# Oil Volatility Risk

Lin Gao, Steffen Hitzemann, Ivan Shaliastovich, and Lai Xu*

December 2016

**Abstract**

In the data, an increase in oil price volatility dampens current and future output, investment, employment, and consumption, controlling for market volatility and other business cycle variables. High oil uncertainty negatively affects equity prices, with a much more pronounced impact in durable industries. We develop a two-sector production model to explain the novel evidence in the data. In the model, oil is an essential input for production and can be stored. At times of high oil volatility, oil suppliers increase oil inventories and curb oil supply to the market. As a result, investment, production, and consumption go down, and oil inventories go up. These mechanisms are directly supported in the data.

*Lin Gao (lin.gao@uni.lu) is at the University of Luxembourg, Steffen Hitzemann (hitzemann.6@osu.edu) is at The Ohio State University, Ivan Shaliastovich (ivan.shaliastovich@wisc.edu) is at the University of Wisconsin-Madison, and Lai Xu (lxu100@syr.edu) is at Syracuse University. We thank Ilan Cooper, John Elder, Francois Gourio, Patrick Grüning, Leonid Kogan, Amir Yaron, as well as conference and seminar participants of the 2016 Western Finance Association conference, the 2016 European Finance Association, the 2016 North American Summer Meeting of the Econometric Society, Chicago Fed, Duke University, and University of Houston for helpful comments and suggestions.

# 1 Introduction

The recent literature has highlighted a significant effect of aggregate uncertainty fluctuations on the macroeconomy and asset markets. In the data, an increase in aggregate macroeconomic uncertainty is typically associated with lower economic growth in the future and lower equity valuations.[1] In this paper, we consider uncertainty emanating from an economically important sector that involves production of oil. We show that oil uncertainty fluctuations have a separate and significant impact on economic growth and asset prices which is not captured by aggregate macroeconomic and financial volatilities or other business cycle variables. An increase in oil uncertainty dampens current and future output, consumption, investment, and employment. It further has a negative impact on asset prices in industries that are sensitive to oil as an input factor (such as Durables and Autos), while the exposure of industries related to the production of oil and oil products is positive. We develop a two-sector production model which features a trade-off between physical capital accumulation and storage of oil to explain the novel evidence in the data.

Our benchmark empirical evidence is based on implied volatility measures constructed from option price data in oil and equity markets. Using regression analysis, we find that an increase in oil volatility predicts a decline in current and future cumulative growth of macroeconomic variables (consumption, output, investment, employment) and an increase in oil inventories, one to four quarters ahead, controlling for the current growth as well as for oil returns and the market variance. Quantitatively, the impact of oil volatility is quite large, and in most cases dominates that of market volatility in its economic and statistical significance. The estimates under a conservative VAR ordering suggest that following a one standard deviation increase in oil variance, in one year consumption declines by about 0.20%, output by 0.25%, employment by 0.30%, and investment by 1.5%. An increase in oil variance further predicts a 0.3% decline in oil consumption and a 0.2% increase in oil inventories a year after a one-

[1] Ramey and Ramey (1995), Fernandez-Villaverde, Guerrón-Quintana, Rubio-Ramirez, and Uribe (2011), Basu and Bundick (2012), Bansal, Kiku, Shaliastovich, and Yaron (2014), Bloom (2014), Gilchrist, Sim, and Zakrajsek (2014), show a negative relation between real economic growth and macroeconomic uncertainty, while Bansal and Yaron (2004), Bansal, Khatchatrian, and Yaron (2005), Lettau, Ludvigson, and Wachter (2008) discuss the link between uncertainty and financial markets.

standard deviation shock to oil uncertainty. At the same time, the aggregate total factor productivity and the production of oil do not seem to be significantly related to movements in oil volatility, which suggests that the response of the endogenous macroeconomic variables to oil volatility is not mechanically inherited from the dynamics of productivity.

We further show that the market equity price drops at times of high oil uncertainty. Oil prices themselves only have a weak relation to oil uncertainty; in fact, the correlation is positive outside the Financial crisis. This evidence is supported by the cross-section of equity returns which suggests that industries which are likely to use oil as an essential input, such as Durables and primarily Autos, have a large negative exposure to oil uncertainty. On the other hand, industries which are involved in the production of oil and oil-related products (Energy) have the largest positive exposure to oil volatility. Consistent with the hypothesis in Bernanke (1983) that the consumption of durable goods can be particularly affected by the uncertainty, we find that the measures of output in durable industries are significantly negatively affected by oil uncertainty, relative to non-durable industries.

We explain our empirical findings in a two-sector macro model in which oil is an essential input for the production of consumption goods. The oil supply from existing wells is subject to exogenous fluctuations, and firms manage oil inventories to mitigate the consequences of oil supply shocks. In times of high oil supply volatility, they therefore increase their inventories to alleviate the probability of a stock-out in the event of a large negative supply shock. As a result of this precautionary savings effect, the amount of oil available for production in the general macro sector is reduced, and production, consumption, and investments decrease. This effect especially dominates the usual precautionary savings effect to increase physical capital investments when uncertainty rises, such that consumption and investment jointly decrease in our model when (oil) uncertainty goes up.

**Related Literature.** Our paper contributes to several strands of literature. In the literature on the macroeconomic impact of oil price fluctuations (e.g., Rotemberg and Woodford 1996; Finn 2000; Kilian 2008; Dvir and Rogoff 2009), it has long been hypothesized that oil-related uncertainty plays a role in addition to (first-moment) oil supply shocks.[2] This

[2] See Kilian (2014) for an overview.

hypothesis originally goes back to the theory of irreversible investments (see Bernanke 1983; Pindyck 1991). Based on the effect that the "option to delay" investing becomes more valuable when oil uncertainty rises, these papers predict an adverse effect of oil uncertainty on investments and other macro variables, which is confirmed empirically (Elder and Serletis 2010 and Jo 2014). Our results, based on market price data to measure uncertainties, corroborate and extend the empirical findings in this literature. Our analysis further reveals an alternative propagation channel for oil uncertainty shocks based on precautionary inventory stock-ups, which has received much less attention in the literature.[3] To rationalize this mechanism theoretically, we build on and contribute to a recent literature that analyzes the interactions of the oil sector with the broader macroeconomy within two-sector production models (Casassus, Collin-Dufresne, and Routledge 2009; Ready 2014; Hitzemann 2016). Our paper is the first to investigate the effect of oil-related supply uncertainty shocks in such general equilibrium type of model.

