oil market and concludes that oil price shocks have been driven mainly by a combination of global aggregate demand shocks and precautionary demand shocks, rather than simple oil disruptions caused by exogenous events in Middle East. He claims that while exogenous political events do affect oil prices, especially in 90s, it is less the physical supply disruptions than the increased precautionary demand for oil triggered by increased uncertainty about future oil supply shortfall is driving price of oil.

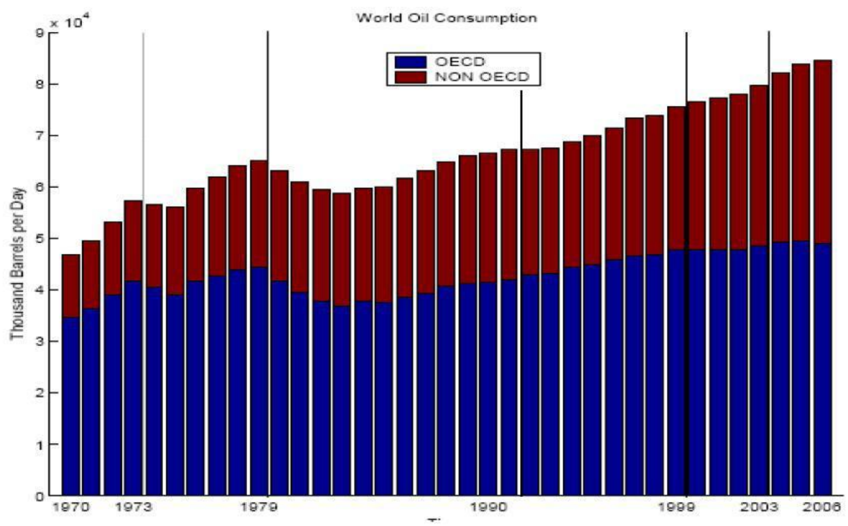

Figure 2: World oil consumption (yearly average)

According to the energy economics literature (Kim and Loungani (1992), Hamilton and Herrera (2004)), oil price movements in 1973 and 1991 were caused by oil supply disruptions during exogenous events in the Middle East (OPEC embargo and Iraq-Kuwait war, respectively). However, as it is shown in Figure 2, yearly average world oil consumption was increasing in the aftermath of 1991, while decreasing during the 1973-75 (OPEC embargo), which means that supply cut argument is not valid for the 1991 oil price shock. Therefore, Kilian(2009) claims that the latter is caused by the precautionary demand motive of the firms using the oil as an input in their production. This motive is usually triggered by a concern about a future oil supply distruption (for example, a highly expected war in the

Middle East).

Based on this motivation, I build a theoretical model to quantify and examine the nature of oil price shocks caused by precautionary demand in the crude oil market. Then I simulate the effects of these demand shocks on the macroeconomic variables, such as GDP and inflation. In order to do that, I will construct a standard DSGE model with the sticky-prices where firms can have access to an oil futures market. In this model, there is also the storage operators, who buy the oil in the spot market and hedge it by selling the oil futures in the futures market.

It is intuitive to think that in the case of an increased uncertainty about future oil supply, the firms using oil as an input will buy futures and/or forwards contracts to guarantee a future price and quantity. Moreover, higher demand in the futures market would encourage the storage operators to increase their inventories and, thus, create scarcity in the spot market for oil. That, in turn, will induce the spot price of oil to increase immediately. This modification was first introduced by Alquist and Kilian (2010) to derive the immediate effect of an uncertainty about the future oil supply shortfalls on the real spot price of oil. They model the oil supply by a foreign country as an stochastic mean-preserving process. When there is a "news" today about the future availability of the oil, the variance of the oil endowment for tomorrow goes up permanently and creates an uncertainty shock. This setup allows us to separate the mean effect (supply shock) from the variance effect (uncertainty shock). Unlike Alquist and Kilian (2010) our model allows also for temporary increase in the uncertainty. Similarly, a "news" about the future availability of the oil supply creates an uncertainty in the market. However, if the concern of the agents are not realized (i.e. no supply shortfall), they will reasonably update their beliefs and become less and less concerned over time.

As another improvement on Alquist and Kilian (2010), we employ this extention in a standard cashless DSGE model with the sticky-prices (Woodford (2003)) to analyze the dynamics of macroeconomic variables when agitated by a future oil supply uncertainty. Since oil is used as an input in the production process, any surge in its price, caused by a future oil supply uncertainty or a current supply shortfall, will increase the production cost and lead to a "supply side" disturbance in the economy.

