

# Oil Consumption, Economic Growth, and Oil Futures: A Fundamental Alternative to Financialization\*

Robert C. Ready<sup>†</sup>

First Draft: July 3, 2014

This Draft: February 6, 2015

## Abstract

I present new evidence on the relations between oil consumption, oil prices, and economic growth, and build on this evidence to develop a real business cycle model to study oil prices. The model features oil driven long-run productivity risk and recursive preferences, and an oil good which is used for both production and final consumption. Calibrated model results can match the relations between oil prices and economic quantities, and can rationalize changes in oil futures markets from 2005 to 2012 as a consequence of a decrease in the responsiveness of the oil supply to prices. The results also suggest a link between increasing North American oil production and more recent changes in futures markets.

Keywords: oil prices, production-based asset pricing, long-run risk

JEL codes: G01, Q04, E02

---

\*This is a substantially revised version of my Job Market Paper “Oil Prices and Long-Run Risk”. I would like to thank my thesis committee: Amir Yaron, Nikolai Roussanov, and Andy Abel, for their helpful comments and advice. I would also like to thank Mark Ready, Colin Ward, Max Croce, Ron Kaniel, and Toni Whited for their support.

<sup>†</sup>Department of Finance, Simon School of Business, The University of Rochester. E-mail: robert.ready@simon.rochester.edu.

# 1 Introduction

The rapid development of financial commodity markets over the last decade has lead to an increased interest in commodities as an asset class. Following Masters and White (2008), much of the focus has been on the “financialization” of commodities, and the potential channels through which increases in financial speculation and index investing can affect commodity prices and returns to commodity futures.<sup>1</sup> The market for crude oil is a particular focus of this recent literature, with several authors, including Baker (2012), Basak and Pavlova (2013), and Hamilton and Wu (2013), developing models that link observed changes in the behavior of oil futures from 2005 to 2012 to changes in financial commodity market participation.

While these models provide theoretical links between oil futures markets and speculative activity, empirical evidence on this front is mixed. For instance, Singleton (2013) suggests that financial investor flows played an import role in oil futures markets over this period, while Irwin and Sanders (2011), Hamilton and Wu (2012), and Kilian and Murphy (2013) find little evidence that purchases by index funds and other financial institutions have had a large impact on oil futures markets. One of the particularly striking changes in oil markets over this period is the increasingly upward sloping term structure of oil futures, and correspondingly lower returns for investors who are long oil in the futures markets. This change is often cited as a potential consequence of increased financial investment, though, as I show here, this changes is unique to oil and energy commodities, despite that fact that financial trading increased across the entire commodity asset class. In this paper I propose an alternative hypothesis: that the behavior in oil futures prices over this period reflected increased worry about the long-run oil supply and an increase in the required premium for bearing oil price risk.

While oil prices have long been emphasized as an important predictor of economic growth (see Hamilton (2008) for an overview), there has been relatively little work on understanding and

---

<sup>1</sup>See for example, Domanski and Heath (2007), Singleton (2013), Buyuksahin and Robe (2011), Tang and Xiong (2012), and Irwin and Sanders (2011) for discussions of the impacts of increased trading in financial futures, and Fattouh, Kilian, and Mahadeva (2013) for a review of work in this area.

quantifying the sources of risk and return associated with oil prices in this context. Theoretical models of oil derivatives generally feature exogenous spot prices (e.g. Gibson and Schwartz (1990)), or exogenous demand processes (e.g. Routledge, Seppi, and Spatt (2000) and Kogan, Livdan, and Yaron (2009)), and are therefore silent on oil’s role in the macroeconomy.<sup>2</sup> The rapidly growing macrofinance literature, including Cochrane (1991), Jermann (1998), Bansal and Yaron (2004), Kung and Schmid (2015), Kaltenbrunner and Lochstoer (2010), Croce (2014), and many others, has had success jointly explaining the behavior of macroeconomic aggregates and asset prices in economies with complete financial markets, but this literature has yet to specifically consider oil prices. In this paper I attempt to bridge this gap with a quantitative real business-cycle model for oil prices. The model is able to match the observed dynamics of oil prices and macroeconomic aggregates, and yields a rich set of implications for pricing oil futures.

The model builds on the production-based framework of Kaltenbrunner and Lochstoer (2010) and Croce (2014), and features exogenous long-run shocks to aggregate productivity growth, and a representative consumer having Epstein and Zin (1989) recursive preferences with an intertemporal elasticity of substitution (IES) greater than one. To this setup I add an exogenous supply of an oil good which is used both as an input to production and as a final household consumption good. Motivated by the existing literature which links oil price increases to low future economic growth, as well as new empirical evidence presented here on the specific relation between oil prices and TFP growth, high oil prices in the model create an externality which reduces productivity growth.

The model provides a general framework for studying the impact of oil supply shocks on macroeconomic aggregates and asset prices, and is able to match the joint dynamics of household oil consumption, economic oil consumption, investment, and labor, while also matching behavior in asset markets. I then use the model framework to show how changes in oil supply fundamentals

---

<sup>2</sup>There are some recent exceptions. Casassus, Collin-Dufresne, and Routledge (2005) develop a general equilibrium model with oil as an input into the production of a single consumption good, and study the implications of oil price risk in this context. Baker and Routledge (2012) examine the consequences of increasing wealth of oil producing countries on oil price risk in a two-country model. Acharya, Lochstoer, and Ramadorai (2013) build a model of hedging demand driven by the changing incentives of oil producers.

impact the return demanded for exposure to oil prices, and in turn how this affects the pricing of oil futures. The model results show that changes in the fundamental conditions of the oil supply, namely a decrease in the ability of the oil supply to respond quickly to changes in prices and a corresponding increase in uncertainty about long-run prices, can explain the observed changes in the behavior of future prices and returns from 2005 to 2012, providing an alternative to theories of financialization.<sup>3</sup>

The intuition behind the model is simple. When the oil supply is constrained and unable to respond to changes in oil prices, oil prices exhibit less mean reversion and shocks to oil prices are expected to persist. These highly persistent shocks have a larger impact on the wealth, and therefore the marginal utility, of the representative agent. The agent is therefore willing to pay a premium to hedge against both oil supply shocks. This hedging premium translates into an upward slope in the term structure of oil future price, consistent with the observed data from 2005 to 2012. Also consistent with the model, the behavior of oil futures over this period implies marked decrease the expected speed of mean reversion of oil prices. The fact that this change in behavior coincides with the increased hedging premium also provides novel evidence of the importance of persistence in determining the risk premium associated with growth shocks, a central mechanism in the LRR literature.

In addition to providing new and general framework for understanding oil price risk, this paper also contributes several new empirical facts about oil's role in the economy. The allocation of oil to both consumption and production is an important feature of the model, and is motivated by new evidence presented here on the relation of household consumption and oil prices. Household gasoline consumption accounts for roughly 65% of petroleum consumption in the U.S. economy, yet oil is often modeled as purely an intermediate input to production.<sup>4</sup> In

---

<sup>3</sup>Though the focus here is on oil futures, the model also has implications for oil option prices. Recent work by Christoffersen and Pan (2014) shows that shocks to oil price volatility appear to be a priced factor in equity markets after 2005. In Section B of the online Appendix I present additional evidence that the variance risk premium in oil options has increased in this period as well. Section B also augments the benchmark model to include stochastic volatility, and shows that the increase in the price of oil variance risk is another outcome of the decreased responsiveness of the oil supply.

<sup>4</sup>See Rotemberg and Woodford (1996) and Casassus, Collin-Dufresne, and Routledge (2005) as examples

such a model, the price of oil is a function of aggregate output and aggregate oil consumption, a relation that holds only loosely in the data. In contrast, when oil directly enters the household's consumption basket, oil prices are then a function of relative levels of household oil consumption and consumption of other goods. I show that this relation is strong in the data, and that real oil price over the last 35 years can be closely approximated by a function of the relative levels of household consumption of gasoline and household consumption of other, non-oil, goods. This new result is an important contribution of the paper, and allows for the study of oil prices in a quantitative macroeconomic model.

A well established stylized fact (see for instance Hamilton (2003) and Hamilton (2008)) is that high oil prices forecast low future GDP growth. In a model where oil is solely an intermediate good, the obvious channel is that high oil prices lower the marginal product of capital, which leads to low future investment and lower capital stocks. However, as noted by Rotemberg and Woodford (1996) and Barsky and Kilian (2004), this channel is unlikely to deliver the quantitative impacts often attributed to oil price shocks. I show that when aggregate output is decomposed into changes in capital, labor inputs, and total factor productivity (TFP), there is very little impact on the capital stock and investment. Instead the growth rate predictability is primarily from changes in the labor supply and TFP, confirming the findings of Barsky and Kilian (2004). I also present new evidence that the impact of oil prices on TFP appears to be distinct from other predictors of TFP growth recently documented by Kung and Schmid (2015) and Ward (2014).

The lack of impact of the oil price on investment is consistent with a model where oil is both both an intermediate and final consumption good. Increased oil prices reduce the marginal product of capital, but also reduce the marginal value of consumption, creating little incentive to substitute from consumption to investment. In contrast, high oil prices do create a substitution

---

of models where oil is solely an input to production. In more recent work, Sánchez (2011) and Bodenstein, Guerrieri, and Kilian (2012) examine the allocation of oil to production and household consumption, however to my knowledge no prior work examines household oil consumption in an asset pricing context.

effect from work to leisure, consistent with the reduced labor supply observed in the data. Finally, although the model does not endogenously generate the relation between future TFP growth and oil prices, this can be imposed as an exogenous externality in the LRR framework, and I find that doing so is important to match the observed behavior in futures markets.

The rest of the paper is organized as follows. Section 2 presents empirical evidence of changes in the behavior oil future prices, as well as evidence on the relation of oil prices and the macroeconomy. Section 3 presents the basic benchmark model. Section 4 calibrates the benchmark model and presents intuition on how changing oil supply conditions impact oil risk the implications for future markets. Section 5 examines the potential impacts of recent increases in North American oil production in the context of the Model. Section 6 concludes.

## 2 Empirical Results

Before presenting the model, this section presents the motivating empirical analysis. The model will be primarily used to explore the potential causes of the changes in oil futures behavior from 2005 to 2012, so I present those changes in detail. I also present new data on the relations between oil consumption, oil prices, and economic growth to motivate the structure of the model.

### 2.1 Data Sources and Sample Period

Data on total U.S. oil consumption comes from the Energy Information Association (EIA). Data on household consumption and GDP come from the BEA's NIPA surveys. Data on TFP, hours worked, and capital supply are from the San Francisco Federal Reserve.<sup>5</sup> Data on oil futures are for the NYMEX West Texas Intermediate (WTI) contract, and come from the Commodity Research Bureau.<sup>6</sup> All data are for the U.S. economy. Data on miles per gallon of the U.S. passenger car fleet are from the National Transportation Safety Board.

---

<sup>5</sup>[http://www.frbsf.org/economics/economists/jfernald/quarterly\\_tfp.xls](http://www.frbsf.org/economics/economists/jfernald/quarterly_tfp.xls) .

<sup>6</sup>Since 2011 there has been a divergence between the WTI and other global oil price indices. In unreported analysis, the tests shown in this section were repeated using Brent Crude futures and yielded qualitatively similar results.

The macroeconomic data and oil spot price are typically available for longer time series. To be consistent with other macroeconomic studies of oil prices, I report data for 1970-2012. The structural change in open interest generally attributed to financialization is usually identified as occurring near the end of 2004 (Hamilton and Wu (2013)). I focus on two subperiods, the pre-financialization period from 1997 to 2004, and a post-financialization period of 2005 to 2012.

## 2.2 Changes in the Term Structure of Commodity Futures

In this section I document changes in the term structures commodity future prices, returns, and volatilities over two subperiods: 1997 to 2004 and 2005 to 2012. The choice of the pre-financialization period is different from previous works, which often uses a much longer pre-financialization sample. Here I focus on equal length time periods to highlight structural changes in this specific time period, rather than longer term trends in futures markets. The analysis here is primarily concerned with oil futures, but I also present results for other commodities over these two time periods. What is striking is that the changes in the term structure of oil futures do not appear in other commodities, despite the fact that financial investment increased across the entire asset class in this time period.

Figure 1 illustrates the two samples at issue. Panel A shows the time-series of both oil spot prices as well as the slope of the term structure of oil future prices, which is measured as the log of the ratio between the 6-month oil future price and 1-month oil future price. As the figure shows, the oil price exhibits markedly different behavior from 2005 to 2012 when compared to the previous 7 years of relative stability.

Panel A also plots the slope of the term structure of oil future prices. Prior to 2005, the slope of the term structure is strongly negatively correlated with changes in spot prices. However, starting around 2005 the slope of this term structure began to increase despite the fact that oil prices were rising over the same period. This slope remains higher, on average, through the remainder of the sample.

The primary implication of this increase in the slope is that long positions in oil futures became much more expensive, or equivalently, the return to investing in oil futures decreased. To illustrate this, Panels B and C of Figure 1 plot the cumulative return to a strategy which takes a long position in oil prices by rolling over short-term futures each month. In each panel this figure is plotted against the cumulative spot price change over the period. In the first subperiod, the low slope of the futures curve means that this strategy yielded a return in excess of the total change in the spot price. In contrast, Panel C shows that in the second period the large positive slope of the term structure translated into returns that were far below the observed increase in the spot price. This difference is substantial, with the rolling strategy losing roughly 50% over the period, despite the fact that oil prices increased by 50% over the same sample.

[Figure 1 about here.]

These differences in returns are a mechanical outcome of the increased slope in the futures curve, but they serve to demonstrate the potential impacts of the changes in this market. This increase in the slope is often identified as an impact of increased financial trading in commodity prices. Though it is true that open interest in oil futures greatly increased over this time, this was true across a broad set of commodities, while these changes in the behavior of term structure were largely unique to oil prices. Figure 2 illustrates this. The Figure graphs the average term structures of oil future prices, as well as the term structure of return volatility, for the two subsamples. For comparison, the figure also plots the term structures for two other commodities, Copper and Wheat. Copper and wheat are chosen as an illustration, since they are respectively the largest metal and agricultural contract in terms of index investment positions, which are often used as a measure of financial investment.