Second, we contribute more broadly to a macroeconomic literature that identifies uncertainty shocks as a main driver of macroeconomic variables and a source of business cycle fluctuations (e.g., Bloom et al. 2014; Christiano, Motto, and Rostagno 2014; Ludvigson et al. 2016). A main challenge to general equilibrium models in this literature is to reproduce the empirically observed co-movement of investment and consumption on impact of an uncertainty shock (e.g., Arellano, Bai, and Kehoe 2012; Gilchrist, Sim, and Zakrajsek 2014; Bloom et al. 2014).[4] Due to the resource constraint, consumption has to go up when investment falls, and vice versa (see also Bloom 2014). The literature proposes different mechanisms to address this issue, such as price and wage rigidities (Christiano, Motto, and Rostagno 2014) or capital flight for the case of small open economies (Fernandez-Villaverde, Guerrón-Quintana, Rubio-Ramirez, and Uribe 2011). We add to this literature by proposing an additional channel

[3]While the important role of inventories is well recognized for commodity markets and for oil in particular (see the classical *theory of storage* literature developed by Kaldor 1939, Working 1948, Working 1949, Telser 1958, and more modern approaches such as Williams and Wright 1991, Deaton and Laroque 1992, Routledge, Seppi, and Spatt 2000, Gorton, Hayashi, and Rouwenhorst 2012), the link of precautionary inventory stock-ups to macroeconomic variables has not been entertained, to our best knowledge.

[4]Empirically, uncertainty shocks typically lead to a drop of both investment and consumption in the short run. Some papers emphasize that in the long run, a rise in uncertainty might actually have a positive effect as a result of growth options (see Gilchrist and Williams 2005; Jones, Manuelli, Siu, and Stacchetti 2005; Kung and Schmid 2014).

based on oil inventories. As we show in this paper, oil uncertainty shocks lead to a stocking up of oil inventories, which negatively affects production, consumption, and investment in the general macroeconomy due to the reduced effective oil supply to the market.

Finally, our paper adds to the literature on asset pricing in general equilibrium production models (Cochrane 1991, 1996; Rouwenhorst 1995; Jermann 1998; Boldrin, Christiano, and Fisher 2001). Related to the modeling difficulties in pure macro models described before, these models typically fail to reproduce a fall in asset prices when uncertainty increases (see Croce 2014; Liu and Miao 2015, for example), which is established empirically (e.g., Bansal, Kiku, Shaliastovich, and Yaron 2014) and critical to generating important features of market risk premia (Bansal and Yaron 2004). In particular, the standard choice of convex capital adjustment costs in this literature leads to an increased accumulation of capital in response to uncertainty shocks, raising the price of capital with the result of positive equity returns. In our two-sector model, an increase in (oil supply) uncertainty leads to a stocking up of oil inventories instead, and general investment as well as aggregate equity prices fall. Additionally, we relate to the cross-sectional production-based asset pricing literature (e.g., Gomes, Kogan, and Zhang 2003; Gomes, Kogan, and Yogo 2009) by exploring the effect on industry returns.

## 2 Empirical Analysis

In this section we present our key empirical findings that an increase in oil price volatility has an adverse effect on aggregate growth. Through a negative cash flow effect, oil volatility also has a negative impact on asset prices, especially in durable-good producing industries that are sensitive to oil as an input factor. We also show that a rise in oil volatility lowers consumption of oil and increases oil inventories, while it does not significantly affect aggregate productivity or oil production. These results motivate and provide empirical support for our economic model which features a trade-off between using oil in production now, or saving it for later.

## 2.1 Data

In our empirical analysis we use macroeconomic data related to production and consumption in the aggregate economy and in the oil sector, equity price data, and option price data for the market index and crude oil prices. All the macroeconomic data are real and seasonally adjusted. Due to the availability of the option data, our benchmark sample runs quarterly from 1990Q1 to 2014Q1.

Our aggregate macroeconomic data are for the United States, and include consumption, comprised of expenditures on nondurable goods and services, GDP, private domestic investment, and employment. The data come from the Bureau of Economic Analysis (BEA). We additionally collect the Total Factor Productivity (TFP) index which corresponds to the estimates of the Solow residual for the US economy. For robustness, we also consider the utilization-adjusted productivity measure proposed by Basu, Fernald, and Kimball (2006).

The oil quantity data come from the U.S. Energy Information Administration.[5] Our oil supply measure corresponds to the world production of crude oil. To measure oil usage and inventories, we use total consumption of petroleum products and total petroleum stocks, respectively. The long sample of oil consumption and stock data is only available for the OECD countries. For robustness, we also check the results using the oil consumption and inventories in the United States.

In terms of the asset price data, we use crude oil futures data to construct excess returns on oil. These data are obtained from the Commodity Research Bureau (CRB). The return data for a broad market portfolio comes from CRSP. We construct a proxy for a real risk free rate by removing expected inflation from the nominal short-term rate. The expected inflation is computed from a linear regression of inflation on its lag and the lag of the nominal rate. We further collect the price and cash flow data for equity portfolios. Following Gomes, Kogan, and Yogo (2009), we use the benchmark input-output accounts table in the BEA to identify industries whose final demand has highest value-added to personal consumption expenditures on durable goods, non-durable goods, and services, respectively.

[5] The data are available at http://www.eia.gov/.

Similar to Eraker, Shaliastovich, and Wang (2015), we aggregate non-durables and services into a single value-weighted non-durable portfolio.[6] In addition, construct a value-weighted portfolio of oil producers. Specifically, we extract the industrial segment information from Compustat Historical Segments database. We then choose only those firms whose SIC codes all correspond to the oil-producing sector and exclude those that have one or more SIC codes outside this sector. We then form value-weighted return portfolios from these firms.[7]

The key object for our analysis is the amount of uncertainty in financial and macroeconomic data. Our benchmark uncertainty measures are constructed using the data on equity and oil option prices. Specifically, we use the volatility index VIX, constructed from the cross-section of S&P 500 index option prices, as the model-free estimate of the aggregate market volatility. In a similar fashion, we construct the option-implied oil volatility measure to capture the ex-ante uncertainty in the oil markets; see Appendix A.1 for details. For robustness, we consider several alternative uncertainty measures. First, we construct realized, rather than ex-ante, uncertainty using the high-frequency return data. That is, we use squared daily equity and oil returns over the quarter to obtain equity and oil realized variation measures, respectively. We further consider other measures of uncertainty, such as the Baker, Bloom, and Davis (2013) economic policy uncertainty index, stochastic volatility of real consumption growth, constructed from an AR(1)-GARCH(1,1) filter to the real consumption growth data, and measures of sectoral uncertainty constructed from the option price data in sugar, corn, gold, and copper markets.