Recently, we became aware of related work by Unalmis, Unalmis and Unsal (2012). They have independently studied the role of storage as a source of oil price shock and examined its macroeconomic effects. Their setup is very similar to ours, however, they introduce speculative demand shock only that ignores precautionary demand motives affected by second-order through the volatlility in oil supply. Besides, unlike Unalmis, Unalmis and Unsal (2012), our step is suitable to study monetary policy implications of oil prices shocks in the presence of storage.

These findings also have important policy implications for thinking about the effects of oil price changes on the U.S. economy. Some recent literature suggests that although high oil prices contributed to recessions, they have never had a pivotal role in the creation of those economic downturns (Bernanke et al. (1997), Leduc and Sill (1995)). In this regard, tight monetary policy is often blamed to exaggerate the adverse effects of oil price shocks.

As different oil price shocks causing different dynamics in income and inflation variation, one has to consider the nature of the shock before any policy formuation to cope with those adverse effects.

We find that under baseline Taylor-type interest rate rule, real oil price overshoots together with inflation and output loss and goes down below steady state at the next period if uncertainties are not realized. However, if the shock is realized, i.e. followed by an actual supply shock, the effect on inflation and output loss is high and persistent. In this case, the existence of storage increases the variability of macroeconomic variables and real price of oil by transmitting future worries into today's decision making process.

The paper is organized as follows. Section 2 presents the model, Section 3 describes competitive equilibrium, market clearing conditions and aggregation. Section 4 discusses calibration and simulation results. Lastly, Section 5 concludes.

2 Literature Review

2.1 The Magnitude of the Oil Price Effect

Hamilton and Herrera (2004) and Hamilton (2005) point out that nine out of ten of the U.S. recessions since World War II and every recession since 1973 were preceded by a spike in oil prices. However, according to the Bureau of Economic Analysis and the Energy Information Administration, between 1970 and 2005, residential and commercial and industrial energy consumption was on average 4.8% and 4% of GDP, respectively. Based on this fact, change in oil prices can only explain a small fraction of the drop in GDP during a recession.

To solve this puzzle, Rotemberg and Woodford (1996) study output impulse response functions and show that under imperfect competition the effect of oil price shock is stronger under perfect competition. They estimate that a 1 percent innovation in energy prices lead declines in U.S. output of 0.25 percent and in U.S. real wages of 0.09 percent about five to six quarters later. Moreover, Finn (2000) shows that one can increase the response of an oil price shock even under perfect competition when one models energy use as a function of capacity utilization. She argues that an increase in the price of energy works as an adverse technology shock to induce a contraction in the economics activity and the magnitude of the force exerted by energy price shock derives from relationship between energy usage and capital services.

However, both papers are silent on the business cycle properties of the model in response to energy shocks. Precisely, they do not report the share of output fluctuations explained by energy price shocks and the other business cycle facts such as volatility of investment, consumption and co-movement of these variables. In fact, by incorporating energy use exclusively on the production side in DSGE models, Kim and Loungani (1992) claim that energy price fluctuations can only generate a small fraction of the output fluctuations observed in U.S. data. They even conclude that all previous recessions would have occurred even without energy shocks, since output is mainly driven by shocks to total factor productivity.

Besides, Dhawan and Jeske (2006) argue that introducing durable goods and household energy consumption actually decreases the relevance of energy price shock for output volatility, despite increasing total energy consumption in the economy. They find that household with two different investment decision (durable and fixed capital) decrease their fixed capital less than the stock of durables to balance their portfolio in response to an exogenous shock (TFP or energy). This leads to fixed capital drop less than in a Kim and Loungiani type economy and therefore explains why energy accounts for less output fluctuations in their model. To solve the controversy of low share in total expenditure, high share in output fluctuations, some studies claim that jump in energy prices make a substantial fraction of the capital stock obsolete.

Bailey (1981) argues that as a result of high energy prices, energy inefficient machines are shut down, and expected profits of machines in operation declines. The value of existing capital decreases as it is not technologically suited to new economic conditions. Besides, firms will not be willing to invest in new machines, unless the high prices period last for a long time. Therefore, this mechanism will lead to low level of stock market prices. Although this link was pronounced in the literature, only Wei (2003) analyzes the causal link between energy price shock and stock marker crush in a partial-equilibrium setup. In a partial-equilibrium putty-model, where the real wage and interest rates are fixed exogenously, she finds that an 80-percent permanent increase in the real energy price leads to a 10-percent decline in the market value of previously installed machines. This impact is even smaller (only 2-pecent decline) in a general-equilibrium putty-clay model, which is extreme case of rigidity in the adjustment of capital ex post. According to Wei (2003), the energy price increase causes real wage to decline by around 3.8 percent. The decline in the real wage is large enough to offset most of the increase in cost coming from capital side.