[Figure 2 about here.]

Panel A graphs the average term structure of future prices, and shows that the term structure of Crude Oil is indeed more upward sloping in the second period. This pattern does not show

up in the other two contracts. For copper, the curve is actually more downward sloping in the second sample, and for wheat there is no apparent change in the slope.

Panel B shows the term structure of the volatility of future returns.<sup>7</sup> This change in the futures term structure has been studied less in the literature, but as the picture shows, the volatility of long term futures has risen substantially, resulting in a flattening of the term structure of future return volatilities for oil. While the volatility of copper and wheat have increased over the period, they do not exhibit the same flattening of volatility shown in oil futures. This increase in long-run futures volatility is important, because it suggests a large increase in the uncertainty regarding long-run oil prices.

In order to test whether or not these changes in Figure 2 are significant, and to show that the results for oil are in fact unique among a larger set of commodities, I estimate two regression specifications involving future prices and returns. I do this as opposed to estimating a full term-structure model of oil futures (such as Gibson and Schwartz (1990)) in order to allow for formal tests of changes in the underlying parameters. These regressions include an indicator variable,  $\mathbb{1}_{>2004}$ , which takes a value one for observations after January 2005, and zero otherwise. The sample period for the regressions is January 1997 to December 2012, in order to have an equal length period before and after the break. Table 1 shows the results.

The first specification is designed to test for a change in the slope of the term structure of prices, while controlling for variation in the slope created by changes in prices and expectations of mean reversion. The slope is estimated as

$$Slope_t = \alpha + \alpha_1(\mathbb{1}_{t>2004}) + \beta r_{t-6,t}^2 + \beta_1(\mathbb{1}_{t>2004})r_{t-6,t}^2 \quad (2)$$

Here the slope at the end of each month, defined as  $f_t^6 - f_t^1$ , is regressed on  $r_{t-6,t}^2$ , the

---

<sup>7</sup>I follow convention and define the log of the excess return to investing to a one-month investment in a fully collateralized future contract maturing at month  $t + j$  as

$$r_{t+1}^j = f_{t+1}^{j-1} - f_t^j \quad (1)$$

Where  $f_t^j$  is the future price at time  $t$  for a contract maturing at time  $t + j$ .

cumulative return of the nearest maturity future for the current month and the previous six months.<sup>8</sup> The coefficient of interest is  $\alpha_1$ , which measures the change in the mean of the slope from 2005 to 2012. The lagged slope and current return are included to control for variations in the expected drift of future oil prices driven by mean reversion. The dummy variable is also interacted with cumulative return measure. The results from this regression are shown in Panel A of Table 1. The intercept on the level dummy  $\alpha_1$  is positive and significant at the 1% level for oil futures, as well as at the 5% level for Heating Oil, which is highly correlated with oil prices. However, for all other major commodities this is not the case. There is no significant change in the average slope of prices for any other commodities, with the exception of a small reduction in the slope of silver and gold, changes which are mostly driven by lower interest rates after the financial crisis.

To test for a change in the expected mean reversion of future prices, I estimate the regression

$$r_t^6 = \alpha^j + \alpha_1^j(\mathbb{1}_{t>2004}) + \beta^j r_t^2 + \beta_1^j(\mathbb{1}_{t>2004})r_t^2 \quad (3)$$

[Table 1 about here.]

Where  $r_t^6$  is the log return on the sixth-nearest futures contract. This return is regressed on the contemporaneous return of the nearest term future contract, again with a dummy included for the intercept and slope. This regression technique is similar to that of Bessembinder, Coughenour, Seguin, and Smoller (1995), who regress changes of long term future prices on innovations in the spot price. As they note, high degrees of expected mean reversion should imply that longer term contracts move less in response to a change in the level of prices.

As the first column of Panel B shows, the coefficient on the interaction of the dummy variable and the near term future contract have strongly significant negative values for Crude

---

<sup>8</sup>The second nearest to maturity contract is used as the nearest term future to avoid excess volatility associated with physical delivery.

Oil, indicating a decrease in the degree of expected mean reversion. This decrease in mean reversion is the cause of the flattening of the volatility term structure. The intercept dummy is positive but not statistically significant. It is interesting to note that over the full period the long-term future does earn a premium over short-term futures, but this is the case over the full time period, and is not unique to the 2005 - 2012 period often associated with financialization.

This increase in persistence of prices is not unique to oil, as several of the commodities had significant decreases in expected mean-reversion in the post 2005 period, but again, only in oil and energy commodities do we see the corresponding increase in the slope of the term-structure of futures prices.

These results show that one of the primary changes in oil futures markets over this period, the increase in the slope of the futures price curve, is in fact unique to oil among commodities. If the explanation is an increase in financial investment, then this is a puzzling result, as one would expect a similar effect across all commodities. This suggests the potential for an alternative explanation of these changes driven by fundamentals of the oil supply. In order to develop a model to study this effect, I now present new evidence on the use of oil in the economy, and the effects of oil prices on economic growth.

### **2.3 Oil Prices, Consumption, and Output**

In the model oil will be used both as a consumption good and an input to production, and oil prices will have an exogenous impact on TFP growth. This section provides support for these features of the model by presenting evidence on the relation between household oil consumption and oil prices, as well as on the relations between oil prices and the various components of aggregate growth.

### 2.3.1 Household Consumption of Oil

To illustrate the importance of oil as a final consumption good, I first consider the expenditure by households on oil consumption relative to total U.S. oil consumption, GDP, and two measures of total household consumption expenditure. Household oil consumption is the nominal expenditure on “Gasoline and Other Energy Goods” from the NIPA survey. Total U.S. oil consumption is calculated using data on “Total Product Supplied” provided by the EIA. To obtain this value, barrels of consumption of each final petroleum product is multiplied by its price in each month.<sup>9</sup> EIA data are not seasonally adjusted, so the data is considered an annual frequency to avoid seasonal effects.

Panel A of Figure 3 shows the proportion of oil consumed by households along with the real price of oil. Household consumption of oil accounts for roughly 65% of oil use in the U.S. economy, and this percentage has been fairly stable over the last 25 years. To the extent there is variation, the proportion of household consumption exhibits a clear negative correlation with spot prices, suggesting that household consumption of oil is more elastic than industrial consumption. Panel B of Figure 3 shows a similar graph, this time with the ratio of total economic consumption of oil to GDP. This ratio exhibits a larger amount of variation, with percentages ranging between 2% and 5% over the sample, and is strongly positively correlated with changes in oil prices.

Finally Panel C of Figure 3 shows the percentage of household consumption expenditure allocated to ‘Gasoline and Other Energy Goods’. The plot shows this percentage as both the percentage of total consumption expenditure (goods and services), as well as the percent of expenditure on goods. As the plot shows, household expenditure on gasoline has been trending downward over time relative to total expenditure, but this is driven primarily by the increase of expenditure on services. Relative to total expenditure on physical goods, the amount of house-

---

<sup>9</sup>Not all products have a published price, but those that do not are a small fraction of the output of an oil barrel. Furthermore they tend to be cruder refined products (ie. petroleum coke) and therefore account for an even smaller portion in dollar value.

hold expenditure on gasoline has no discernible trend, but again is highly positively correlated with oil prices.

[Figure 3 about here.]

### 2.3.2 Household Consumption and Oil Prices

To help understand how households allocate resources to oil consumption, I first specify a general intratemporal function for household utility over an aggregate consumption good, ( $C_t$ ) and an oil consumption good ( $G_t$ ).

$$V_t(C_t, G_t) = \left[ (1 - a_G)C_t^{1-\frac{1}{\xi_G}} + a_G G_t^{1-\frac{\eta}{\xi_G}} \right]^{\frac{\xi_G}{\xi_G-1}} \quad (4)$$

The function is the Generalized Constant Elasticity of Substitution (GCES) felicity function of Pakos (2004). A Cobb-Douglas utility function is a special case, where  $\xi_G$  and  $\eta$  are equal to one. The parameter  $\xi_G$  is the elasticity of substitution between oil consumption and aggregate consumption. The parameter  $\eta$  allows non-homotheticity in the utility function. In the data  $\eta < 1$ , implying that oil demand rises more slowly than demand for basic consumption goods as wealth rises (ie., oil is a necessary good as opposed to a luxury good).

First order conditions imply that  $p_t$ , the log of the price of a unit of oil consumption  $G_t$  in terms of units of the numeraire good  $C_t$ , is given by

$$p_t = \log \left( \frac{a_G}{1 - a_G} \right) + \frac{1}{\xi_G} (c_t - \eta g_t) \quad (5)$$

To estimate the utility parameters, I use the dynamic OLS method described by Stock and Watson (1993), which includes both leads and lags of the growth rates of the independent variables to control for endogeneity.<sup>10</sup> The form for the regression is

---

<sup>10</sup>The analysis is similar to Bentzen and Engsted (1993) and Ramanathan (1999), who use aggregate income and economy wide oil use to estimate elasticities of demand for oil.

$$p_t = \beta_0 + \beta_1 c_t + \beta_2 g_t + \sum_{t=-k}^k \Gamma_{1,k} \Delta c_{t+k} + \sum_{t=-k}^k \Gamma_{2,k} \Delta g_{t+k} \quad (6)$$

The coefficients are related to the parameters of the utility function  $V_t$  by  $\beta_1 = \frac{1}{\xi_G}$  and  $\beta_2 = \frac{\eta}{\xi_G}$ . It is worthwhile to note here the implications of considering oil directly as a consumption good. While clearly consumers do not consume crude oil, and ultimately I will be concerned with pricing futures for delivery of crude oil, there is a very tight relation between crude oil prices and the price of gasoline. Gasoline then enters households' consumption primarily through automobile use. To account for changes in the efficiency of converting oil to consumable goods, I adjust the level of oil consumption by the multiplying it by average miles per gallon taken from the Bureau of Transportation Statistics. The assumption underlying this adjustment is that the household consumption good is not actually gasoline, but rather miles driven. Therefore, I also adjust the price of oil by miles per gallon to obtain a measure of price per mile. Accordingly, in the regression of Equation (6), I substitute  $p_t$  with  $(p_t - \log(mpg_t))$ , and  $g_t$  with  $(g_t + \log(mpg_t))$ .

I estimate this regression using two different measures of aggregate consumption. The first is consumption of nondurable goods and services, and the second is a Cobb-Douglas aggregate of nondurable goods and services and the stock of durable goods constructed as in Yogo (2006). I also include two different measures of oil consumption. The first is the measure of household consumption from NIPA data, while the second, following Bentzen and Engsted (1993) and others, is the economy-wide measure of product supplied from the EIA. For comparison I also estimate the regression using personal income and GDP in place of consumption. To be consistent with previous studies I do not adjust these variables for efficiency, however doing so does not significantly alter the results. Table 2 reports these regressions for 1981 to 2012, the period for which I have data on aggregate U.S. oil consumption.

[Table 2 about here.]

As this table shows, the measurement of oil consumption from NIPA data does a much

better job of explaining oil prices than the measure of aggregate economy-wide oil consumption obtained from the EIA. To illustrate the improvement in fit from using household data as opposed to Figure 4 graphs the predicted values from a simple regression of the log of the oil prices on the logs of aggregate consumption and energy consumption from 1981 to 2012. The relative measures of consumption captures the short term dynamics as well as the long-term trend, while the relative measures of output and total oil consumption do a poor job of capturing both.

[Figure 4 about here.]

### 2.3.3 Oil Prices and Economic Growth

A common stylized fact from the macroeconomic literature on oil prices is the predictive relation between increases in oil prices and low future economic growth. For instance, Hamilton (2008) estimates a regression of GDP growth on lags of GDP growth and lags of oil price changes, and finds that changes increases in oil prices predict low GDP growth for up to four quarters in the future. Here I revisit this analysis to attempt to shed light on the source of this change in output.

Using data from San Francisco Federal Reserve which decomposes changes in output into its component parts, I estimate a Vector Autoregression (VAR) for the log changes of hours worked, total capital stock, total factor productivity, and the real price of oil. The VAR is estimated with four lags over the period from 1970 to 2012. Figure 5 plots the impulse response functions for this VAR to a one standard deviation change in the price of oil. The figure shows that the future reduction in growth is not driven by a reduction in capital, as the capital stock shows little discernible response to an increase in oil prices. Instead, the future drop in output is driven by a change in future Total Factor Productivity, along with a reduction in total hours worked.

[Figure 5 about here.]

While the standard VAR framework provides evidence that oil prices impact TFP growth,

there are a some issues with this regression, particularly when considered in the context of the model. One confounding feature of the total TFP measure in the VAR is the fact that oil itself is an input into total output. Another is that a portion of U.S. GDP comes from U.S. oil production. To address these issues I again utilize data reported by the San Francisco Federal Reserve which reports utilization adjusted TFP, and decomposes total TFP into “Investment” TFP, including investment goods and consumer durables, and “Consumption” TFP, consisting of TFP for all other output including oil.

In a model with recursive preferences, long-run growth impacts will have important implications for asset prices. In order to study growth impacts at longer horizons than the one year used in the standard VAR framework, I use the ratio of household expenditure on gasoline to expenditures on other goods (excluding services). I then test to see if this variable, which is strongly related to the real oil price, but which has no discernible time trend over a very long sample, is able to predict TFP growth.

Additionally, in the model, the oil price impact on growth will be distinct from a separate, long-lived shock to aggregate growth. To provide support for this assumption I test for the predictive power of the oil consumption ratio controlling for two other predictors of TFP growth in the recent literature. Kung and Schmid (2015) show that aggregate R&D intensity has predictive power for TFP growth, and Ward (2014) shows a similar result for the price-dividend ratio of the IT sector. For R&D Intensity the data is annual from 1953, while the IT sector price-dividend is available quarterly from 1973.

I estimate forecasting regressions of the form

$$\Delta TFP_{t,t+k}^i = \alpha + \beta^{G/C}(ConsRatio_t) + \beta^X X_t \quad (7)$$

Here  $TFP_{t,t+k}^i$  is the log of utilization adjusted TFP growth from time  $t$  to  $t+k$  for two different sets of goods.  $TFP_{t,t+k}^I$  is productivity growth of investment goods and consumer

durables, while  $TFP_{t,t+k}^C$  is all other goods and services, including oil.  $ConsRatio_t$  is the log-ratio of total expenditure on gasoline and other energy goods to household consumption expenditure on all other goods (excluding services).  $X = RDI$  is R & D intensity calculated as in Kung and Schmid (2015), and  $X = IT$  is P/D ratio of the IT industry as in Ward (2014).