The key summary statistics for the data are reported in Table 1. In our sample, the real aggregate growth rates average between 1 and 2%. The volatilities of the standard aggregate production and consumption series are about 1%, with the exception of real investment whose volatility is 7%. The oil-related measures are about twice more volatile than the consumption and output growth in the United States. Most of the macroeconomic variables are mildly persistent, except for the oil-related measures for which the autocorrelation coefficients are

[6] Our results are similar when using only the non-durable-good producing firms in the portfolio.

[7] Firms operating in multiple sectors can use real hedges to insure against oil risk, so we exclude them in our benchmark analysis. Our results, however, remain very similar if we do not restrict the firms to be only in the oil-producing sector, as in Chiang, Hughen, and Sagi (2015).

close to zero or even negative. In terms of the asset-price moments, the equity risk premium is about 6% in our sample, while the average excess oil return is 4%. The volatility of oil returns is almost 40%, which is twice as high as the volatility of equity returns. The implied oil volatility is also larger than the implied equity volatility, and is twice as volatile.

We show the time series of returns and volatilities in equity and oil markets in Figure 1. Both oil and equity returns are quite volatile and further, the amount of conditional volatility varies persistently in the sample. As shown in Table 2, volatilities in oil and equity markets are quite correlated: the correlation coefficient is about 60% in the benchmark sample, though, it drops to 50% excluding the Financial Crisis. In equity markets, the two largest volatility spikes correspond to the stock market crash in November of 1987 and the Great Recession at the end of 2008. The equity volatility is also elevated in the LTCM crisis of 1998 and the dotcom crash in 2002. All of the turbulent equity market periods are associated with a significant decline in equity prices. Oil volatility has significantly larger level and variation, relative to equity volatility. Further, a rise in oil volatility can be associated with both sharp increases in the underlying prices, as in the Gulf War of 1990, or decreases in oil prices, as in the Great Recession in 2008 and during the oil price collapse in 1986 caused by the decision of Saudi Arabia and several of its neighbors to increase its share in the oil markets.

## 2.2 Oil Volatility and Current Growth

We start our analysis by considering contemporaneous correlations of volatility with aggregate macroeconomic variables. The first panel of Table 2 shows our evidence for the benchmark sample from 1990 to 2014, and the bottom panel shows the robustness to Financial Crisis period which features abnormally large movements in the volatility. The Table shows that all the considered measures of economic growth, such as consumption, GDP, investment, dividend, and employment growth, decline significantly at times of high oil volatility. For example, the correlation between GDP growth and oil implied volatility is -0.55, and it is -0.49 for investment growth and -0.55 for change in employment.

The economic growth rates also decline at times of high equity volatility. However, the growth rate correlations with equity volatility are all smaller, in absolute value, compared to those with oil volatility. For example, for a benchmark sample, the correlation of GDP growth with oil volatility is -0.55, relative to -0.40 for equity volatility, and the magnitudes are -0.49 and -0.37, respectively, for investment growth, and -0.55 and -0.49 for employment growth. The evidence is quite similar excluding the Great Recession period, as shown in the bottom panel, and in the longer 1983-2014 sample which uses realized variances to compute oil and market uncertainties (see Appendix Table A.1).

Next we consider the covariation of volatility with oil-related quantities. Oil consumption declines when oil volatility is high: the contemporaneous correlation is -0.36 both in the benchmark sample and excluding the crisis. The correlations are much weaker for equity volatility. Indeed, the correlation between oil consumption growth and equity volatility is in fact zero outside the Financial crisis. In our benchmark sample, oil inventories go up at times of high oil volatility, however, these correlations are rather weak. To the extent that there are delays in adjusting oil stock in real world, we expect the oil inventories to increase in the future, rather than contemporaneously. Further, the correlation evidence may be contaminated due to an exclusion of other related factors. We examine the evidence in a more detail in the predictive regression setup.

We further examine the link between the volatility and the productivity measures in aggregate and oil sectors. In our model, the TFP and oil production growth are the exogenous processes which drive the economy, so it is important to establish how much of oil volatility effect exists at the level of the economic primitives. Table 2 shows that the TFP growth rates are negatively correlated with oil volatility. However, these correlations are weaker relative to other macroeconomic variables. For example, excluding the Financial Crisis, the correlation of oil volatility with TFP growth is about twice lower, in absolute value, than the correlations of oil volatility with consumption, output, investment, and employment. Similarly, the correlation of oil supply growth with volatility is two to three times weaker than the correlation of oil consumption growth with oil volatility. This suggests that the effect of oil volatility on endogenous macroeconomic variables is larger than that on the exogenous driving processes.

Finally, we show the evidence for the co-movements of the aggregate variables with oil return itself. Oil return is weakly procyclical, however, the correlations of oil returns with standard macroeconomic variables are nearly zero outside the Financial Crisis. Oil prices have more substantial correlations with oil-related quantities. In the data, growth rates in oil production and oil stock contemporaneously decline at times of high oil prices, while oil consumption increases.

Our key results are based on the benchmark sample from 1990 to 2014, given the availability of the option data. To show the robustness of our results, we also consider a longer sample starting from 1983, for which we can use realized volatility measures computed from the daily oil and equity returns. As shown in Table A.1, the results for the 1983-2014 sample are very similar to our benchmark findings.