The intuition for the decline in real wages is that with ex post Leontief technology, labor cannot be reallocated to relatively efficient machines, which in turn reduces labor demand.On the labor side, we should observe lower consumption and lower leisure as the high energy prices generate wealth effect on the consumption behavior of the households. Lastly, the real wage has to decline to clear the labor market. Lastly, some authors have argue that stagflation of the 1970s were largely due to factors other than oil. Barsky and Kilian (2002) claim that stagflation may have been partly caused by exogenous changes in monetary policy, which coincided in time with the rise in oil prices. Bernanke, Gertler and Watson (1997) argue that much of the decline in output and employment was due to the rise in interest rates, resulting from the Feds endogenous response to the higher inflation induced by oil shocks.

2.2 What has changed lately?

Blanchard and Gali (2007) define an oil shock as an episode where the overall increase in oil price has been of more than 50% and has lasted for more than one year. Following this criteria four oil shocks are identified for the period 1970-2005. Despite the fact that these oil shocks are similar in magnitude, they have been associated with very different macroeconomic performances. While the first two episodes (1973:2-1974:1 and 1978:4-1980:2) of oil price increase coincide with an increase in all inflation variables and a decrease in GDP growth and real wage, the last two episode (1998:4-2000:4 and 2001:4-2005:3) coincide with a positive

GDP growth rate, an increasing real wage and low inflation. In the light of these evidences, Blanchard and Gali (2007) try to explain the difference between various oil shocks assuming that the source of the change in oil price is always the same, i.e. an exogenous increase in oil price. They consider differences in monetary policy, in the degree of wage rigidity and in the proportion of oil used in the production and show that a change in each of them can reduce the volatility of both prices and quantities in response to the same oil shock.

However, Kilian (2009), Yucel, Brown, Nathan(??) and Campolini (2007) challenge the idea that oil price shocks were alike, i.e. exogenous. They underline the importance of identifying supply vs. demand shocks to oil prices. Campolini (2007) and Yucel,Brown, Nathan(??) formulate the oil price shocks of 2000s as a persistent increase in foreign productivity, while in 70s there was, simply, a reduction in oil supply. It is intuitive to expect different sources of oil price increase to convey different dynamics. Namely, an exogenous reduction in the supply of oil followed by high oil prices will boost marginal costs and therefore deliver an increase in inflation. This scenario is consistent with the observed data of 70s, but cannot be applied to 2000s. An exogenous and persistent increase in productivity of foreign country (such as China) in a simple two-country model leads to an increase in foreign GDP. Given the increased production, a persistent shock will induce a higher oil demand and therefore drive the oil price up. The home economy will still experience higher oil prices because of reduction in oil supply. However, there will be a reduction in the price of the imported goods, as the foreign country is more productive now.As a result, CPI inflation in the home country may actually decrease, which will, in turn, generate an increase in real wages.

Lastly, richer foreign country will buy more home-produced goods, and therefore output in home country will also increase. Apparently, this story tells us that dynamics of oil price, inflation, real wages and GDP observed in 2000s is consistent with an increase in oil demand driven by an increase in productivity in countries like China and India.

On the other hand, Kilian (2010) takes this analysis further and claims that there is even third type of oil price shock. He provides a decomposition of real oil price into oil supply shock, shocks to the aggregate global demand for industrial commodities and demand shocks that are specific to the oil market (i.e. precautionary oil demand). Using this decomposition, he claims that, while the oil price increase in 70s is mainly due to precautionary demand increase, in the current increase a crucial role is played by aggregate demand shocks.

3 The Model

This study extends the standard cashless Dynamic New Keynesian model as in Woodford (2003) by adding an oil market. The are two countries in this model: an oil-importer and an oil-exporter. The oil-importing country uses oil as an input in the production of intermediate goods. Oil is supplied by the oil-exporting country, who recieves a random endowment in each period. The oil-exporting country uses oil income to purchase the final good produced by the final good producers in the oil-importing country.

3.1 The Oil-Importing Country

The oil-importing country consists of households, intermediate good producers, final good producers and storage operators. Oil is used in the production of intermediate goods, which are produced in a monopolistically competitive market. Oil is sold both at the spot and the futures market.