Table 3 shows the results. The ratio of household oil consumption to total consumption strongly negatively predicts  $TFP^I$  in both the quarterly and annual data at both short and long horizons, and this relation is robust to the inclusion of the other predictor variables. Moreover, the power of the other predictors are concentrated in  $TFP_{t,t+k}^C$ , suggesting that the predictive power of oil prices for TFP growth is distinct from previously documented effects.

[Table 3 about here.]

I now turn to the model, which incorporates the empirical evidence on consumption and oil prices, as well as the relation between oil prices and TFP growth. The model shows how an unresponsive oil supply can generate changes in the dynamics of oil futures which are consistent with those observed from 2005 to 2012.

### 3 The Benchmark Model

The model presented here adds an exogenous oil supply to the model of Kaltenbrunner and Lochstoer (2010) and Croce (2014). As in Kaltenbrunner and Lochstoer (2010) the model features households with recursive preferences in the manner Epstein and Zin (1989), and following Croce (2014), the model includes exogenous persistent shocks to the growth-rate of TFP, similar to the long-run shocks to consumption growth in Bansal and Yaron (2004). Oil is used in the economy for final consumption as well as production of a basic good which is consumed by households and used for investment in capital.<sup>11</sup>

---

<sup>11</sup>Oil storage and stochastic oil production volatility are not qualitatively important for the primary results, so they are excluded here for simplicity. Section B of the Online Appendix presents empirical data on storage and futures prices, as well results from a version of the model augmented to include oil storage and stochastic oil volatility.

The model is a partial equilibrium framework in the sense that the oil supply is modeled as an exogenous process. Rather than focusing on the oil production decision, the model focuses on the implications of supply constraints on the aggregate economy.<sup>12</sup> This choice is in contrast to traditional models of commodity futures, many of which consider the problems associated with storage ((Kaldor (1939), (Williams and Wright (1991), Deaton and Laroque (1992), Deaton and Laroque (1996), Routledge, Seppi, and Spatt (2000)) or oil production (Casassus, Collin-Dufresne, and Routledge (2005), Carlson, Khokher, and Titman (2007), Kogan, Livdan, and Yaron (2009)), and usually rely on risk-neutral settings or an exogenously specified risk premium.

### 3.1 Households

The representative household derives utility from direct consumption of oil,  $G_t$ , consumption of a basic good  $C_t$ , and leisure  $n_t$ .

I define the household's consumption basket

$$\tilde{C}_t = \left[ (1 - a_G)C_t^{1 - \frac{1}{\xi_G}} + a_G G_t^{1 - \frac{1}{\xi_G}} \right]^{\frac{\xi_G}{\xi_G - 1}} \quad (8)$$

as a CES aggregate of oil consumption and basic consumption.<sup>13</sup>

Intertemporal utility is then given by embedding the intratemporal utility across basic consumption, oil consumption, and leisure in the recursive setting of Epstein and Zin (1989)

$$U_t = \left[ (1 - \beta) \left( \tilde{C}_t^{1 - \phi} N_t^\phi \right)^{1 - \frac{1}{\psi}} + \beta \left( E_t[U_{t+1}^{1 - \gamma}] \right)^{\frac{1 - 1/\psi}{1 - \gamma}} \right]^{\frac{1}{1 - 1/\psi}} \quad (9)$$

Where  $\gamma$  is the coefficient of risk aversion and  $\psi$  is the intertemporal elasticity of substitution (IES). As in Croce (2014),  $N_t = A_{t-1}n_t$  is the leisure share multiplied by the lag of the aggregate

---

<sup>12</sup>The approach here is analogous to the one taken in a consumption-based asset pricing model (see Cochrane (2001)). If the constraints on the oil production generate the observed dynamics, then the risk associated with financial contracts will be the same as if the oil endowment is specified exogenously.

<sup>13</sup>Here I do not allow for non-homotheticity in the utility function, though it is a feature of the data on oil consumption. Non-homotheticity can be accounted for by specifying an endowment for oil which ensures that the percentage expenditure on oil is stationary on the balanced growth path. This yields very little change in asset-pricing the implications for the model and is thus omitted for simplicity.

technology shock to ensure model stationarity.  $N_t$  can therefore be interpreted as leisure adjusted for the standard of living.

### 3.2 Production

The household supplies labor to a representative firm which produces the basic good using a capital stock ( $K_t$ ), oil ( $O_t$ ), and labor  $L_t$ . The productivity of the firm is impacted by exogenous productivity shocks ( $A_t$ ) so that output  $Y_t$  is given by

$$Y_t = \left[ (1 - a_O) (K_t^\alpha (A_t L_t)^{1-\alpha})^{1-\frac{1}{\xi_O}} + a_O O_t^{1-\frac{1}{\xi_O}} \right]^{\frac{\xi_O}{\xi_O-1}} \quad (10)$$

The constraints on capital and labor are standard, and the overall supply of hours for labor and leisure are normalized to one.

$$Y_t = C_t + I_t \quad (11)$$

$$1 = L_t + n_t$$

The capital stock evolves according to

$$K_{t+1} = (1 - \delta_k) K_t + \Phi\left(\frac{I_t}{K_t}\right) K_t \quad (12)$$

Where  $\Phi$  is an adjustment cost function parameterized as in Jermann (1998).

The oil supply in each period is  $W_t$  is allocated for production of the final good or direct household consumption so that

$$W_t = G_t + O_t \quad (13)$$

### 3.3 Technology and the Oil Supply

There are three exogenous state variables in the Benchmark Model. The first is the log level of technology process  $a_t$ , the second, following Croce (2014), is the long run persistent component of technology growth,  $x_t$ , and the final variable is the log of the supply of oil produced in each period,  $w_t$ . To ensure balanced growth, the supply of oil and is cointegrated with the level of aggregate technology. The dynamics of the three variables are given by

$$\Delta a_{t+1} = \mu_z + x_t + \zeta w_t + e^{v_t} \sigma_a \epsilon_{t+1}^a \quad (14)$$

$$x_{t+1} = \rho_x x_t + e^{v_t} \sigma_x \epsilon_{t+1}^x \quad (15)$$

$$\Delta w_{t+1} = \mu + (\rho_w - 1)(w_t - a_t - \bar{w}) + \kappa x_t + \sigma_w \epsilon_{t+1}^w \quad (16)$$

$$(17)$$

Here,  $\rho_x$  and  $\rho_w$  govern speeds of mean reversion, the parameter  $\kappa$  allows for the oil supply to respond to increases in expected growth of technology, while  $\zeta$  allows for the level of the oil supply to have an exogenous impact on future TFP growth. Since  $w_t$  is an exogenous variable in the model the social planner is unable to adjust allocations to mitigate this growth effect. The impact of oil prices on TFP in the model can therefore be considered a growth externality of high oil prices.<sup>14</sup> The shocks in the model are distributed  $N(0, 1)$  and assumed to be orthogonal.

### 3.4 Equilibrium

Markets are complete so the solution to the model can be computed by solving the social planner's problem of maximizing  $U_t$ , by choosing consumption, labor, investment, and the allocation of oil between households and production, subject to the exogenous shocks and the resource constraints.

---

<sup>14</sup>This externality is similar to the externalities associated with exports considered in the context of international trade. See Feder (1983) and Melo and Robinson (1992).

Setting basic consumption,  $C_t$ , as the numeraire good, and following standard calculations (see for instance Yogo (2006)), the stochastic discount factor in the economy is given by

$$\frac{M_{t+1}}{M_t} = \beta \left( \frac{C_{t+1}}{C_t} \right)^{-\frac{1}{\psi}} \left( \frac{\tilde{C}_{t+1}/C_{t+1}}{\tilde{C}_t/C_t} \right)^{\frac{1}{\xi_G} - \frac{1}{\psi}} \left( \frac{N_{t+1}/\tilde{C}_{t+1}}{N_t/\tilde{C}_t} \right)^{(1-\frac{1}{\psi})(\phi)} \left( \frac{U_{t+1}}{E_t \left[ U_{t+1}^{1-\gamma} \right]^{\frac{1}{1-\gamma}}} \right)^{\frac{1}{\psi} - \gamma} \quad (18)$$

The risk-free rate is

$$R_t^f = E[M_{t+1}]^{-1} \quad (19)$$

The first order conditions with respect to  $C_t$  and  $G_t$  imply that the spot price of oil is given by

$$P_t = \frac{a_G}{(1-a_G)} \left( \frac{C_t}{G_t} \right)^{\frac{1}{\xi_g}} \quad (20)$$

Future contracts are assumed to be marked to market each period, so future prices in the model can be calculated recursively using

$$0 = E_t[M_{t+1}(F_{t+1}^{j-1} - F_t^j)] \quad (21)$$

with  $F_t^0 = P_t$ .

As in Croce (2014), aggregate equity returns are calculated as the levered return on investing in  $K_t$ , the stock of basic capital. The marginal value of a unit of extra capital is given by

$$Q_t = \frac{1}{\Phi' \left( \frac{I_t}{K_t} \right)} \quad (22)$$

The normalized return to investing in a unit of capital is given by

$$R_{t+1} = \frac{\frac{dY_{t+1}}{dK_{t+1}} + Q_{t+1} \left[ \Phi \left( \frac{I_{t+1}}{K_{t+1}} \right) - \Phi' \left( \frac{I_{t+1}}{K_{t+1}} \right) \frac{I_{t+1}}{K_{t+1}} - \delta_k \right]}{Q_t} \quad (23)$$

These returns are then an input to the excess levered return on equity

$$R_{ex,t}^{LEV} = \phi_{lev}(R_t - R_{t-1}^f) + \epsilon_t^d \quad (24)$$

Here  $\phi_{lev}$  represents the effect financial leverage, and  $\epsilon_t^d \text{ i.i.d. } N(0, \sigma_d)$  is an idiosyncratic dividend shock, which does not effect the representative agent's consumption. The idiosyncratic dividend shock does not impact expected returns, but allows the model to better match the observed volatility of equity returns.

## 4 Benchmark Model Results

The solution to the benchmark model is obtained using perturbation methods to accommodate the high number of state and control variables.<sup>15</sup> The model is calibrated for two parameterizations, representing a “responsive” and “unresponsive” oil supply. The only difference between the two regimes is in the persistence of oil price shocks  $\rho_w$ , which is closer to one in the unresponsive calibration. The complexity of the model makes an explicit regime shifting process computationally infeasible, so I instead I perform the comparative static of examining two different calibrations of the model parameters and comparing them to the two different time periods in the data

One way to interpret this exercise is that it considers an unanticipated change in supply conditions.<sup>16</sup> For instance, if a sudden increase of world wide oil demand rapidly outstripped available supply capacity, the oil industry may have been quickly forced into a regime where it was unable to respond to subsequent shocks. If this was not anticipated ex ante, the risks

---

<sup>15</sup>See Appendix A for a full set of equilibrium conditions and description of the solution method.

<sup>16</sup>The model can be augmented to include a time-varying process for  $\rho_w$ , in unreported results I solve the model for this case and simulate a path with a sudden unexpected change in persistence. The asset pricing implications of the model are largely unchanged.

associated with this change in supply conditions would not be reflected in future contracts in the first period. While it would be interesting to examine the effects of explicit regime changes, I focus here on the simple exercise of comparing the two regimes, and leave a more general model to future work.

Table 4 presents the calibrated model parameters for utility and the production processes. Most of the parameters are chosen as in Croce (2014) to facilitate comparison. The exceptions are a lower volatility of aggregate consumption but a higher risk aversion, due to the lower observed consumption volatility of the more recent sample period used in this paper. Parameters related to oil production and consumption are calibrated to match observed behavior of prices and oil expenditure by households and producers.

Small changes in the levels of  $\rho_w$  and  $\zeta$  can have large impacts on the risk premium associated with oil futures prices. It is therefore important that they are disciplined by other moments in the data.

The levels of  $\rho_w$  across the two specifications are not chosen arbitrarily, but are rather calibrated to match the observed term structure of future return volatility, which are very precisely estimated even in short samples, and on which they have a first order effect.

Likewise the parameter  $\zeta$  is set at -0.004 so that a unit increase in the log of the oil consumption ratio leads to a decrease of approximately 1% in the log of production growth, consistent with the annual regressions in Table 3, which are the more conservative estimates.

The parameter  $\xi_G$  is set at 0.25 to match the value from the regressions in Table 2, and the panel  $\xi_O$  is set at 0.225 to match the negative comovement of oil prices and the share of oil used for household consumption.

In both calibrations, the parameter of  $\kappa$  is set to 0.8. This is done so that shocks to long-run growth expectations have minimal impact on the long-run expected oil price growth, since the oil supply is assumed to be able to respond equally to long-run growth shocks in both cases. This assumption is made so shocks to  $x_t$  do not impact the term structure of oil futures returns,

keeping the focus of the analysis on oil supply shocks. While it is interesting to study the interaction of long-run productivity growth shocks and oil prices, the lack of consensus in the literature about the precise nature of these shocks makes this questions a difficult one, so I do not attempt to approach it here.

Panels A and B of Table 5 present aggregate market moments and oil specific moments respectively. These calibrations are shown for unresponsive and responsive scenarios for the Benchmark Model.

[Table 4 about here.]

[Table 5 about here.]

Panel A of Table 5 shows that the model is able to do a reasonable job matching macroeconomic moments. The ability of this type of model to match volatilities of macroeconomic aggregates and asset prices over a longer sample period is shown by Croce (2014). Since the sample period here exhibits lower volatility than that in Croce (2014) the model's fit is not quite as good. However, the model is able to generate low consumption volatilities and a reasonably high levered equity premium of 4.98% in the responsive supply calibration.

As Panel B of Table 5 shows, the model is also able to match many of the features of oil futures data. A decrease in the responsiveness of the oil supply leads to a flattening of the term structure of future volatilities, and a more upward sloping term structure of returns and prices.