## 2.3 Oil Volatility and Future Growth

To show that oil volatility has a distinct information about current and future economic growth, we consider a predictive regression setup:

$$\frac{1}{h}\sum_{j=1}^{h}\Delta y_{t+j} = a_h + b_h' x_t + error,$$

where $y$ is the predictive variable of interest, and $x_t$ is the set of predictors. When $h = 0$ we consider a contemporaneous relation between $\Delta y_t$ and the variables in $x_t$; if one of the $x_t$ includes $\Delta y_t$ itself, we lag it by one period. For $h > 0$ it corresponds to the predictive relation $h$ quarters ahead. The benchmark regressions are performed on a quarterly frequency from 1990 to 2014, and use the lag of the predictive variable itself, oil option-implied variance, equity option-implied variance, and oil return as the predictors. We consider multiple robustness checks to make sure our results are not sensitive to the sample, inclusion of the Financial Crisis, adding asset-price predictors, and alternative measurements of the volatilities.

Table 3 summarizes the predictability evidence for future growth in consumption, GDP, investment, employment, and the TFP. For the first four macroeconomic variables, the signs of the loadings on oil variance are negative across all the horizons. That is, controlling for equity variance, oil return, and lag of the predictive variable, a rise in oil variance forecasts a decline in current and future aggregate growth 1 to 4 quarters ahead. All the slope coefficients on oil variance are statistically significant at 1 quarter horizon, while the significance drops with the horizon.[8] The Tables further shows that the signs of the equity variance loadings tend to be negative as well. However, across all the horizons the estimates of the impact of equity variance are never significantly different from zero. In terms of the effect of oil prices, the signs of the coefficients are negative for consumption and GDP growth, positive for employment, and the evidence is mixed for future investment growth. The $R^2$s in these predictability regressions are quite high, and vary from about 20% for future GDP and investment, 30% for future consumption, and can be as high as 70-80% for future employment growth.

Oil variance also predicts a decline in the TFP initially, but after 2 quarters the signs on the oil variance loadings turn positive.[9] All of the coefficients in the TFP regressions are insignificantly different from zero. The coefficients on equity variance are positive, and also insignificant. Finally, the $R^2$s in these regressions are quite low, and below 10%. Overall, consistent with our contemporaneous correlation evidence in Table 2, the data do not feature a strong link between current or future aggregate TFP and oil volatility.

To help assess a relative impact of variance shocks, we compute the cumulative impulse responses of future consumption, output, investment, employment, and TFP growth to a one-standard deviation shock in oil or equity volatility. The impulse responses are based on a lower-triangular Cholesky decomposition of a VAR(1) model fitted to the macroeconomic,

[8]The responses are magnified and the statistical significance improves in the period which excludes very volatile observations of the Financial Crisis, as shown in Table A.4.

[9]The utilization-adjusted TFP growth loads positively and insignificantly on the two volatility measures.

volatility, and asset-price variables.[10] We use block bootstrap to compute 90% and 68% confidence intervals. To identify volatility shocks, we rely on a conservative identification scheme where the corresponding macroeconomic variable and the oil price return are assumed to be the most exogenous, followed by the two volatilities, and subsequently, by the risk-free rate and the market price-dividend ratio. Naturally, the impact of volatility shocks is magnified if the volatility shocks lead macro variables in the VAR, which we show in the Appendix in Figure A.1. In that case, the volatility shocks have a large negative effect on impact, and the dynamic responses are the largest among all the considered alternatives.

We consider two identification approaches to separate the impacts of oil and equity variance shocks. In the first, conservative case, equity variance comes first, so that oil variance is endogenous to equity variance. The Figure 2 shows that in this case, the two variances have a comparable negative impact on future macroeconomic variables. One year after the impact of oil (equity) volatility shock, consumption declines by 0.20% (0.25%), output by 0.25% (0.25%), employment by 0.30% (0.40%), and investment by 1.5% (1.6%). The effects remain statistically significant up to 10 quarters for oil volatility; for equity volatility, only the effects on consumption and employment are significant throughout. We then consider an alternative ordering where oil volatility shocks lead market volatility, and show the results in Figure 3. Under this ordering, the effects of equity volatility sizeably diminish, while the effects of oil volatility become much larger compared both to the ones under a conservative ordering, and to the equity volatility effects under any ordering. In this scenario, following a one-standard deviation shock in oil (equity) volatility, consumption declines by 0.30% (0.15%), output by 0.35% (0.10%), employment by 0.40% (0.20%), and investment by 2% (1%). Unlike for oil volatility, most impulse responses to equity volatility shocks are insignificant. Finally, Figure 4 documents that, independent of the ordering, the oil variance has an economically and statistically insignificant impact on future TFP. Overall, our impulse response results are consistent with our earlier predictability evidence, and suggest a significant role of oil volatility shocks for the endogenous macroeconomic variables, above and beyond equity volatility.

[10] The choice of 1 lag in VAR is supported by the BIC information criterion.

Table 4 shows the predictability evidence for the oil-sector quantities. For oil production, the sign of the predictive coefficient on oil variance is initially negative, but insignificantly different from zero. The $R^2$s in these regressions are all below 10%. While the data do not indicate a strong relation between oil production and oil volatility, future oil consumption tends to drop, while future oil inventories increase following an increase in oil variance. Indeed, Table 4 shows that oil variance has negative and significant effect on oil consumption 1 quarter ahead, and a positive and significant effect for next-quarter oil inventory growth.

To gauge a quantitative impact of variance shocks, we consider the cumulative impulse responses of future oil consumption, oil inventory, and oil supply to oil and equity volatility shocks. We compute the impulse responses for oil consumption and inventories, we fit a VAR(1) to oil supply growth, oil return, two variances, oil inventory or oil consumption growth, risk-free rate, and the market price-dividend ratio, in that order. In this exercise, oil inventories and oil consumption react to the primitive shocks in oil supply, oil prices, and oil and equity volatilities. As before, we consider two alternative orderings for the volatility variables: the conservative one, in which market variance precedes oil variance, and the alternative one in which oil variance comes first. Figure 5 and 6 show that following an oil volatility shock, oil inventories rise, and oil consumption drops. A year after the impact, oil inventories rise by about 0.20%, and consumption falls by about 0.30%. The effects are significant for oil consumption, and are borderline significant for oil inventories (at a 5% significance level). The impulse responses for equity volatility are smaller and by and large insignificant, especially in the case when oil volatility is ordered first. The top panel of the Figure also shows the cumulative impulse response of oil supply growth, which is computed in a similar way as for the aggregate macroeconomic variables. Oil supply does not respond to shocks in oil and equity volatility: the responses are effectively zero and are very insignificant for both volatilities and under both identification schemes. These findings are consistent with our predictability evidence documented earlier.