3.1.1 The Final Good Sector

Final good is produced under perfect competition using continuum of differentiated intermediate goods as inputs. The technology is defined by Dixit-Stiglitz aggregation formula,

$$Q_t = \left[\int_0^1 Q_t(i)^{\frac{\varepsilon-1}{\varepsilon}} \, di \right]^{\frac{\varepsilon}{\varepsilon-1}} \tag{1}$$

Profit-maximization and zero-profit condition for these firms implies that the demand for intermediate good $Q_t(i)$ and the aggregate price level P_t are

$$Q_t(i) = \left[\frac{P_t(i)}{P_t} \right]^{-\varepsilon} Q_t \tag{2}$$

$$P_t = \left[\int_0^1 P_t(i)^{1-\varepsilon} \, di \right]^{\frac{1}{1-\varepsilon}} \tag{3}$$

3.1.2 The Intermediate Good Sector

There is a continuum of firms producing different varieties of intermediate goods under monopolistic competition. These firms have monopoly power over their output prices, however, they compete for inputs on competitive factor markets. Therefore, they act as price takers on factor markets, including the oil market. Besides, since these firms are very small, they take aggregate variables as given. The production function for an intermediate good producer type of i takes the following Cobb-Douglas form:

$$Q_t(i) = A_t K_t(i)^{\alpha_k} L_t(i)^{\alpha_l} O_t(i)^{\alpha_o} \tag{4}$$

Intermediate good producers are exposed to a common techonological shock, A_t, which evolves exogenously according to $a_t = \eta_a a_{t-1} + \xi_{a,t}$, where $a_t \equiv \log A_t$ and $\xi_{a,t}$ is a white noise with zero mean and σ_a^2 variance.

Price Setting

Intermediate good producers operate in a monopolistically competitive market. I follow the literature on sticky-price models (Calvo(1983), Yun(1996)) and assume that although the firms have monopoly power over their own prices, they reset their prices only infrequently. At time t, only $1-\theta$ fraction of firms adjust their prices. The rest of the firms cannot adjust their prices and therefore set $P_t(i) = P_{t-1}(i)$.

A firm will maximize the expected discounted flow of future profits, if it gets a chance to change its price $P_t(i)$. The intermediate firm's problem in the goods market is as follows:

$$\max_{\tilde{P}_t(i)} E_t \ \Sigma_{k=0}^{\infty}(\theta)^k \Lambda_{t,t+k}[\tilde{P}_t(i)Q_{t+k}(i) - P_{t+k}mc_{t+k}Q_{t+k}(i)]$$

subject to downward-sloping demand function

$$Q_{t+k}(i) = \left(\frac{\tilde{P}_t(i)}{P_{t+k}}\right)^{-\varepsilon} Q_{t+k}$$

where $Q_{t+k}(i)$ is the demand for output produced by the firm i, and $\Lambda_{t,t+k}$ is the discount factor for the future nominal profits.

Futures Market:

Intermediate good producers also have an access to the financial markets. In order to avoid uncertainty about future supply and about the price of oil, they buy futures contracts (X_t) supplied by storage operators[1]. As I discuss in next section, there is no delivery in the futures market. Firms incur a profit (lost), if the price for futures fixed at t to be delivered at $t+1$ is less (higher) than the spot price of oil at $t+1$. The intermediate firm's problem in the futures market is:

$$\max_{X_t} \ E_0 \Sigma_{t=0}^{\infty}(\frac{1}{1+r_t})^t \Big[\frac{P_{t+1}^o}{P_{t+1}} - \frac{F_t}{P_{t+1}}\Big] X_t$$

[1]I state two different maximization problem for intermediate good producers: goods market and futures market. However, one may suggest to combine these problems. In other words, in addition to factor inputs, in each period firms can simultaneously choose the fraction of futures to be delivered, instead of settled by cash payment. In this case, firms will buy oil from the spot market if they need any in excess of the futures contracts provide them. However, I found out that the governing equations for this problem are the same as in maximazing two different problems.

3.1.3 Storage Operators

Storage operators buy oil at spot market to fill their inventories. I assume that the storage operators are risk-neutral, so all inventory is hedged by taking a long position in the oil futures market. This implies that at time t the storage operator promises to sell a certain amount of oil for F_t at time $t+1$. However, in the model there is no delivery, but only cash settlement. The operator sells all the inventory carried from previous period at the spot market ($P_t^o I_t$), settles the cash payments with the futures contract holders ($(F_{t-1} - P_t^o)I_t$), and chooses the amount of inventory for the next period (I_{t+1}). Besides, following the commodity pricing literature (Brennan (1991), Pyndick (1994, 2001)), we introduce the convenience yield, $g(I_t, \sigma^2)$, which refers to the flow of benefits to the inventory holders. These benefits arise from the fact that in the case of supply disruptions, the inventories can help to satisfy the demand in the market and smooth the production process. Therefore, the convenience yield is increasing in the level of inventories ($g_1(I_t, \sigma_t^2) > 0$)[2], but the marginal convenience yield of an additional inventory is decreasing ($g_{11}(I_t, \sigma_t^2) < 0$). Additionally, since higher uncertainty about the future oil supply (high σ_t^2) is more like to cause scarcity in the market, the marginal convenience yield is increasing ($g_{12}(I_t, \sigma_t^2) > 0$) in σ_t^2. Lastly, in order to ensure that the level of inventories is always positive, we assume that Inada condition $\lim_{I_t \to 0} \; g_1(I_t, \sigma_t^2) = \infty$ holds. The optimization problem for the storage operator