Figure 6 plots the changes in the term structures of future prices, returns, and return volatilities across the two benchmark specifications alongside the term structures from the data. As the figure shows, the model is able to account for many of the changes in the futures curve across the two regimes. An unresponsive oil supply creates an upwardly sloping term structure of prices, which is driven by a decrease in expected returns across the entire curve.

[Figure 6 about here.]

Unlike reduced form models of oil prices, the model is disciplined by matching many of the macro moments, and therefore fails to perfectly match the quantitative size of the asset pricing facts, but the observed effects are of the same order of magnitude as those observed in the data.

Another shortcoming of the model is that the slope of the futures curve has a strong upward slope in both calibrations due to the lognormal nature of the model. The log of the oil price has zero average growth in the model, but the high volatility of oil prices leads to expected growth in the level of prices over time which is reflected in the upward slope of the future price curves. Reduced form models, such as Gibson and Schwartz (1990) account for this by imposing an exogenous drift term in prices to offset this effect and match the observed curves in the data, but here the requirements of a balanced growth path and lognormality for tractability preclude this adjustment.

Finally, the model is also able to match the levels and dynamics of oil expenditure by households and by the economy as a whole. Figure 7 graphs a sample path of the model and shows both the ratio of household oil consumption to total oil consumption, and the ratio of total oil expenditure to aggregate output. Panel A of this figure shows that the model is able to match the positive correlation between oil prices and the ratio of total oil expenditure to output, and Panel B illustrates the same negative correlation between oil prices and the ratio of household oil consumption to total oil consumption seen in the data.

[Figure 7 about here.]

To further explore the implications of the model, I now turn to impulse response functions to help understand the mechanisms which generate the observed results for macroeconomic quantities and future markets.

## 4.1 Model Mechanisms

### 4.1.1 Output, Labor, and Investment

Figure 8 shows the impact of the three model shocks on capital, labor, and TFP. As in the data, the effect is concentrated mainly a reduction of hours worked as workers substitute away from consumption (which requires oil) and into leisure, and this effect is quite strong in either the unresponsive or responsive state. In contrast, the investment effect is more muted, particularly in the responsive case.

The lack of investment response to an oil shock in the responsive regime is due to the fact that oil is both a final and intermediate good. When oil is needed for both production and consumption, an increase in oil prices does not create a substitution effect from capital goods to consumption goods. Furthermore, since the shocks are short-lived, the wealth effect is also small, and investment is essentially unchanged. However, when oil shocks are expected to persist, a negative oil shock has a long lasting impact on TFP growth, and investment responds following the same intuition involving long-run productivity shocks in the models of Kaltenbrunner and Lochstoer (2010) and Croce (2014). Even in the unresponsive case, the investment effect in the benchmark calibration is small when compared to the shocks to technology growth.

[Figure 8 about here.]

### 4.1.2 The Term Structure of Oil Futures

In the model, expected returns to oil futures are determined by the exposure of oil future prices to the various shocks as well as the prices of risk associated with those shocks. Changes in these exposures and prices of risk across the two regimes generate the different behavior of the futures curves in the model.

To illustrate this, consider Equation 21. If prices are lognormally distributed, this equation can be restated as

$$f_t^j = E_t[f_{t+1}^{j-1}] + \frac{1}{2}\text{var}_t(f_{t+1}^{j-1}) + \text{cov}_t(f_{t+1}^{j-1}, m_{t+1}) \quad (25)$$

Setting  $j = 1$  and subtracting  $p_t$  from both sides gives an expression for the futures basis, or the slope of the term structure of future prices at the short end of the futures curve

$$f_t^1 - p_t = E_t[p_{t+1} - p_t] + \frac{1}{2}\text{var}_t(p_{t+1}) + \text{cov}_t(p_{t+1}, m_{t+1}) \quad (26)$$

Therefore the slope of the term structure of future prices at a given time includes the expected growth in price, which has both a mean and variance term due to the lognormal nature of the model, as well as a risk premium generated by the covariance of prices and the stochastic discount factor

To see how the various shocks in the model impact oil prices and the stochastic discount factor across the two regimes, Figure 9 plots these impulse response functions for the benchmark case.

The increase in the slope of the term structure of future prices is driven by the changing risk premium associated with shocks to  $w_t$ . In the responsive case, there is a slight positive return created by a negative correlation with  $M_t$  coming from the short-run productivity shocks, and a small negative return created by the positive correlation with  $M_t$  from shocks to oil production. The two effects yield a slight upward slope in the futures curve.

When oil prices impact future growth, more persistent oil price shocks command a larger level of risk, as evidenced by their increased impact on the SDF in the unresponsive regime. This leads to a stronger positive covariance of  $M_t$  and future returns at all maturities, and equivalently a more upwardly sloping term structure of future prices.

[Figure 9 about here.]

## 4.2 Alternate Calibrations

In order to highlight the mechanisms necessary to generate the observed behavior in the futures curve, the model is recalibrated using two alternate scenarios. In the first, the impact of the oil supply on TFP growth is removed ( $\zeta = 0$ ) and in the second,  $\bar{w}$  is increased so that oil expenditure relative to total output is roughly 50% of what it is in the Benchmark calibration. In both cases the model is again simulated in an unresponsive and responsive oil supply regime.

[Table 6 about here.]

Table 6 shows the model moments under the two alternate scenarios as well as the Benchmark Model for comparison, and Figure 10 shows the term structures of oil futures.

[Figure 10 about here.]

As the table and figure show, the calibration without an exogenous impact of the oil supply on future TFP growth exhibits none of the increase in the term structure of average future prices that are observed in the data. In contrast, the scenario with an exogenous growth impact but more plentiful oil generates futures term structures similar to the benchmark model. This suggests that, when considering the behavior of oil futures, the persistence of price shocks may be more important than their aggregate level.

## 5 Recent Changes in the Oil Futures Curve and North American Production

This section considers more recent changes in oil markets. While concerns about the long-run supply of oil appear to be able to explain much of the behavior observed from 2005 to 2012, the more recent period has seen large increases in production from technological advancements in extracting oil from shale fields in the United States. If these advancements have the potential

to reduce long-run uncertainty about oil prices, the model suggests that this should translate into changes in the futures curve. I show here that this appears to be the case.

Panel A of Figure 11 shows estimates of the persistence of oil price shocks implied by the behavior of long-term futures, as well as the slope of the futures curve adjusted for changes in the level of prices. The figure shows evidence the persistence of oil price shocks has undergone a drastic drop, suggesting more stable expectations for long run prices. This drop in persistence has also coincided with a shift towards a more downward sloping term structure of future prices.

Panel B plots U.S. oil production and financial open interest in oil futures over the same period, and shows that these changes in the futures curve coincide with a rapid increase in North American production production. In contrast, this period has seen little change in the amount of open interest in oil futures.

This increase in production has come primarily from high cost sources of oil, and thus far has had little impact on overall price levels. Despite this high price, the additional supply capacity may still have a large impact on the riskiness of oil futures, by reducing uncertainty about long-run price levels. The observed behavior of oil futures is consistent with these effects, indicating that the market anticipates these new sources of production will have a significant reduction on long-run supply uncertainty.

[Figure 11 about here.]

## 6 Conclusion

The recent focus in commodity markets has been squarely on the behavior of financial speculators. However, using financialization to explain observed behavior in these markets may be premature when there is still not yet a clear understanding of how these commodities interact more broadly with macroeconomic risk. This paper contributes several new empirical facts regarding the use of oil in the economy and the relation between oil prices and future growth,

and uses these facts to develop a production-based asset pricing model for studying oil price risk. The model is able to match key features of the relation of oil to various macroeconomic aggregates, and illustrates how a change in the dynamics of the the oil supply may provide an explanation for observed changes in the term structure of oil futures from 2005 to 2012.

The data and the model suggest that a key driver of the riskiness of oil price shocks is their persistence, potentially more so than the level of oil prices. This provides novel evidence for the importance of persistence in determining risk premia, a central mechanism in the LRR literature. This finding also provides hope for the future. New North American sources of production may keep prices more stable in the long term, reducing the persistence and importance of oil price shocks. Indeed, the recent behavior of futures prices shows evidence of these effects.

The results here also highlight the importance of understanding the exact relation between oil prices and economic output. This paper provides evidence that oil price shocks affect future productivity growth and illustrates the potential importance for asset prices. Endogenizing this relation between economic growth and oil prices is an important avenue for future research.

## References

- Acharya, Viral V, Lars A Lochstoer, and Tarun Ramadorai, 2013, Limits to arbitrage and hedging: Evidence from commodity markets, *Journal of Financial Economics* 109, 441–465.
- Baker, Steven D, 2012, The Financialization of Storable Commodities, *Working Paper*.
- Baker, Steven D, and Bryan R Routledge, 2012, The Price of Oil Risk, *Working Paper*.
- Bansal, Ravi, and Amir Yaron, 2004, Risks for the Long Run: A Potential Resolution of Asset Pricing Puzzles, *The Journal of Finance* 59, 1481–1509.
- Barsky, Robert, and Lutz Kilian, 2004, Oil and the macroeconomy since the 1970s, Working paper, National Bureau of Economic Research.

- Basak, Suleyman, and Anna Pavlova, 2013, A model of financialization of commodities, *Available at SSRN 2201600*.
- Bentzen, Jan, and Tom Engsted, 1993, Short- and long-run elasticities in energy demand: A cointegration approach, *Energy Economics* 15, 9–16.
- Bessembinder, Hendrik, Jay Coughenour, Paul Seguin, and Margaret Monroe Smoller, 1995, Mean Reversion in Equilibrium Asset Prices: Evidence from the Futures Term Structure, *Journal of Finance* 50, 361–75.
- Bodenstein, Martin, Luca Guerrieri, and Lutz Kilian, 2012, Monetary policy responses to oil price fluctuations, *IMF Economic Review* 60, 470–504.
- Buyuksahin, Bahattin, and Michel Robe, 2011, Does’ paper oil’matter? Energy markets financialization and equity-commodity co-movements, *Energy Markets Financialization and Equity-Commodity Co-Movements (July 28, 2011)*.
- Carlson, Murray, Zeigham Khokher, and Sheridan Titman, 2007, Equilibrium Exhaustible Resource Price Dynamics, *Journal of Finance* 62, 1663–1703.
- Casassus, Jaime, Pierre Collin-Dufresne, and Bryan R. Routledge, 2005, Equilibrium Commodity Prices with Irreversible Investment and Non-Linear Technology, *SSRN eLibrary*.
- Christoffersen, Peter, and Xuhui Nick Pan, 2014, Oil Risk Exposure and Expected Stock Returns, *Available at SSRN 2399677*.
- Cochrane, John H, 1991, Production-based asset pricing and the link between stock returns and economic fluctuations, *The Journal of Finance* 46, 209–237.
- Cochrane, John H, 2001, Asset pricing, .
- Croce, Mariano Massimiliano, 2014, Long-run productivity risk: A new hope for production-based asset pricing, *Forthcoming, Journal of Monetary Economics*.

- Deaton, Angus, and Guy Laroque, 1992, On the Behaviour of Commodity Prices, *The Review of Economic Studies* 59, 1–23.
- Deaton, Angus, and Guy Laroque, 1996, Competitive Storage and Commodity Price Dynamics, *The Journal of Political Economy* 104, 896–923.
- Domanski, Dietrich, and Alexandra Heath, 2007, Financial investors and commodity markets, *BIS Quarterly Review*, March.
- Epstein, Larry G., and Stanley E. Zin, 1989, Substitution, Risk Aversion, and the Temporal Behavior of Consumption and Asset Returns: A Theoretical Framework, *Econometrica* 57, 937–969.
- Fattouh, Bassam, Lutz Kilian, and Lavan Mahadeva, 2013, The role of speculation in oil markets: What have we learned so far?, *Energy Journal* 34.
- Feder, Gershon, 1983, On exports and economic growth, *Journal of development economics* 12, 59–73.
- Gibson, Rajna, and Eduardo S. Schwartz, 1990, Stochastic Convenience Yield and the Pricing of Oil Contingent Claims, *The Journal of Finance* 45, 959–976.
- Hamilton, James D., 2003, What is an oil shock?, *Journal of Econometrics* 113, 363 – 398.
- Hamilton, James D., 2008, Understanding Crude Oil Prices, NBER Working Papers 14492 National Bureau of Economic Research, Inc.
- Hamilton, James D, and Jing Cynthia Wu, 2012, Effects of index-fund investing on commodity futures prices, Working paper, Working paper, University of California, San Diego.
- Hamilton, James D, and Jing Cynthia Wu, 2013, Risk premia in crude oil futures prices, *Journal of International Money and Finance*.

- Irwin, Scott H, and Dwight R Sanders, 2011, Index funds, financialization, and commodity futures markets, *Applied Economic Perspectives and Policy* 33, 1–31.
- Jermann, Urban J., 1998, Asset pricing in production economies, *Journal of Monetary Economics* 41, 257 – 275.
- Kaldor, Nicholas, 1939, Speculation and Economic Stability, *The Review of Economic Studies* 7, 1–27.
- Kaltenbrunner, Georg, and Lars A. Lochstoer, 2010, Long-Run Risk through Consumption Smoothing, *Review of Financial Studies* 23, 3190–3224.
- Kilian, Lutz, and Daniel P Murphy, 2013, The role of inventories and speculative trading in the global market for crude oil, *Journal of Applied Econometrics*.
- Kogan, Leonid, Dmitry Livdan, and Amir Yaron, 2009, Oil Futures Prices in a Production Economy with Investment Constraints, *The Journal of Finance* 64, pp. 1345–1375.
- Kung, Howard, and Lukas Schmid, 2015, Innovation, growth and asset prices, *Journal of Finance*.
- Masters, Michael W, and Adam K White, 2008, The Accidental Hunt Brothers—Act 2, *Index Speculators Have Been a Major Cause of the Recent Drop in Oil Prices. Special Update September* 10.
- Melo, Jaime de, and Sherman Robinson, 1992, Productivity and externalities: models of export-led growth, *Journal of International Trade & Economic Development* 1, 41–68.
- Pakos, Michal, 2004, Asset Pricing with Durable Goods and Nonhomothetic Preferences, MPRA Paper 26167 University Library of Munich, Germany.
- Ramanathan, R., 1999, Short- and long-run elasticities of gasoline demand in India: An empirical analysis using cointegration techniques, *Energy Economics* 21, 321 – 330.