We consider multiple alternative specifications to check the robustness of our results. We use a longer sample from 1983 and rely on realized variance measures to capture movements in uncertainty (Table A.2). We consider the continuous variation measure in oil prices, computed following Bollerslev and Todorov (2011), to ensure that our results are not driven by a few large spikes in oil prices (Table A.3). Alternatively, we remove the turmoil episode of the Financial Crisis (Table A.4). We add additional asset-price controls, such as the market price-dividend ratio, real rate, and the term spread (Table A.5). We also replace market variance by alternative measures of aggregate uncertainty, such as the Baker-Bloom-Davis economic policy uncertainty index (Table 5), and the conditional variance of output growth (Table 6). We also also considered controlling for measures of uncertainty in other economic sectors, such as in corn, sugar, copper, and gold markets. All the results are quantitatively very similar to the benchmark findings, and suggest that oil variance captures a significant information about current and future aggregate macroeconomic and oil variables, above and beyond standard volatility measures.

## 2.4 Oil Volatility and Asset Prices

The correlation evidence in Table 2 suggests that equity returns drop at times of high oil variance. Indeed, the correlation of equity returns with oil implied variance is -0.30 in the benchmark sample, and about -0.15 excluding the crisis. The negative relation also holds controlling for the market variance, as we show in the impulse responses in Figures A.2 and A.3. Oil returns, on the other hand, have a much weaker relation to oil variance. Excluding the crisis, the correlation of oil returns with oil variance is positive and equal to 0.03. This is consistent with our earlier discussion that an increase in the underlying oil variance can be caused by large positive or negative spikes to oil prices. Finally, as shown in the bottom panels of Figures A.2 and A.3, risk-free rates decrease at times of equity volatility. They also go down at times of high oil volatility in a setting where oil volatility shocks are exogenous to the market volatility.

The effects of oil volatility on asset valuation vary considerably across industries. In particular, we regress durable, non-durable, and oil producer equity portfolio returns on the market return, oil return, and the equity and oil implied volatilities, which allows us to estimate the sensitivity of the industry portfolios to these factors. Table 7 shows that the durable portfolio exhibits the largest exposure to oil uncertainty, with a negative and statistically significant beta of -0.36. On the contrary, the impact of oil uncertainty on the non-durable and oil producer portfolio is small in magnitude, positive and statistically insignificant.[11] Using an alternative sorting based on 30 Fama-French industries, we find that the largest negative effect of oil uncertainty is concentrated in the Auto sector, for which the oil variance exposure is -0.70, while Chemicals and Oil portfolios have positive exposures.

The asset prices are driven by shocks to discount rates (risk premia) or future cash flows. In our sample, we do not find a significant link between the risk premia and oil or equity variance. For example, the impulse responses in Figures A.2 and A.3 show that the negative relationship between the market prices and the two volatilities is strongest on impact, and becomes insignificant after 1-2 quarters. This is consistent with Christoffersen and Pan (2014), who show that the implied oil volatility does not have a predictive power for equity returns in a long sample, but only in the financialization period starting in 2004. On the other hand, we find that oil volatility has a significant impact on output measures across sectors, consistent with our earlier evidence for the aggregate macro series. Table 8 shows the results using the industrial production index for the aggregate economy, durable and non-durable consumer good sectors, auto sector, and crude oil mining. While oil volatility negatively impacts current and future aggregate production, its effect more than doubles for the durable consumer good sector, and is especially large for the manufacturers of motor vehicles. For example, 1 quarter ahead slope coefficients increase, in absolute value, from -0.10 for the aggregate series to -0.40 and -0.82 for durables and autos, respectively. Interestingly, nondurable consumer and oil mining sectors do not significantly respond to oil volatility, as all the slope coefficients are essentially zero. For robustness, the lower panel of the Table documents that our findings remain similar using earnings data for durable and non-durable industries and the oil producers. Consistent with the predictability evidence, the impulse responses in Figure 7 show that oil volatility shocks have an insignificant impact on future industrial production in nondurable consumer goods and oil mining sectors. On the other hand, they significantly impact the durable goods sector, and especially the Auto component

[11] These findings are robust to excluding the Financial Crisis, as shown in the bottom panel, or starting a sample in 1983 (see Table A.6).

of it. The results for an alternative ordering when oil volatility shocks are exogenous to the market volatility are similar, and shown in the Appendix in Figure A.4.

Our portfolio evidence is consistent with the hypothesis in Bernanke (1983) and the empirical evidence in Elder and Serletis (2010) that oil price uncertainty has a more significant effect on the aggregate consumption of durable goods. The heterogeneity in cash flow exposures to oil volatility also helps explain a much more pronounced negative impact of oil uncertainty on asset prices in the durable sector and autos relative to non-durable sector and the aggregate economy. In the next section we provide an economic intuition for this empirical evidence based on a differential sensitivity of durables and non-durables industries to oil as an input factor.

# 3 Model

We explain our empirical findings within a macro model in the style of Ready (2014) and Hitzemann (2016), featuring an oil sector and a general macro sector. As the main novel ingredient, we introduce stochastic uncertainty of the oil supply into the model. Shocks to oil supply uncertainty endogenously translate to changes in oil price volatility, motivating the use of the price-based oil uncertainty measure in our empirical analysis. We show that in line with a *precautionary savings* motive, oil producers stock up their inventories when oil supply uncertainty increases and sell less oil to the market. The decrease in effective oil supply translates to the macro sector and depresses output, consumption, and investment.

## 3.1 Setup

**Final goods producer** The representative firm in our model produces a final good

$$Y_t = (A_t N_t)^{1-\alpha} Z_t^{\alpha} \tag{3.1}$$

with the input of labor $N_t$ and an intermediate good $Z_t$, where the total factor productivity is denoted by $A_t$. Production of the intermediate good requires general capital $K_t$ and oil $J_t$ as an input. More specifically, the intermediate good is a CES aggregate of these two input factors,

$$Z_t = [(1-\tilde{\iota})K_t^{1-\frac{1}{o}} + \tilde{\iota}J_t^{1-\frac{1}{o}}]^{\frac{1}{1-\frac{1}{o}}}, \tag{3.2}$$

where $\tilde{\iota} = \iota^o$ describes the oil share and $o$ is the constant elasticity of substitution.