[2]We denote g_i as the derivative of g with respect to i^{th} term, where g_{ij} implies cross-sectional derivative of g with respect to i and j.

is:

$$\max_{I_{t+1}} E_0\Sigma_{t=0}^{\infty}(\frac{1}{1+r_t})^t\Big[\frac{F_{t-1}}{P_t}I_t - \frac{P_t^o}{P_t}I_{t+1} + g_t(I_{t+1},\sigma_{t+1})\Big] \tag{5}$$

The first-order condition for this problem yields the no-arbitrage condition for the storage market:

$$E_t\Big[\frac{1}{1+r_t}\frac{F_t}{P_{t+1}}\Big] = \frac{P_t^o}{P_t} - g_1(I_{t+1},\sigma_{t+1}) \tag{6}$$

3.1.4 Households

A representative household in the oil-importing country maximizes the following utility function:

$$E_0\ \Sigma_{t=0}^{\infty}\beta^t\Big[\log C_t - \frac{L_t^{1+\psi}}{1+\psi}\Big] \tag{7}$$

Households earn labor income $w_tP_tL_t$, invest in risk-free bonds B_{t+1}, collect rent $r_t^kP_t\bar{K}_t$ from intermediate good producers and dividends ${\Pi_t}^f$ for their ownership in the firms.[3]

$$P_tC_t + B_{t+1} = R_{t-1}B_t + w_tP_tL_t + P_tr_t^k\bar{K}_t + {\Pi_t}^f \tag{8}$$

Maximizing the utility function with respect to C_t, B_t and L_t will give us the following

[3]Note that the aggregate capital stock is fixed at $\bar{K}_t$. Since the effects of oil price shocks on macro variables last 4-5 quarters at most, it is plausible to assume that capital is fixed.

first-order conditions:

$$C_t {L_t}^{\psi} = w_t \tag{9}$$

$$\frac{1}{C_t} = \beta E_t \Big[\frac{1}{C_{t+1}} \frac{R_t P_t}{P_{t+1}} \Big] \tag{10}$$

Equation(9) and (10) jointly characterizes the household's decision rules for consumption, labor supply and bond holding.

3.2 Monetary Policy

We assume that the monetary authority in the oil-importing country follows a standard Taylor-type interest rate rule is similar to the one estimated by Clarida, Gali and Gertler (2000) to characterize the historical U.S. monetary policy. This policy sets the nominal interest rate for the risk-free bond to adjust output-inflation gap.

$$\hat{R}_t - \phi_R \hat{R}_{t-1} = (1 - \phi_R)\phi_\pi \pi_t + (1 - \phi_R)\phi_y \hat{y}_t \tag{11}$$

where $\hat{R}_t$ is the log deviation from steady-state nominal interest rate level ($\bar{R}$), $\pi_t = \log P_t/P_{t-1}$ and $\hat{y}_t$ is the log deviation of value-added from its steady state value. Since there is no cross-border borrowing, the value-added (GDP) in the oil-importing country will be

$$Y_t = C_t = Q_t - p_t^o \Omega_t \tag{12}$$

3.3 Oil-Exporting Country

The oil-exporting country is modelled as an endowment economy and acts as a price-taker in the spot market for oil. In each period, it receives a random oil endowment Ω_t. Oil revenues are used to buy consumption good produced in the oil-importing country.

In each period, the oil-exporting country acts as a price-taker in spot market for oil and uses revenues to buy consumption goods from final good procuders.

$$P_t C_t^F = P_t^o \Omega_t \tag{13}$$

In order to disentangle "news shock" from the mean shock, I assume that the percentage deviation of the stochastic oil endowment from its steady state ($\hat{\omega}_t \equiv ln(\Omega_t) - ln(\bar{\Omega})$) has the following property:

$$\hat{\omega}_{t+1} = \rho \hat{\omega}_t + \ \xi_{t+1} \tag{14}$$

$$\xi_{t+1} = u_t \varepsilon_{t+1} \tag{15}$$

$$u_t = \lambda u_{t-1} + \sigma_u \eta_t \tag{16}$$

To be more concise, if there is no "news", ($\eta_t = 0$), or in other words no uncertainty about the future availability of the oil supply, the oil endowment will be at steady-state level. On the other hand, if there is a "news shock" at time t ($\eta_t > 0$), the variance of the $\hat{\omega}_{t+1}$ will be positive. However, this does not neccesarily imply that the supply will be less at $t+1$, since there is a chance that the "news" will not be realized. In that case, agents will update their beliefs about the future (scale by $\lambda < 1$), and become less concerned.