- Rotemberg, Julio J, and Michael Woodford, 1996, Imperfect Competition and the Effects of Energy Price Increases on Economic Activity, *Journal of Money, Credit and Banking* 28, 549–577.
- Routledge, Bryan R., Duane J. Seppi, and Chester S. Spatt, 2000, Equilibrium Forward Curves for Commodities, *The Journal of Finance* 55, 1297–1338.
- Sánchez, Marcelo, 2011, Oil shocks and endogenous markups: results from an estimated euro area DSGE model, *International Economics and Economic Policy* 8, 247–273.
- Singleton, Kenneth J, 2013, Investor flows and the 2008 boom/bust in oil prices, *Management Science*.
- Stock, James H., and Mark W. Watson, 1993, A Simple Estimator of Cointegrating Vectors in Higher Order Integrated Systems, *Econometrica* 61, pp. 783–820.
- Tang, Ke, and Wei Xiong, 2012, Index Investment and the Financialization of Commodities, *Financial Analysts Journal* 68.
- Ward, Colin, 2014, Is the IT revolution over? An asset pricing view, *Working Paper*.
- Williams, J.C., and B.D. Wright, 1991, *Storage and Commodity Markets*. (Cambridge University Press Cambridge, UK).
- Yogo, Motohiro, 2006, A Consumption-Based Explanation of Expected Stock Returns, *Journal of Finance*, Vol. 61, No. 2, 2006.

**Table 1: Tests for Changes in the Term Structure of Oil Futures**

This table reports regressions testing for changes in the term structure of future prices and returns for the period 1997 to 2012.  $\mathbb{1}_{t>2004}$  is a dummy variable that takes the value one for observations after December 2004, and zero otherwise.  $r_t^j$  is the return to investing in the  $j$ -nearest futures contract.  $r_{t-6,t}^j$  is the cumulative return from the month period and the previous six months.  $Slope_t$  is the log difference of the sixth future price and nearest maturity price. Data are monthly. Newey-West standard errors with 6 lags in parentheses.

**Panel A: Tests for Changes in Term Structure of Prices**

	Energy			Agricultural			Softs			Livestock			Metals			
	Crude Oil $Slope_t$	Htg. Oil $Slope_t$	Nat. Gas $Slope_t$	Wheat $Slope_t$	Corn $Slope_t$	Soybeans $Slope_t$	SB Oil $Slope_t$	Sugar $Slope_t$	Cocoa $Slope_t$	Coffee $Slope_t$	Cotton $Slope_t$	Hogs $Slope_t$	Cattle $Slope_t$	Copper $Slope_t$	Gold $Slope_t$	Silver $Slope_t$
$\mathbb{1}_{t>2004}$	1.23** (0.27)	0.83* (0.37)	1.10* (0.50)	0.24 (0.49)	-0.64 (0.62)	0.60 (0.46)	0.29 (0.28)	0.48 (0.77)	-0.48 (0.38)	0.36 (0.86)	-0.60 (0.86)	1.18 (0.87)	0.48 (0.32)	-0.66* (0.36)	-0.11 (0.10)	-0.08 (0.09)
$r_{t-6,t}^2$	-4.21** (1.05)	-5.20** (1.47)	-5.16** (1.04)	-5.43** (1.95)	-4.04** (1.06)	-5.78* (1.68)	-2.84* (1.25)	-4.63** (1.21)	-4.19** (1.46)	-5.34 (3.71)	-1.97 (1.50)	-9.68** (2.24)	-10.06** (2.45)	-3.77** (0.91)	-1.65** (0.34)	-1.17** (0.24)
$\mathbb{1}_{t>2004} * r_{t-6,t}^2$	2.25* (1.12)	4.27*** (1.50)	1.02 (1.58)	-0.06 (2.67)	0.36 (1.54)	3.93* (1.88)	2.61** (1.25)	-0.28 (1.94)	2.88 (1.64)	3.71 (3.83)	-3.44 (4.00)	0.10 (2.90)	6.16* (2.82)	2.19* (1.08)	1.90** (0.65)	1.10** (0.32)
Constant	-0.49* (0.24)	-0.17 (0.33)	0.58* (0.32)	1.97** (0.41)	2.10** (0.34)	-0.54 (0.38)	0.39 (0.27)	-0.47 (0.46)	1.13** (0.34)	1.28 (0.84)	1.71** (0.35)	0.29 (0.68)	0.35 (0.24)	0.06 (0.25)	0.51* (0.05)	0.42** (0.06)
Observations	192	192	192	192	192	192	192	192	190	192	192	192	192	192	192	192
R-squared	0.30	0.26	0.25	0.30	0.31	0.28	0.29	0.29	0.29	0.32	0.30	0.24	0.25	0.31	0.32	0.27

**Panel B: Tests for Changes in Term Structure of Returns**

	Energy			Agricultural			Softs			Livestock			Metals			
	Crude Oil $r_t^6$	Htg. Oil $r_t^6$	Nat. Gas $r_t^6$	Wheat $r_t^6$	Corn $r_t^6$	Soybeans $r_t^6$	SB Oil $r_t^6$	Sugar $r_t^6$	Cocoa $r_t^6$	Coffee $r_t^6$	Cotton $r_t^6$	Hogs $r_t^6$	Cattle $r_t^6$	Copper $r_t^6$	Gold $r_t^6$	Silver $r_t^6$
$\mathbb{1}_{t>2004}$	0.19 (0.28)	0.16 (0.39)	-0.91 (0.54)	0.15 (0.36)	0.21 (0.25)	0.54 (0.41)	-0.00 (0.20)	2.37** (0.64)	0.54 (0.31)	0.82* (0.36)	0.28 (0.56)	0.30 (0.78)	0.73 (0.40)	0.31 (0.24)	-0.07 (0.08)	-0.05 (0.08)
$r_t^2$	0.72** (0.02)	0.65** (0.06)	0.51** (0.05)	0.68** (0.03)	0.68** (0.02)	0.73** (0.06)	0.89** (0.03)	0.50** (0.05)	0.87** (0.02)	0.71** (0.04)	0.62** (0.05)	0.15* (0.07)	0.28** (0.07)	0.85** (0.02)	0.98** (0.01)	0.95** (0.01)
$\mathbb{1}_{t>2004} * r_t^2$	0.16** (0.04)	0.25** (0.06)	0.19** (0.06)	0.05 (0.05)	0.07 (0.04)	0.16* (0.07)	0.08** (0.03)	0.02 (0.07)	-0.06 (0.04)	0.18** (0.04)	0.08 (0.07)	-0.04 (0.09)	0.09 (0.10)	0.09** (0.03)	0.02* (0.01)	0.05** (0.01)
Constant	0.60** (0.21)	0.36 (0.33)	1.51** (0.45)	0.56** (0.21)	0.32* (0.13)	0.04 (0.31)	0.43* (0.18)	-0.53 (0.47)	-0.34 (0.23)	-0.30 (0.33)	0.15 (0.42)	1.57* (0.63)	-0.32 (0.30)	0.51** (0.14)	0.06* (0.03)	0.20** (0.06)
Observations	192	192	192	192	192	192	192	192	191	192	192	192	192	192	192	192
R-squared	0.94	0.89	0.85	0.87	0.93	0.85	0.97	0.60	0.94	0.93	0.75	0.05	0.25	0.96	1.00	1.00

Newey-West Standard Errors in Parentheses

\*\* p < 0.01, \* p < 0.05

**Table 2: Oil Prices and Oil Consumption**

Estimation of Stock and Watson (1993) regressions of log real spot price on logs of economic variables.

$$p_t = \beta_0 + \beta_1 x_t^1 + \beta_2 x_t^2 + \sum_{t=-k}^k \Gamma_{1,k} \Delta x_{t+k}^1 + \sum_{t=-k}^k \Gamma_{2,k} \Delta x_{t+k}^2$$

The spot price is the WTI index adjusted by the CPI less energy and divided by average miles per gallon of the U.S. passenger car fleet. Log of Aggregate Cons. is the log of a Cobb-Douglas aggregate of the stock of durable consumption goods and nondurables and services consumption expenditure as in Yogo (2006). Log of nondurables is log of nondurables and services from NIPA tables. Log of household oil consumption is log of consumption of gasoline and other energy goods taken from the NIPA tables and adjusted for U.S. passenger car fleet miles per gallon, log of total oil consumption is the measure of oil "Product Supplied" taken from EIA data. Personal oil consumption, household aggregate consumption and personal income are measured per capita. All data is in real terms. Regressions are performed with contemporaneous differences, as well two leads and lags. Coefficients on difference terms as well as constants are suppressed. Standard errors are Newey-West with two lags.

Variables	(1) $p_t$	(2) $p_t$	(3) $p_t$	(4) $p_t$	(5) $p_t$	(6) $p_t$	(7) $p_t$	(8) $p_t$
Log Aggregate Cons.	2.417** (0.135)				3.321** (0.397)			
Log Nondurables		4.112** (0.228)				0.985 (0.813)		
Log GDP			2.525** (0.145)				2.664** (0.468)	
Log Personal Income				2.950** (0.168)				3.589** (0.528)
Log Household Oil Use	-5.977** (0.241)	-6.763** (0.267)	-6.416** (0.262)	-6.230** (0.257)				
Log Total Oil Use					-8.296** (1.102)	-2.820* (1.316)	-6.641** (1.300)	-7.757** (1.260)
Observations	127	127	127	127	127	127	127	127
R-squared	0.881	0.889	0.888	0.879	0.558	0.256	0.444	0.492

Standard errors in parentheses

\*\* p < 0.01, \* p < 0.05

**Table 3:** Forecasting TFP Growth with Oil and Other Predictors

This table shows results of regressions of the form

$$\Delta TFP_{t,t+k}^i = \alpha + \beta^{G/C} (ConsRatio_t) + \beta^X X_t$$

$TFP_{t,t+k}^i$  is the log of utilization adjusted TFP growth from period  $t$  to  $t+k$ , reported by the San Francisco Federal Reserve.  $i = I$  is productivity of investment goods and consumer durables, and  $i = C$  is TFP for all other products.  $ConsRatio_t$  is equal to the log of the ratio of household consumption of “gasoline and other energy goods” divided by expenditure total expenditure on non-durable and durable goods in the NIPA personal consumption survey.  $X = RDI$  is aggregate R & D intensity constructed as in Kung and Schmid (2015), and  $X = IT$  is the price-dividend ratio of the IT sector constructed as in Ward (2014). Newey-West and Hodrick (1992) standard errors with  $k$  lags in parentheses. Results in Panel A are quarterly from 1973Q1 to 2012Q4, and results in Panel B are annual from 1953 to 2012.

Panel A: Quarterly Data (1973 - 2012)

Univariate Predictive Regressions of TFP Growth on Oil Expenditure Ratio of Households

$\Delta TFP_{t,t+k}^I$	$\beta^{G/C}$	NW SE	H SE	$R^2$	$\Delta TFP_{t,t+k}^C$	$\beta^{G/C}$	NW SE	H SE	$R^2$
1 Qtr	-0.009*	(0.004)	(0.004)	0.047	1 Qtr	-0.003	(0.003)	(0.003)	0.009
4 Qtr	-0.031*	(0.013)	(0.014)	0.085	4 Qtr	-0.007	(0.008)	(0.011)	0.010
8 Qtr	-0.075**	(0.021)	(0.025)	0.216	8 Qtr	-0.012	(0.016)	(0.019)	0.013
12 Qtr	-0.118**	(0.036)	(0.036)	0.332	12 Qtr	-0.013	(0.021)	(0.028)	0.013

Multivariate Predictive Regressions with IT Sector P-D Ratio

$\Delta TFP_{t,t+k}^I$	$\beta^{G/C}$	NW SE	$\beta^{IT}$	NW SE	$R^2$	$\Delta TFP_{t,t+k}^C$	$\beta^{G/C}$	NW SE	$\beta^{IT}$	NW SE	$R^2$
1 Qtr	-0.008	(0.004)	0.001	(0.001)	0.049	1 Qtr	-0.002	(0.004)	0.001	(0.001)	0.012
4 Qtr	-0.020	(0.014)	0.008	(0.006)	0.114	4 Qtr	0.000	(0.011)	0.006	(0.005)	0.040
8 Qtr	-0.057*	(0.023)	0.015	(0.009)	0.258	8 Qtr	0.008	(0.020)	0.016*	(0.008)	0.131
12 Qtr	-0.092*	(0.036)	0.022	(0.013)	0.390	12 Qtr	0.020	(0.023)	0.029**	(0.008)	0.297

Panel B: Annual Data (1953 - 2012)

Univariate Predictive Regressions of TFP Growth on Oil Expenditure Ratio of Households

$\Delta TFP_{t,t+k}^I$	$\beta^{G/C}$	NW SE	H SE	$R^2$	$\Delta TFP_{t,t+k}^C$	$\beta^{G/C}$	NW SE	H SE	$R^2$
1 Year	-0.010**	(0.004)	(0.004)	0.094	1 Year	-0.002	(0.003)	(0.003)	0.008
2 Year	-0.021**	(0.007)	(0.007)	0.196	2 Year	-0.003	(0.005)	(0.005)	0.008
3 Year	-0.030*	(0.011)	(0.011)	0.245	3 Year	-0.003	(0.006)	(0.007)	0.004
4 Year	-0.036*	(0.015)	(0.014)	0.229	4 Year	-0.001	(0.007)	(0.009)	0.000

Multivariate Predictive Regressions with R & D Intensity

$\Delta TFP_{t,t+k}^I$	$\beta^{G/C}$	NW SE	$\beta^{RDI}$	NW SE	$R^2$	$\Delta TFP_{t,t+k}^C$	$\beta^{G/C}$	NW SE	$\beta^{RDI}$	NW SE	$R^2$
1 Year	-0.010**	(0.004)	-0.002	(0.004)	0.098	1 Year	-0.001	(0.003)	0.009**	(0.003)	0.185
2 Year	-0.022**	(0.007)	-0.007	(0.007)	0.219	2 Year	-0.001	(0.004)	0.018**	(0.005)	0.295
3 Year	-0.031**	(0.011)	-0.011	(0.012)	0.276	3 Year	-0.001	(0.005)	0.029**	(0.007)	0.433
4 Year	-0.036*	(0.015)	-0.011	(0.016)	0.248	4 Year	0.001	(0.005)	0.041**	(0.009)	0.559

Newey-West and Hodrick (1992) standard errors in parentheses

\*\* p < 0.01, \* p < 0.05

**Table 4: Model Parameters**

Model parameters for the benchmark calibrations. Model is calibrated at a monthly frequency.