The oil input of the firm is purchased from oil producers as described below. On the other hand, the firm maintains a general capital stock $K_t$ in line with the classical real business cycle framework. Accordingly, the capital accumulation equation is given by

$$K_{t+1} = (1-\delta)K_t + I_t - G_t K_t, \tag{3.3}$$

where $I_t$ is physical capital investment and $G_t$ is an adjustment cost function

$$G_t(I_t/K_t) = I_t/K_t - (a_0 + \frac{a_1}{1-\frac{1}{\xi}}(I_t/K_t)^{1-\frac{1}{\xi}}) \tag{3.4}$$

as proposed by Jermann (1998).

The firm generates revenues by selling the part of the final output that is not invested again to the households, creating a cash-flow of $Y_t - I_t$. On the other hand, the oil input $J_t$ is purchased from the oil producer at price $P_t$, and workers are paid wages $W_t^N$ for their hours worked $N_t$. Overall, the final goods producer maximizes the expected sum of discounted cash-flows

$$\mathbb{E}_t \sum_{s=0}^{\infty} M_{t+s}(Y_{t+s} - I_{t+s} - P_{t+s}J_{t+s} - W_{t+s}^N N_{t+s}), \tag{3.5}$$

where $M_{t+s}$ is the $s$-period stochastic discount factor at time $t$.

**Oil Producer** The oil sector is represented by an oil producing firm which is endowed with an amount of oil wells containing

$$U_t = A_t\overline{U} \tag{3.6}$$

barrels of oil below ground. To ensure balanced growth, we assume that the oil wells grow with the general macroeconomy at $A_t$. This is in line with a model where firms endogenously invest a certain amount of their output $Y_t$ to drill new oil wells (see Hitzemann 2016). Keeping the model as simple as possible, we do not explicitly consider the oil drilling decision in here and take the amount of oil wells as exogenous. Accordingly, the amount of below-ground oil in existing wells is also not reduced by oil extraction in this model.

The production of oil takes place at a stochastic extraction rate $\kappa_t$, such that

$$E_t = \kappa_t U_t \tag{3.7}$$

barrels of oil are extracted and added to the producer's above-ground inventories. The oil inventories are actively managed and evolve as

$$S_{t+1} = (1-\omega)S_t - \Pi_t A_t + E_{t+1} - D_{t+1}. \tag{3.8}$$

Accordingly, the oil producer decides at each point in time how much oil $D_t$ to sell to the firms for production and how much to store above ground at an inventory cost of $\omega$. An important restriction is that inventories cannot become negative, which gives rise to a precautionary savings motive that is at the center of the economic mechanism studied in this paper. Technically, we approximate the non-negativity condition by a smooth stock-out cost function

$$\Pi_t(S_t/A_t) = \frac{\pi}{2}(S_t/A_t)^{-2}, \tag{3.9}$$

as proposed by Hitzemann (2016).

Given these ingredients, the oil producer maximizes the expected discounted cash-flows from oil sales to the final goods producing firm, which are given by

$$\mathbb{E}_t \sum_{s=0}^{\infty} M_{t+s} P_{t+s} D_{t+s}. \tag{3.10}$$

**Macro and Oil Productivity Risk** In our model, both the general macro sector and the oil sector are subject to productivity risk. We specify the productivity of the macro sector in line with Croce (2014), i.e.,

$$A_{t+1} = A_t \exp\{\mu + x_t + e^{w_t}\varepsilon^A_{t+1}\}, \tag{3.11}$$

$$x_{t+1} = \phi x_t + e^{w_{t+1}}\varepsilon^x_{t+1}, \tag{3.12}$$

$$w_{t+1} = \rho_w w_t + \varepsilon^w_{t+1}. \tag{3.13}$$

Here $\varepsilon^A_t \sim N(0, \sigma^2_A)$ are short-run shocks to macroeconomic productivity growth while $\varepsilon^x_t \sim N(0, \sigma^2_x)$ are persistent (long-run) shocks to productivity growth. In addition, we also consider uncertainty shocks $\varepsilon^w_t \sim N(0, \sigma^2_w)$ to macro productivity.

The productivity risk in the oil sector stems from fluctuations in the extraction rate from existing oil wells given by

$$\kappa_{t+1} = \eta(1-\chi) + \chi\kappa_t + e^{v_t}\eta\varepsilon^\kappa_{t+1}, \tag{3.14}$$

$$v_{t+1} = \rho_v v_t + \varepsilon^v_{t+1}. \tag{3.15}$$

In addition to the level shocks $\varepsilon^\kappa_t \sim N(0, \sigma^2_\kappa)$, we introduce oil-specific supply uncertainty shocks $\varepsilon^v_t \sim N(0, \sigma^2_v)$ into the model. As oil supply uncertainty shocks endogenously translate to changes of oil price volatility in our model, we identify the impact of these shocks with the effects of fluctuating oil price volatility documented in our empirical analysis.

All shocks considered in our model are i.i.d. and mutually independent.

**Household** The representative household consumes a CES bundle of the final consumption good $C_t$ and leisure $L_t$, given by

$$\tilde{C}_t = \left[\tau C_t^{1-\frac{1}{\xi_L}} + (1-\tau)(A_{t-1}L_t)^{1-\frac{1}{\xi_L}}\right]^{\frac{1}{1-\frac{1}{\xi_L}}}, \tag{3.16}$$

and maximizes Epstein and Zin (1991) utility

$$V_t = \left[(1-\beta)\tilde{C}_t^{1-\frac{1}{\psi}} + \beta \mathbb{E}_t \left[V_{t+1}^{1-\gamma}\right]^{\frac{1-\frac{1}{\psi}}{1-\gamma}}\right]^{\frac{1}{1-\frac{1}{\psi}}} \tag{3.17}$$

with risk aversion $\gamma$ and an intertemporal elasticity of substitution $\psi$. The utility maximization is subject to the standard wealth constraint

$$W_{t+1} = (W_t - C_t + W_t^N N_t) R_{t+1}^W \tag{3.18}$$

and the labor supply constraint

$$N_t + L_t = 1. \tag{3.19}$$

## 3.2 Equilibrium

To calculate the model's equilibrium, we derive the firms' and the household's first order conditions.[12] As a result, we obtain, first, the intratemporal conditions for the oil price

$$P_t = Q_t^S = \frac{\partial Y_t}{\partial J_t} = \alpha \tilde{\iota} \frac{Y_t}{J_t^{\frac{1}{o}} Z_t^{1-\frac{1}{o}}} \tag{3.20}$$

and for labor wages

$$W_t^N = \frac{\partial \tilde{C}}{\partial L_t} / \frac{\partial \tilde{C}}{\partial C_t} = (1-\alpha)\frac{Y_t}{N_t}. \tag{3.21}$$