4 Equilibrium, Market Clearing and Aggregation

4.1 Sticky-price Equilibrium

We assume a symmetric monopolistic competition equilibrium in which all intermediate good producing firms have identical behavior. In this equilibrium, at a given time some of the intermediate good producing firms cannot adjust their prices. However, those firms that optimize their profits, decide to charge the same price $\tilde{P}_t$. Therefore, the aggregate price index will be:

$$P_t = [(1-\theta)\tilde{P}_t^{\,1-\varepsilon} + \theta P_{t-1}^{1-\varepsilon}]^{\frac{1}{1-\varepsilon}} \tag{17}$$

If we denote $\tilde{p}_t = \frac{\tilde{P}_t}{P_t}$, then

$$\tilde{p}_t = \left[\frac{1-\theta\bar{\pi}_t^{\varepsilon-1}}{1-\theta}\right]^{\frac{1}{1-\varepsilon}} \tag{18}$$

4.2 Aggregation

Aggregate price dispersion has a distortionary effect on the aggregate output. If we denote aggregate price dispersion by $\Delta_t = \int_0^1 (\frac{P_t(i)}{P_t})^{-\varepsilon} di$, aggregate output will be the following:

$$Q_t = \frac{A_t {K_t}^{\alpha_k} L_t^{\alpha_l} O_t^{\alpha_o}}{\Delta_t} \tag{19}$$

where

$$L_t = \int_0^1 L_t(i)\ di \tag{20}$$

$$K_t = \int_0^1 K_t(i)\ di \tag{21}$$

$$O_t = \int_0^1 O_t(i)\ di \tag{22}$$

In the production factors market, monopolistic distortion caused by the intermediate good producing firms implies that labor, capital and oil are paid below their marginal product.

$$w_t L_t = \alpha_l mc_t Q_t \Delta_t \tag{23}$$

$$r_t^k K_t = \alpha_k mc_t Q_t \Delta_t \tag{24}$$

$$p_t^o O_t = \alpha_o mc_t Q_t \Delta_t \tag{25}$$

where real marginal cost $mc_t = \frac{p_t^{o\,\alpha_o} w_t^{\alpha_l} r_t^{k\,\alpha_k}}{A_t \alpha_o^{\alpha_o} \alpha_l^{\alpha_l} \alpha_k^{\alpha_k}}$ is common for all firms. Under flexible prices, monopoly distortion measured by mc_t is constant and less than unity. However, when prices are sticky, it responds to the real and nominal shocks in the economy. Therefore, an oil price shock affects the inputs market through the pertubation in mc_t.

Optimal price-setting decision ($\tilde{P}_t$) by an intermediate good producing firm is governed by the following equations:

$$\frac{\tilde{P}_t}{P_t} \equiv \tilde{p}_t = \frac{E_t \Sigma_{k=0}^{\infty} (\beta\theta)^k \frac{Q_{t+k}}{C_{t+k}} X_{t,k}^{-\varepsilon} \frac{\varepsilon}{\varepsilon-1} mc_{t+k}}{E_t \Sigma_{k=0}^{\infty} (\beta\theta)^k \frac{Q_{t+k}}{C_{t+k}} X_{t,k}^{1-\varepsilon}} \equiv \frac{N_t}{D_t} \tag{26}$$

$$N_t = \frac{\varepsilon}{\varepsilon - 1} mc_t \frac{Q_t}{C_t} + \beta\theta E_t \bar{\pi}_{t+1}^{\varepsilon} N_{t+1} \tag{27}$$

$$D_t = \frac{Q_t}{C_t} + \beta\theta E_t \bar{\pi}_{t+1}^{\varepsilon} D_{t+1} \tag{28}$$

Decision rules for the intermediate firms and the storage operators in the financial markets, which determine the equilibrium level of oil inventories and futures contracts, are characterized by the following equations:

$$E_t\ (p^o_{t+1}) = E_t\ (\frac{F_t}{P_{t+1}}) \tag{29}$$

$$E_t\Big[\frac{1}{1+r_t}\frac{F_t}{P_{t+1}}\Big] = p^o_t - g_1(I_{t+1}, \sigma^2_{t+1}) \tag{30}$$

4.3 Market Clearing

In equilibrium, net supply of riskless bonds should be zero. Besides, since there is no capital accumulation, aggregate demand for capital is equal to the fixed supply.

$$B_t = 0 \tag{31}$$

$$K_t = 1 \tag{32}$$

In the oil market, oil supply is determined by the stochastic endowment (Ω_t) and the change in the level of inventories (ΔI_{t+1}). Therefore, the aggregate demand for oil, O_t, is equal to $\Omega_t - \Delta I_{t+1}$.