Description	Parameter	Value
<b>Utility</b>		
Intertemporal Elasticity of Substitution	$\psi$	2
Risk Aversion	$\gamma$	18
Discount Factor	$\beta$	$.98^{1/12}$
Elasticity of Oil Substitution in Consumption	$\xi_G$	0.25
Oil Share in Consumption	$a_G$	0.05
Leisure Share in Consumption	$\phi$	0.2
<b>Production</b>		
Average Growth of TFP	$\mu$	$.18/12$
Volatility of Short Run Shocks	$\sigma_a$	0.0052
Volatility of Long Run Shocks	$\sigma_x$	0.00052
Mean Reversion of $x_t$	$\rho_x$	0.982
Elasticity of Oil Substitution in Production	$\xi_O$	0.225
Share of Oil in Production	$a_O$	0.55
Capital Share in Production	$\alpha$	0.32
Jermann Adj. Cost Parameter	$\chi$	7
Depreciation Rate	$\delta$	$.06/12$
<b>Oil Supply Dynamics</b>		
Volatility of Oil Supply Shocks	$\sigma_w$	0.024
Exogenous Effect of Oil Supply on TFP	$\zeta$	-0.004
Oil Supply Reaction to Expected Growth	$\kappa$	0.8
		Responsive      Unresponsive
		Supply      Supply
Mean Reversion of Oil Supply	$\rho_w$	0.943      0.987

**Table 5: Moments: Data and Benchmark Calibration**

Data and Model moments from the benchmark calibration. Lowercase denotes logs.  $Y_t$  is U.S. GDP in the data and total output of the basic (non-oil) good in the model.  $C_t$  is consumption of nondurables and services and consumption of the basic good in the model.  $I_t$  is aggregate investment in the data, and investment in the basic good in the model.  $G_t$  and  $O_t$  are household consumption of oil and oil used as an input into production.  $r_{ex}^{LEV}$  is the excess market return in the data, and the excess return to capital investment in the model.  $f_t^j$  and  $r_t^j$  are the log price and log return on investing in the  $j$  month future contract.  $\beta_2^{12}$  is the slope of a regression of 12-month future returns on contemporaneous returns to the 2-month future. The unresponsive and responsive regimes differ in their values of  $\rho_w$  as described in Table 4. The model is simulated for 100 simulations of 480 months, and moments are calculated as the average means or standard deviations of the last 360 months of each simulation.

Panel A: Aggregate Moments						
	Data			Benchmark Model		
	1970 - 2012			Resp. Supply	Unresp. Supply	
	Estimate	Std. Err.				
Macroeconomic Quantities						
$E[\Delta y]$	3.08	(0.24)		1.80	1.80	
$\sigma(\Delta y_t)$	1.85	(0.12)		2.21	2.24	
$\sigma(\Delta c_t)$	1.20	(0.15)		1.36	1.29	
$\sigma(\Delta i_t)$	4.67	(0.28)		7.35	7.13	
$E[I/Y]$	16.76	(0.11)		22.43	22.33	
Stock Market and Risk Free Rate						
$E[r_f]$	1.89	(0.20)		2.07	2.41	
$\sigma(r_f)$	1.53	(0.10)		0.64	0.63	
$E[r_{ex}^{LEV}]$	6.20	(1.97)		4.98	4.53	
$\sigma(r_{ex}^{LEV})$	15.87	(0.28)		7.22	7.17	
Panel B: Oil Price Moments						
	Data				Benchmark Model	
	1997 - 2004		2005-2012		Resp. Supply	Unresp. Supply
	Estimate	Std. Err.	Estimate	Std. Err.		
Oil Expenditure Ratios						
$E[\frac{(G+O)P}{Y}]$	2.89	(0.09)	4.08	(0.22)	3.76	3.75
$E[\frac{G}{G+O}]$	66.34	(0.04)	64.23	(0.05)	62.76	62.77
Oil Futures Prices and Returns						
$E[f_{12} - f_1]$	-5.31	(2.40)	1.78	(1.30)	2.68	7.91
$E[r^2 - \Delta p]$	6.84	(0.66)	-14.04	(0.57)	-0.46	-5.66
$\sigma[r^2]$	31.25	(1.14)	32.91	(1.55)	33.78	33.74
$\sigma[r^{12}]$	17.82	(0.72)	27.37	(1.29)	17.02	28.01
$\beta_2^{12}$	0.45	(0.02)	0.77	(0.03)	0.45	0.75

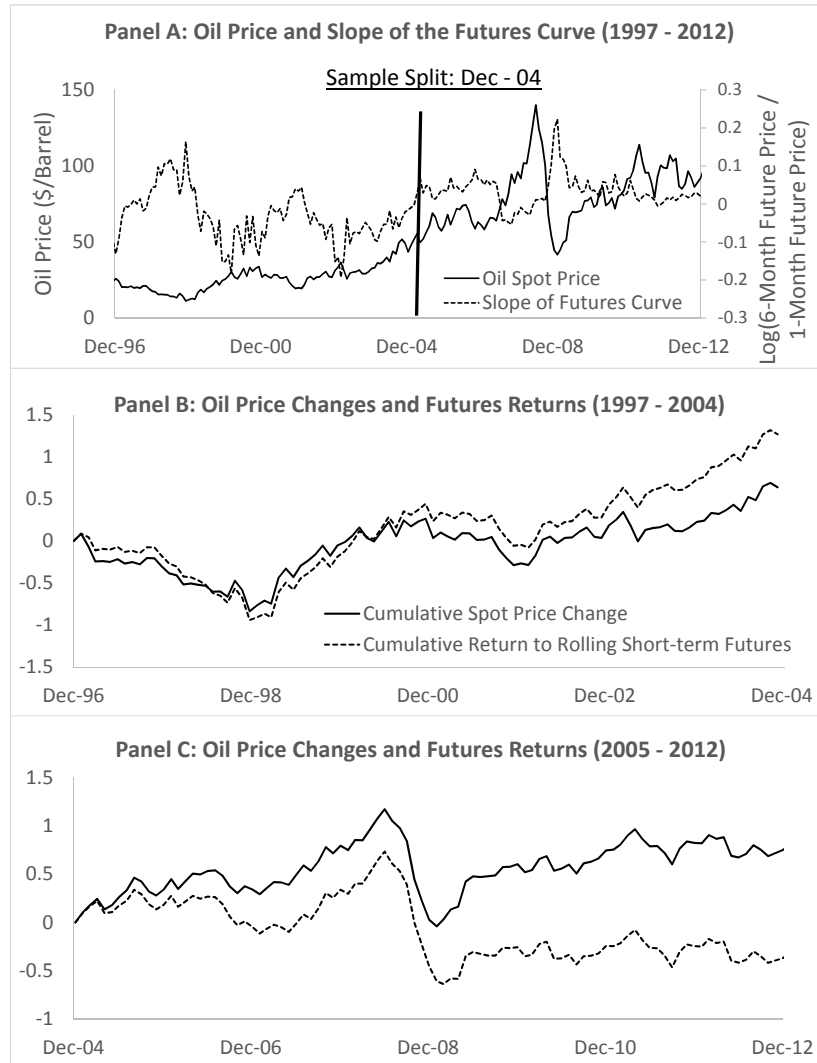
**Table 6: Moments: Benchmark and Alternate Model Specifications**

This table lists unconditional moments for aggregate and oil specific variables from six different parameterizations of the model. The unresponsive and responsive regimes differ in their values of  $\rho_w$  as described in Table 4. Variables are described in 5. For the “No Exogenous TFP Effect” specification the parameterizations are the same as the benchmark except that the variable  $\zeta = 0$ . For the “Low Oil Expenditure” calibration the mean level of the oil endowment  $\bar{w}$  is higher than the benchmark specification so that the total average expenditure on oil is roughly half that of the benchmark calibration. The model is simulated for 100 simulations of 480 months, and moments are calculated as the average means or standard deviations of the last 360 months of each simulation.

Panel A: Aggregate Moments						
	Benchmark Model		No Exogenous TFP Effect		Low Oil Expenditure	
	Responsive Supply	Unresponsive Supply	Responsive Supply	Unresponsive Supply	Responsive Supply	Unresponsive Supply
Macroeconomic Quantities						
$E[\Delta y]$	1.80	1.80	1.80	1.80	1.80	1.80
$\sigma(\Delta y_t)$	2.21	2.24	2.24	2.21	2.07	2.10
$\sigma(\Delta c_t)$	1.36	1.29	1.35	1.31	1.10	1.18
$\sigma(\Delta i_t)$	7.35	7.13	7.21	7.16	7.04	6.80
$E[I/Y]$	22.43	22.33	24.02	23.08	22.98	22.79
Stock Market and Risk Free Rate						
$E[r_f]$	2.07	2.41	2.33	1.78	2.10	2.50
$\sigma(r_f)$	0.64	0.63	0.64	0.62	0.59	0.63
$E[r_{EV}^{LEV}]$	4.98	4.53	5.06	5.04	4.89	4.46
$\sigma(r_{EV}^{LEV})$	7.35	7.10	7.20	7.18	7.32	7.06
Panel B: Oil Moments						
	Benchmark Model		No Exogenous TFP Effect		Low Oil Expenditure	
	Responsive Supply	Unresponsive Supply	Responsive Supply	Unresponsive Supply	Responsive Supply	Unresponsive Supply
Oil Expenditure Ratios						
$E[\frac{(G+O)P}{Y}]$	3.76	3.75	3.60	3.69	1.51	1.48
$E[\frac{G}{G+O}]$	62.76	62.77	62.31	62.66	63.02	63.01
Oil Futures Prices and Returns						
$E[f_{12} - f_1]$	2.68	7.91	0.26	1.17	3.24	9.15
$E[r^2 - \Delta p]$	-0.46	-5.66	3.66	3.05	-0.95	-6.67
$\sigma[r^2]$	33.78	33.74	34.23	34.18	35.54	35.51
$\sigma[r^{12}]$	17.02	28.01	17.74	29.42	17.99	29.69
$\beta_2^{12}$	0.45	0.75	0.47	0.77	0.46	0.75

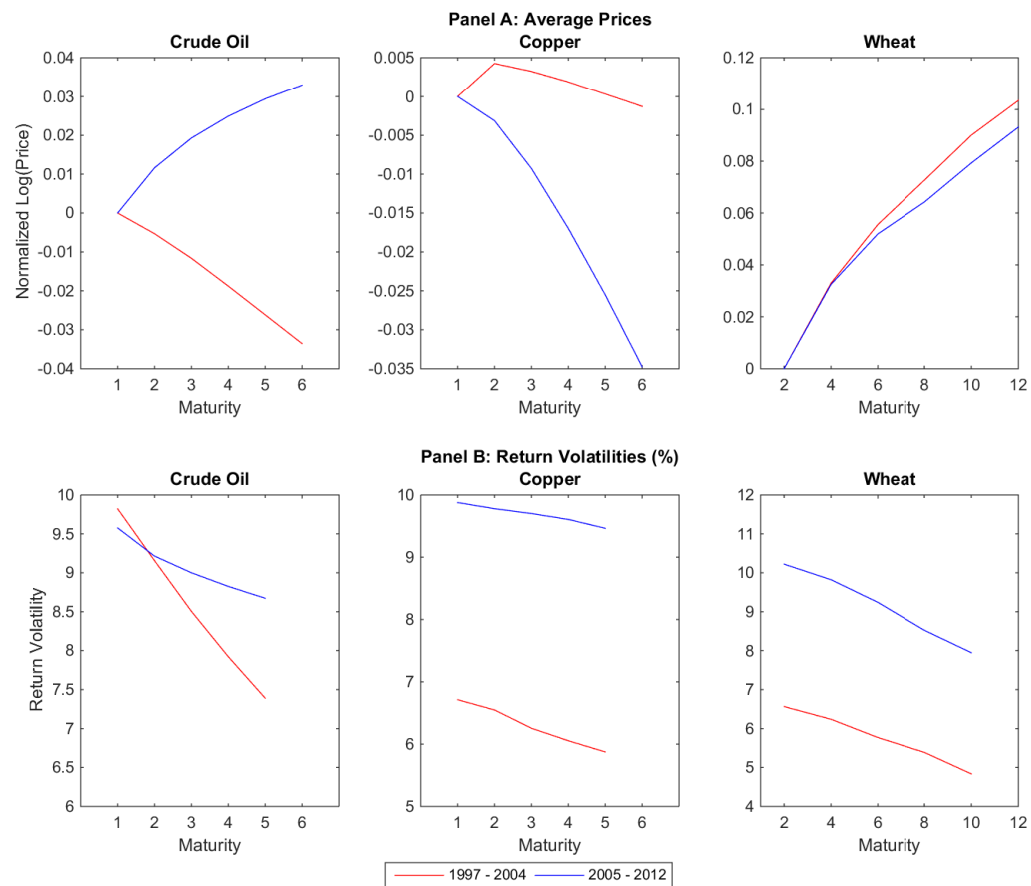
**Figure 1: Oil Spot Prices and Slope of Futures Term Structure: 1997 - 2012**

Panel A plots the time series of the spot price of oil as well as the slope of the future price curve, which is measured as the log of the ratio of the 6-month future price to the 1-month future price. The black line denotes the January 1, 2005 sample break point. Panel's B and C plot the cumulative change of the spot price in logs, as well as the cumulative return to a strategy which buys the second nearest future in each month and then closes out the position by selling the nearest future at the end of the month. Futures prices are the NYMEX WTI contract.