Second, the intertemporal Euler condition

$$\mathbb{E}_t \left[M_{t+1} R_{t+1}\right] = 1 \tag{3.22}$$

holds for the returns of all assets traded in the economy, with the pricing kernel given by

$$M_{t+1} = \beta \left(\frac{C_{t+1}}{C_t}\right)^{-\frac{1}{\xi_L}} \left(\frac{\tilde{C}_{t+1}}{\tilde{C}_t}\right)^{\frac{1}{\xi_L}-\frac{1}{\psi}} \left(\frac{V_{t+1}}{\mathbb{E}_t \left[V_{t+1}^{1-\gamma}\right]^{\frac{1}{1-\gamma}}}\right)^{\frac{1}{\psi}-\gamma}. \tag{3.23}$$

[12]The household's first order conditions are the same as in an endowment economy with the same consumption goods. For the derivation of the firms' first order conditions, see Appendix A.2.

The Euler equation applies to the return of investment in the general macro sector

$$R^I_{t+1} = \frac{\alpha(1-\tilde{\iota})\frac{Y_{t+1}}{K_{t+1}^{\frac{1}{o}} Z_{t+1}^{1-\frac{1}{o}}} + ((1-\delta) + G_{t+1}{}' \frac{I_{t+1}}{K_{t+1}} - G_{t+1})Q^I_{t+1}}{Q^I_t}, \tag{3.24}$$

with $Q^I_t = \frac{1}{1-G'_t}$, and the return on oil inventories

$$R^S_{t+1} = \frac{(1-\omega-\Pi'_t)Q^S_{t+1}}{Q^S_t}. \tag{3.25}$$

With these expressions, we can define the equity market return $R^M_{t+1}$ as the weighted average of the returns to general macro and oil sector.

Given the risk-free rate

$$R^f_t = \frac{1}{\mathbb{E}_t[M_{t+1}]}, \tag{3.26}$$

we calculate the unlevered equity risk premium as

$$R^{LEV}_{ex,t} = (1+\overline{DE})(R^M_t - R^f_{t-1}) \tag{3.27}$$

and account for financial leverage by assuming an average debt-to-equity ratio $\overline{DE}$ of 1 (see, e.g., Croce 2014).

Having the first order conditions as well as the market clearing conditions, $C_t + I_t = Y_t$ and $D_t = J_t$, we can reformulate the model as a central planner's problem according to the welfare theorems. We solve this problem numerically by a third-order approximation using perturbation methods as provided by the `dynare++` package.

## 3.3 Calibration

Table 9 shows the parameters of the calibrated model. Following the literature on long-run risk in consumption- and production-based asset pricing (Bansal and Yaron 2004; Croce 2014), we set the relative risk aversion $\gamma$ to 10 and the intertemporal elasticity of substitution $\psi$ to 2, such that households in our model have a preference for the early resolution of uncertainty. We set the subjective discount factor $\beta$ to 0.97. The parameters $\alpha$, $\delta$, $\mu$, $\tau$, $\sigma_A$, $\phi$, $\sigma_x$, $\rho_w$, and $\sigma_w$ describing the macro sector are chosen in line with Croce (2014). We set the constant elasticity of substitution $\xi_L$ between leisure and consumption to 0.9. For the oil sector, we fix the oil inventory cost $\omega$ as well as the mean $\eta$ and the mean-reversion $\chi$ of the oil production rate according to the benchmark calibration of Hitzemann (2016). We calibrate the adjustment cost parameter of the macro sector $\xi$ to match the volatility of general consumption relative to output, and the oil inventory stock-out cost parameter $\pi$ to the level of oil inventories relative to yearly oil production (see the first panel of Table 10). The elasticity of substitution $o$ of oil as a production input is set to 0.225 in line with Ready (2014), and we calibrate the oil share $\iota$ to match the ratio of oil input relative to general consumption. Finally, we match the oil price volatility's level, mean-reversion, and volatility by calibrating the corresponding parameters of the oil supply process $\sigma_k$, $\rho_v$, and $\sigma_v$. This way, we especially ensure that a one standard deviation shock to oil price volatility — as considered in the empirical section — corresponds to a one standard deviation shock to oil supply volatility in the model.

The second panel of Table 10 reports price and quantity moments that the model is not explicitly calibrated to. Overall, we see that all important moments are in a reasonable order of magnitude, and deviations are in line with the model without an oil sector as proposed by Croce (2014).

### 3.4 Inspecting the Mechanism

Our model provides insights into the economic mechanism behind our main empirical finding that an increase of uncertainty in the oil sector depresses macroeconomic growth. The mechanism is illustrated by the impulse response functions for an oil supply uncertainty shock based on our model, as presented by Figure 8. We see that a rise in uncertainty regarding oil supply prompts the oil producer to stock up above-ground oil inventories. The reason is that a positive shock to oil supply uncertainty makes large negative and positive oil supply (level) shocks more likely. To be able to cushion a large negative oil supply shock and to smooth oil consumption over time, oil producers need to increase their inventories to alleviate the probability of a stock-out. As a result of this *precautionary savings effect*, the oil producer curbs the amount of oil that is sold to the market.

As oil is an important input factor for the production of goods in the general macro sector, the reduced oil supply negatively affects the output of the final consumption and investment good. Therefore, the precautionary savings effect in the oil sector spills over to the general macroeconomy. In consequence of the declining output, the investment and consumption of the general good also decreases. The magnitude of the effect of oil supply uncertainty shocks on the macro sector strongly depends on the substitutability of oil, as specified by the CES parameter $o$. This becomes obvious when we vary the value of $o$, as shown by Figure 10. In the case of a lower $o$, the impact on the macro sector is clearly more pronounced than in the benchmark calibration, while it is the other way round for a higher $o$.