The oil-exporting country spends all the oil revenues on consumption good produced by the final good producers in the oil-importing country. Therefore, in the equilibrium, goods market clearing implies:

$$C^F_t = p^o_t O_t \tag{33}$$

$$C^F_t + C_t = Q_t \tag{34}$$

5 Calibration and Results

We follow the literature to calibrate the parameters for the utility and production functions. We set $\beta = 0.99$ corresponding to %4 annual steady-state real interest rate. Utility is logarithmic and the parameter $\psi = 1$ implying unit Frisch labot elasticity. There is no capital accumulation in the model, so the aggregate level of capital, $\bar{K}$, is set to 1. The labor, capital and oil elasticities of gross output are set to 0.63, 0.32 and 0.05, respectively. The elasticity of substition among intermediate goods, ε, is set to 7.66 to match a steady-state price mark-up of %15 implying $\mu = 1.15$. Together with the oil elasticity of gross output, $\alpha_o = 0.05$, the price mark-up matches the average oil consumption share of U.S. GDP, which is 0.04. We assume that the intermediate firms can optimize their profits only once a year, so the Calvo price adjustment parameter, θ, is set to 0.75.

For the baseline analysis, we calibrate the monetary policy using the findings Orphanides (2001). Therefore, we set our baseline parameters to $\phi_R = 0.79$, $\phi_\pi = 1.8$ and $\phi_y = 0.27$. We will later simulate the model using alternative policies by changing the coefficients of the interest rate smoothing parameter and the coefficients of the contemporaneous inflation and the log-deviation of the output.

The persistence parameters for the technology (η), oil endowment (ρ) and the variance (λ) shocks are all set to 0.5. The calibration of these parameters do not have any significant qualitative effect on the results, as long as they are set positive numbers less than one.

Following (Gorton et al. (2007)), we set the marginal convenience yield parameters for the inventory and the variance at -130 and 40, respectively. The steady-state value of oil endowment and the inventory are chosen to be 0.5 and 0.05.

We solve the model by taking second-order Taylor expansion around deterministic steady-state with zero inflation in order to capture the variance effect and calculate impulse response functions for the specific shocks. To be more precise, the solution method follows the algorithm proposed by Benigno, Benigno and Nistico (2010), which proposes a second-order appproximation method for the solution of the dynamic stochastic models, where exogenous state variables display time-varying risk.

5.1 Precautionary Demand Shock

We model precautionary demand shock as a "news shock" to the variance of oil endowment. Once there is a shock to the σ_{t+1}, firms become worried about the future availability of the oil supply and demand more futures contracts to offset that uncertainty. On the other hand, the storage operators increase their inventories to sell more futures contracts. In order to show formally how the uncertainty about future oil supply may increase the real spot price oil, we solve the maximization problem for the storage operators and the intermediate good producing firms, and aggregate production to get the following equation:

$$\underbrace{mc_t Q'(\Omega_t - \Delta I_{t+1})}_{p_{o,t}} = E_t[\frac{1}{1+r_t}\underbrace{mc_{t+1}Q'(\Omega_{t+1} - \Delta I_{t+2})}_{p_{o,t+1}}] + g_1(I_{t+1}, \sigma_{t+1}) \tag{35}$$

When there is a "news shock" at time t, not followed by any change in the mean at time $t+1$ (i.e. no realization), right-hand side of the equation goes up, since $g_{12} > 0$ and $E[Q'(\cdot)]$

is disturbed upward by Jensen inequality as $Q'(\cdot)$ is convex. In order to offset that wedge, the level of inventory holdings decided to hold at time t to be used at time $t+1$, I_{t+1}, will increase to raise the left-hand side through ΔI_{t+1} and lower the right-hand side of the equation through ΔI_{t+2} and $g_1(\cdot)$. Meantime, we will observe a spike in the real spot price of oil, $p_{o,t}$, since it is equal to $mc_t Q'(\Omega_t - \Delta I_{t+1})$.