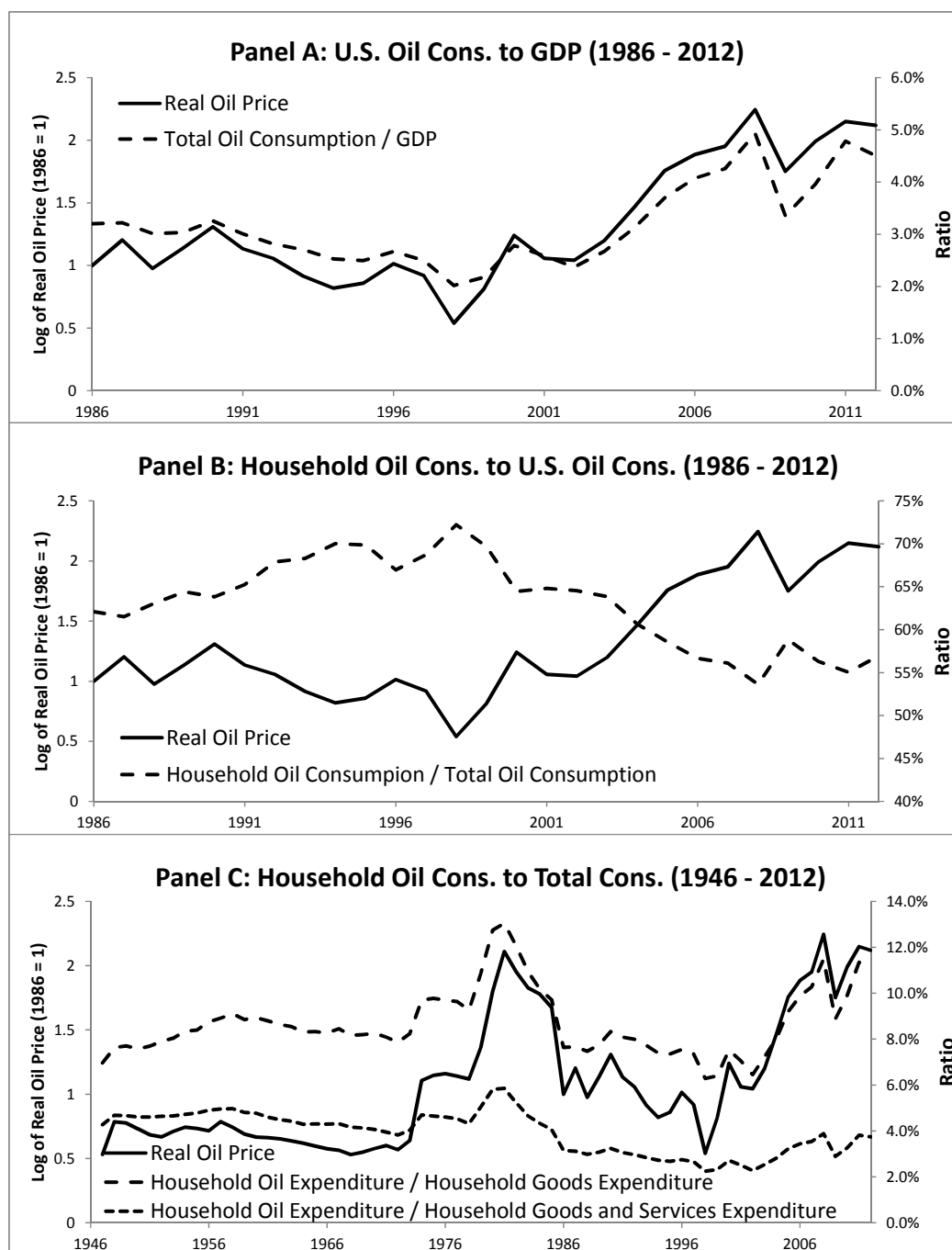
**Figure 2: Changes in the Futures Term Structure: Oil, Copper, and Wheat**

This figure reports features of the futures term structure using the six nearest term futures contracts for Crude Oil, Copper and Wheat over two subperiods, 1997 - 2004 and 2005 - 2012. Panel A reports the average log of future prices for the two subsamples. Price curves are expressed in log differences relative to the nearest term contract. Panel B reports monthly volatility of returns for different maturities.



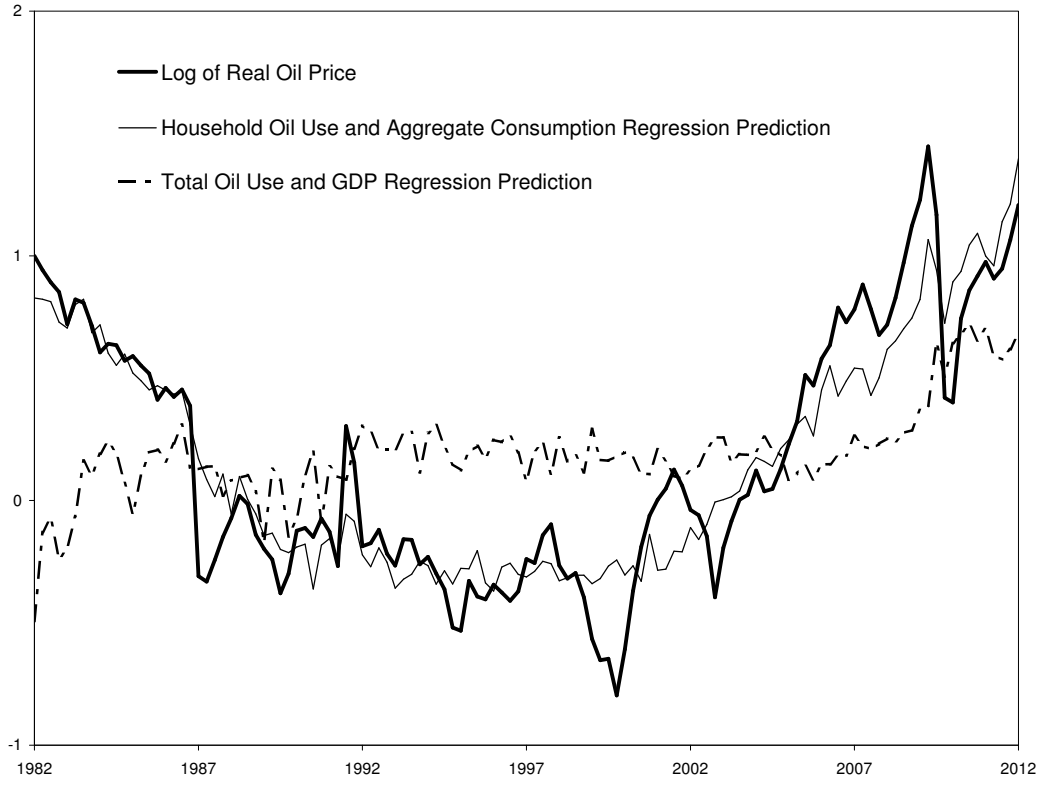
**Figure 3: Oil Consumption in the U.S. Economy**

Panel A plots the fraction of total U.S. oil consumption accounted for by households along with the real price of oil. Panel B plots total U.S. oil consumption relative to U.S. GDP. Panel C plots household oil consumption relative to both household goods expenditure, and total household consumption expenditure (goods and services). Household oil consumption is “Gasoline and Other Energy Goods” from the NIPA survey. Total oil consumption is calculated using consumption data and prices from the EIA. Real price of oil is the WTI index deflated by the CPI (excluding energy) goods. Data are annual.



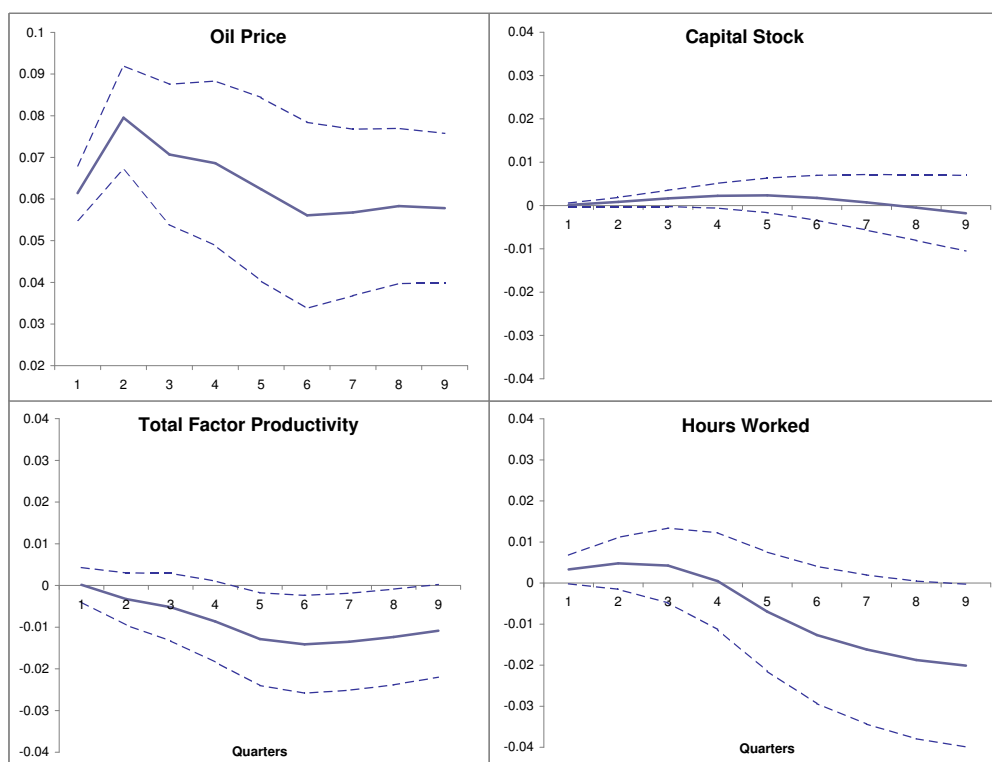
**Figure 4: Approximating the Spot Price of Oil with Consumption**

Predicted prices are the predicted value from the regression  $p_t = \beta_0 + \beta_1 x_t^1 + \beta_2 x_t^2 + \epsilon_t$ , where  $p_t$  is the log of the WTI spot price adjusted by CPI excluding energy costs and of the mpg of the U.S. passenger car fleet. The household oil use and aggregate oil line is the predicted value when household oil consumption and the CES aggregation of the stock of durable consumption and expenditure on nondurable consumption (excluding energy goods) are on the right hand side of the regression. The total oil use and GDP line uses product supplied and real GDP on the right hand side of the regression. Household oil consumption is adjusted by the MPG of the U.S. passenger car fleet.



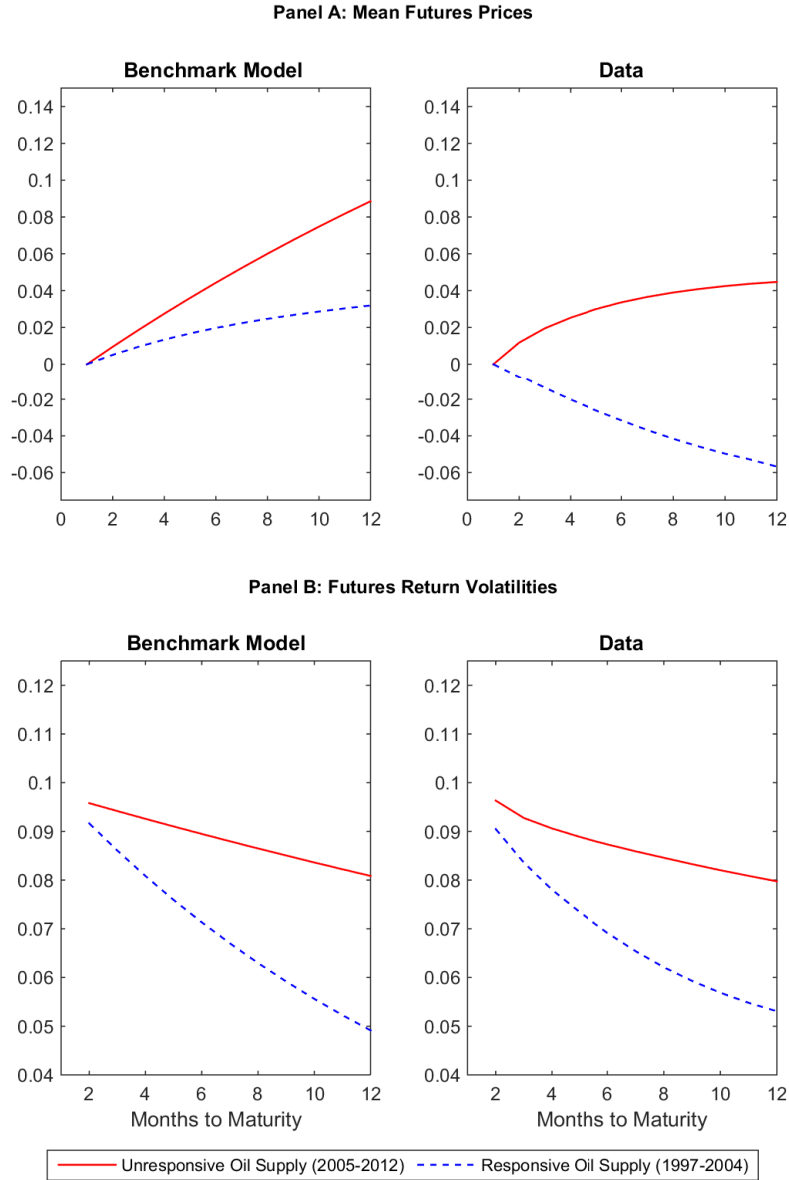
**Figure 5: Response of Components of Output to Change in Oil Price**

This figure plots the cumulative orthogonalized impulse response functions of a four-variable VAR on the growth rates of the log of real oil prices, hours worked, capital stock, and total factor productivity. Data for components of output are from the San Francisco Federal Reserve. The data are quarterly and the VAR is estimated with four lags. 95% confidence intervals shown in dashed lines.



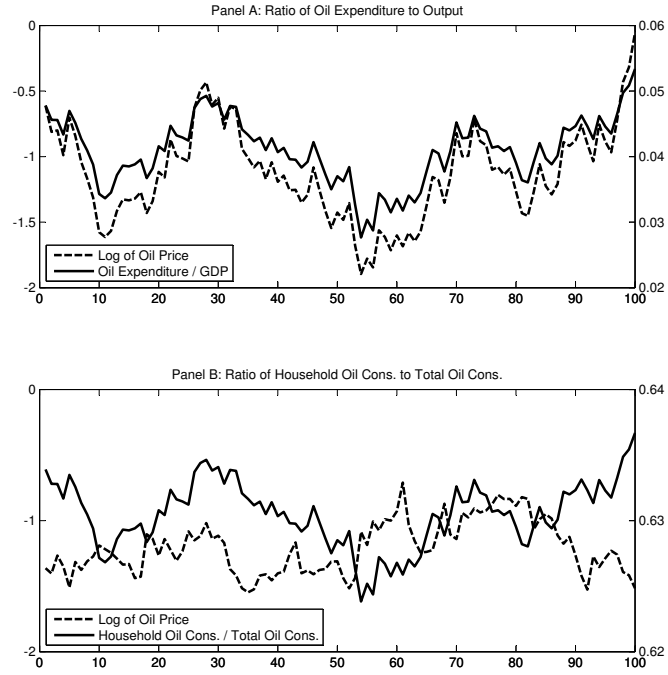
**Figure 6: Model Future Prices and Returns**

This figure shows average future prices, returns, and return volatilities for the model with both an unresponsive and responsive supply. The two regimes differ in their values of  $\kappa$  and  $\rho_w$  as described in Table 4. The model is simulated for 100 simulations of 480 months, and moments are calculated as the average means or standard deviations of the last 360 months of each simulation. Future prices are shown in logs and normalized so  $E[f_1] = 0$ . Future returns means and standard deviations are monthly.



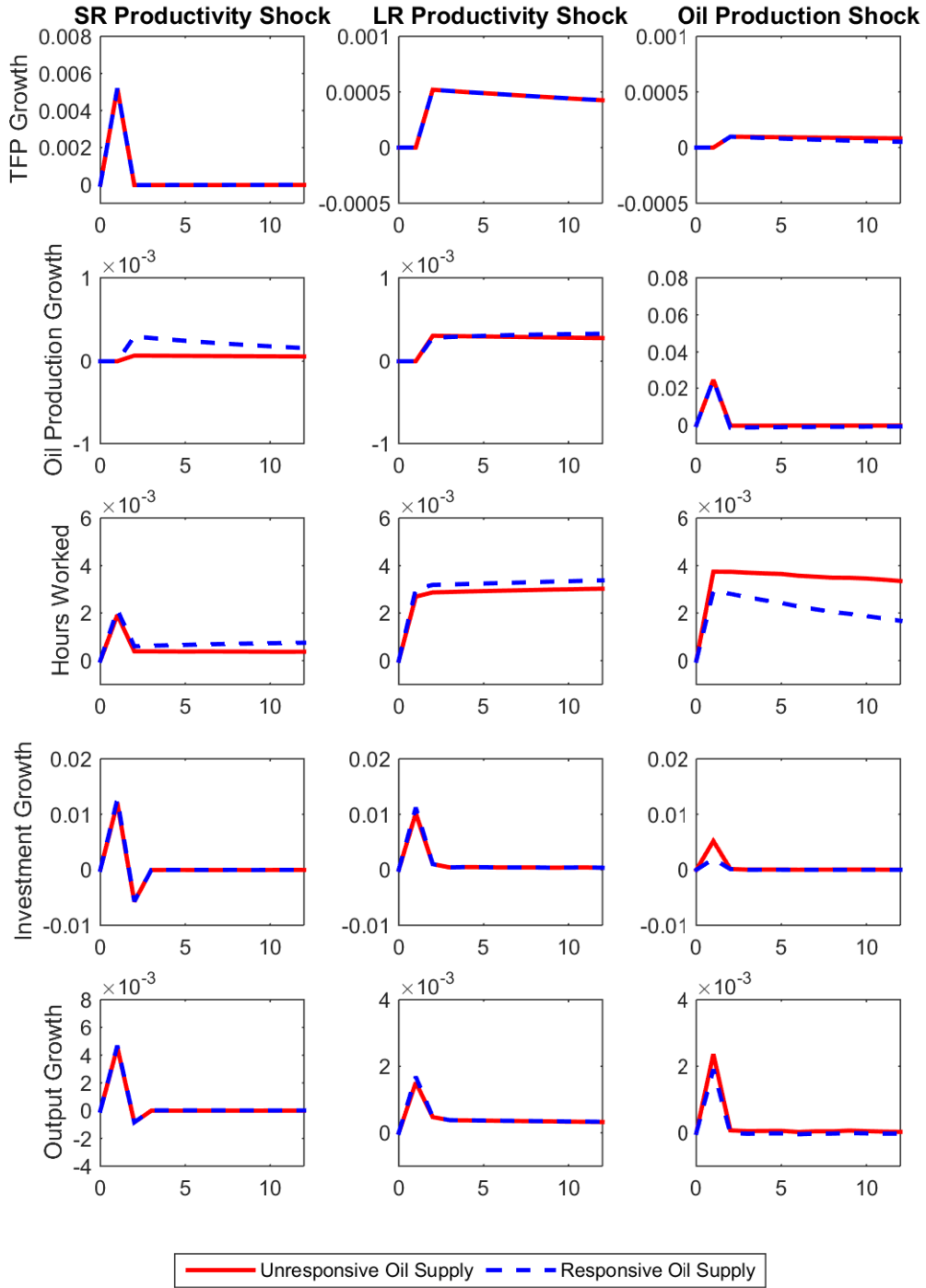
**Figure 7: Model Expenditure Ratios**

This figure plots time series of oil prices and expenditure ratio from a single simulation of the Benchmark Model with a responsive oil supply. Panel A plots the log of the oil price and the ratio of total oil consumption to aggregate output, calculated as  $\frac{P_t(O_t+G_t)}{Y_t}$ . Panel B plots the log of the oil price and ratio of household consumption of oil to total consumption of oil, calculated as  $\frac{G_t}{G_t+O_t}$ .



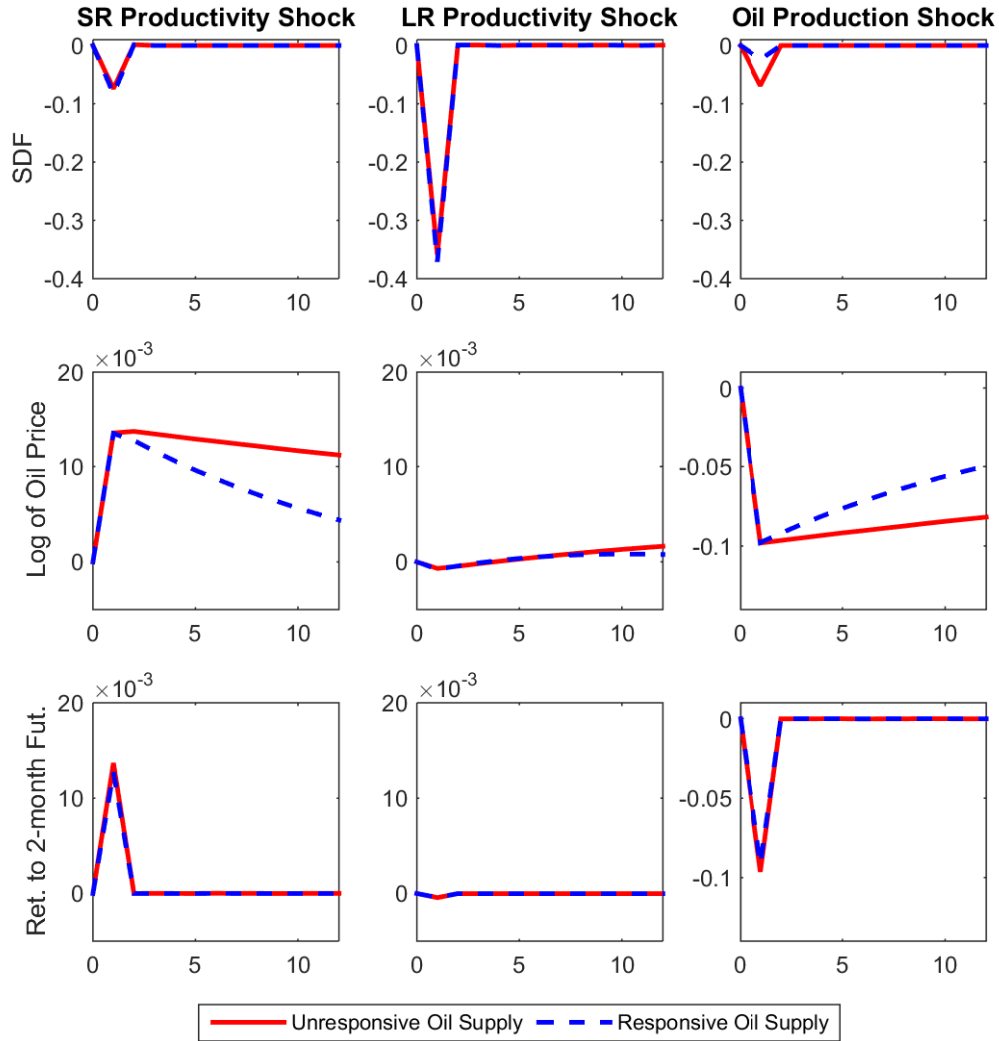
**Figure 8: Model Impulse Response: Output Variables**

Response of model variables to one standard deviation shocks to both short and long-run aggregate productivity as well as the oil supply. Results are shown for the responsive and unresponsive cases of the Benchmark Model described in Table 5.



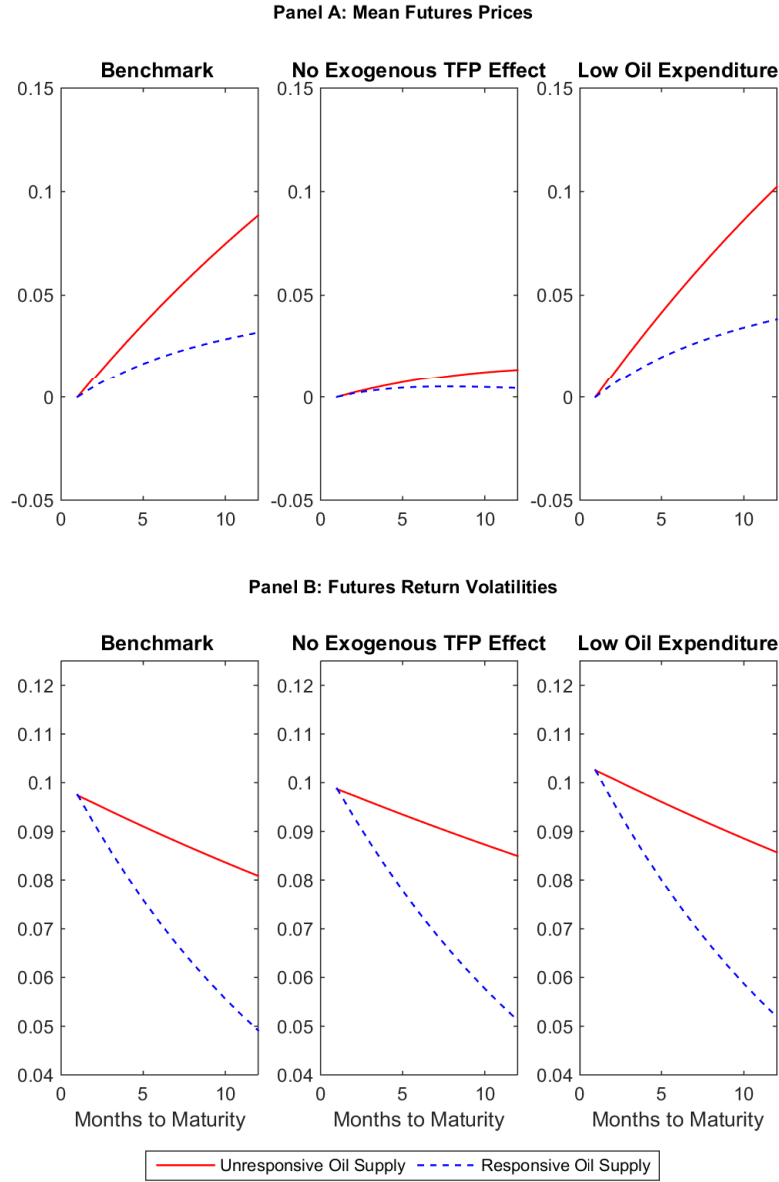
**Figure 9: Model Impulse Response: Oil Spot and Future Prices**

Response of model variables to one standard deviation shocks to both short and long-run aggregate productivity as well as the oil supply. Results are shown for the responsive and unresponsive cases of the Benchmark Model described in Table 4.



**Figure 10: Oil Futures: Benchmark and Alternate Model Specifications**

Average future prices and return volatilities of six different parameterizations of the model. The unresponsive and responsive regimes differ in their values of  $\rho_w$  as described in Table 4. For the “No Exogenous TFP Effect” specification the parameterizations are the same as the benchmark except that the variable  $\zeta = 0$ . For the “Low Oil Expenditure” calibration the mean level of the oil endowment  $\bar{w}$  is lower than the benchmark specification so that the total average expenditure on oil is roughly half that of the benchmark calibration. The model is simulated for 100 simulations of 480 months, and moments are calculated as the average means or standard deviations of the last 360 months of each simulation. Future prices are shown in logs and normalized so  $E[f^1] = 0$ . Future returns averages and standard deviations are monthly.



**Figure 11: Increasing U.S. Production and Oil future prices**

A plots an measure of the slope adjusted for recent changes in the level of the oil price as well as a measure of persistence. The adjusted slope is the  $\alpha$  from a rolling regression using three years weekly data.

$$Slope_t = \alpha + \beta_p \Delta f_t^1 + \beta_{Slope} Slope_{t-1}$$

Where  $Slope_t = f_t^{12} - f_t^1$  is the difference between logs the 12 and the 1 month future prices. Data are weekly so synthetic constant maturity future contracts are constructed by linearly interpolating the two nearest maturity future prices. The measure of persistence is  $\beta$  from a rolling regression using three years of weekly data.

$$\Delta f_t^{12} = \alpha + \beta \Delta f_t^1$$

Panel B graphs North American production of crude oil from the EIA, and total open interest of Financial Investors in COMEX oil future contracts from the CFTC.