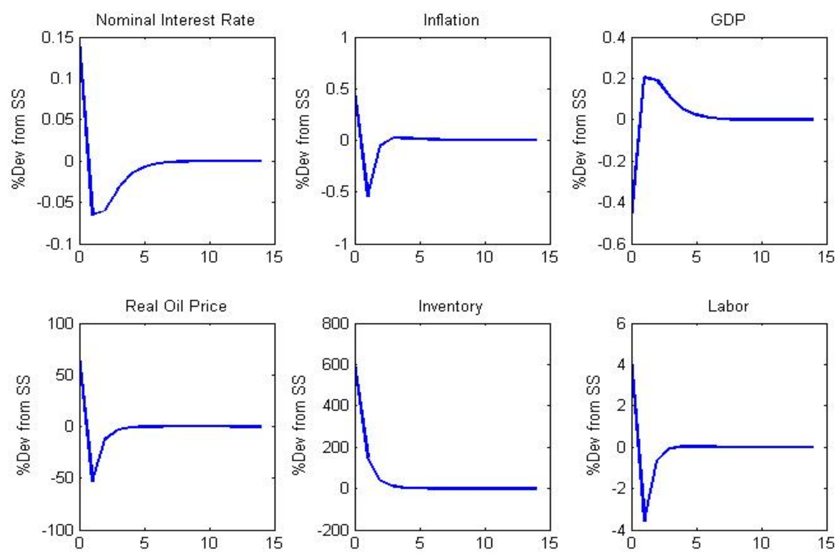

Figure 3: Shock to the variance ($\eta_t = 1$), no realization ($\varepsilon_t = 0$ for all t)

We simulate the model with the benchmark Taylor-rule estimated by Orphanides (2001) using real-time data for 1979:1995. Figure 3 shows the dynamics of inflation, percentage deviation of GDP, inventory, real oil price and interest rates from their steady state values responding one standard deviation in σ_{t+1}.

In accordance with the model, changes in inflation, inventories and oil price are positive and output is negative at the first period. However, they turn to negative (positive for output) during the second period, since oil supply shortfall does not occur. The level of oil inventories do not go back to the steady-state level immediately, since there is still concern, although less, about $t + 2$. Besides, the amount of oil in the economy, $\Omega - \Delta I_{t+2}$ is higher than its steady state value, so the spot price of oil and inflation are below and output above their steady-state values. Oil abundance lasts as long as the uncertainty is not vanished and oil supply shortfall does not occur.

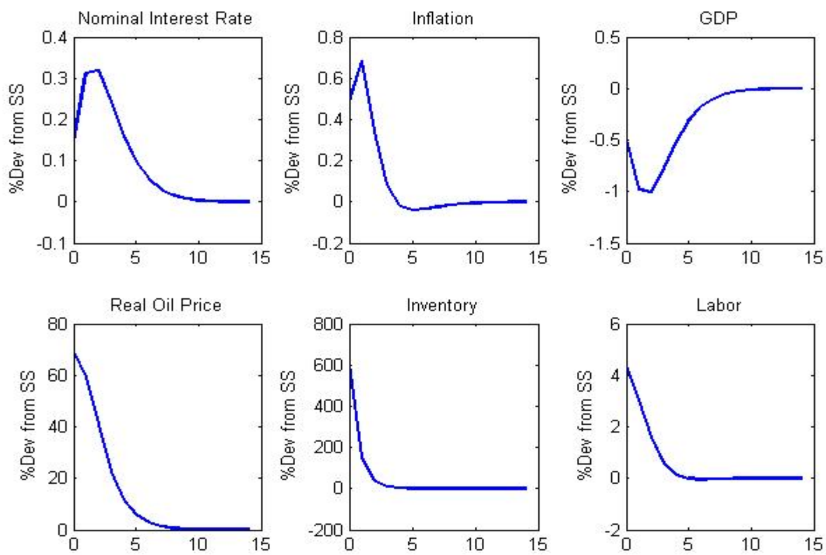

Figure 4: Shock to the variance ($\eta_t = 1$) followed by a shock to the mean ($\varepsilon_{t+1} = -1$)

The difference can be seen in Figure 4, where an uncertainty shock at time t is followed by a supply shock at time $t+1$. Since there is no more oil abundance in the economy during the later periods, inflation and oil price stay above and output below their steady-state values.

6 Conclusion

In this study we model and quantify the effect of uncertainty about future availability of oil supply on the macroeconomy. Our setup allows us to separate mean effect (supply shock) from variance shock (uncertainty effect). Under baseline Taylor-type interest rate rule, real oil price overshoots (and perturbates inflation and output loss) and goes down below steady state at the next period if uncertainties are not realized. However, if this shock is realized, i.e. followed by an actual supply shock, the effect on inflation and output loss is high and persistent.

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