On the quantitative side, a one standard deviation increase of oil supply uncertainty in the model leads to a rise in oil inventories by almost 1%, reducing the effective oil supply to the market by more than 0.5%. In the macro sector, this yields a decrease in output by 0.5%, a fall in consumption by 0.4%, and investments declining by more than 0.7%. These effects on the macroeconomy are comparable to the ones observed in the data.

It is important to understand how the effect of oil uncertainty shocks differs from shocks to the uncertainty of macroeconomic productivity, $w_t$. In general, increasing uncertainty in one or the other sector leads to a stronger motive for precautionary savings, which results in two actions taken by the agents. On the one hand, they want to increase investments in the macro sector at the expense of current consumption as in Croce (2014). On the other hand, agents increase oil inventory holdings and reduce the effective supply of oil to the productive sector.

We see in Figure 8 that in our benchmark calibration, the effect of stocking up oil inventories dominates for both oil and macro uncertainty shocks, resulting in very similar impulse responses for both types of shocks. This is the case because capital adjustment costs in the macro sector are relatively high, making it difficult for agents to increase investments.

Figure 9 shows that this changes for higher values for the capital adjustment parameter $\xi$, leading to a more flexible adjustment of capital in the macro sector: Now, oil uncertainty shocks still lead to a precautionary stock-up of inventories, but for a macro uncertainty shock the incentive to increase investments dominates, which then also results in a positive market return on impact. Therefore, the effects of oil and macro uncertainty shocks on macroeconomic aggregates can be very different, unless one of the precautionary savings measures that agents can take is much more costly than the other one.

### 3.5 Effect on Oil Prices and Equity Returns

The model also explains the behavior of oil prices and equity in response to oil uncertainty shocks. Figure 8 shows that oil prices increase in response to a rise in oil supply volatility. The reason is that oil becomes effectively more scarce for the market when agents have a strong incentive to stock up their inventories. In this sense, our model rationalizes the notion of *precautionary demand shocks* for oil, which Kilian (2009) finds to be an important driver of oil prices.

Figure 8 also illustrates the effect of oil volatility fluctuations on equity returns. As a result of the depressing effect on output, consumption, and investment, there is also a clear negative influence on aggregate equity returns, in line with what we see in the data. Considering the cross-section of different industries reveals that this negative effect is clearly present in the returns of the final goods producing macro sector, $r_t^I$ (see also Figure 10), but not for the return of oil firms, $r_t^S$. The oil firm's return is actually positive, in line with higher revenues for oil producers due to the increasing oil price. This intuition explains why the response of aggregate equity to increasing oil uncertainty is clearly negative in the data, but there is no such effect (or even a positive one) for oil producing industries.

Furthermore, an important result of our empirical analysis is that the negative aggregate equity return is primarily driven by durable goods producers, as opposed to non-durables producing firms. The differential behavior of durables and non-durables industries is considered by the existing asset pricing literature and rationalized in the context of general equilibrium models (see Yogo 2006; Gomes, Kogan, and Yogo 2009). When it comes to energy consumption, a special property of durable-good producers is that their production is more sensitive to oil input factor.[13] By changing the elasticity of substitution between oil and capital from low to high, we show in Figure 10 that the negative response of equity returns is much more pronounced for the low $o$ case. Such a comparative statics result can help rationalize why the returns of durable firms (low $o$) are more exposed to oil volatility risks relative to non-durable ones (high $o$).

# 4 Conclusion

We show novel empirical evidence that oil price variance captures significant information about economic growth and asset prices. An increase in oil variance predicts a decline in current and future growth rates of consumption, output, investment, and employment 1 to 4 quarters ahead, controlling for current growth rate in the corresponding variables, current oil returns, and the market variance. We further show that the market equity price drops at times of high oil uncertainty, and the effect is even more pronounced for durable-good producing firms.

We provide a two-sector macro model to explain these empirical findings. In the model, oil producers manage oil inventories to mitigate the consequences of oil supply shocks. In times of high oil supply volatility, they increase their inventories to alleviate the probability of a stock-out. As a result of this precautionary savings effect, the amount of oil available for production in the general macro sector is reduced, and production, consumption, and investments decrease. This effect dominates the usual precautionary savings effect to increase physical capital investments when uncertainty increases, such that consumption and investment jointly decrease in our model when oil uncertainty rises. These economic mechanisms are directly supported in the data.

[13] Alternatively, one can capture durability through the household's preference side, building up on Ready (2014) or Hitzemann (2016).

# Tables and Figures

Table 1: **Summary Statistics**

| | Mean | Std. Dev. | AR(1) |
|---|---|---|---|
| Consumption growth | 1.68 | 0.80 | 0.54 |
| GDP growth | 1.83 | 1.29 | 0.47 |
| Investment growth | 2.76 | 6.63 | 0.40 |
| TFP growth | 1.02 | 1.27 | 0.12 |
| Employment growth | 1.50 | 1.12 | 0.91 |
| Excess equity return | 6.21 | 17.19 | 0.02 |
| Excess oil return | 4.00 | 38.68 | -0.08 |
| Equity volatility | 20.08 | 7.61 | 0.58 |
| Oil volatility | 34.38 | 13.58 | 0.59 |
| Oil consumption growth | 0.60 | 2.22 | -0.20 |
| Oil production growth | 1.15 | 2.72 | -0.07 |
| Oil inventory growth | 0.68 | 2.50 | 0.01 |

The table reports summary statistics for the macroeconomic variables, excess equity and oil returns, and the implied oil and equity volatility measures. Consumption, output, investment, TFP, and employment data are real and per capita. Dividends and stock returns are computed for the broad market portfolio. The implied oil and equity volatilities, constructed from the oil and equity option data, are quarterly from 1990Q1 to 2014Q1, and are expressed in implied volatility (standard deviation) units. Oil consumption, production, and inventory data are quarterly from 1984Q2 to 2014Q1. All the other data are quarterly from 1983Q2 to 2014Q1. Means and standard deviations are annualized.

Table 2: **Correlation Evidence**

| | Oil IV | Equity IV | Oil return |
|---|---|---|---|
| | *1990-2014 sample* | | |
| Consumption growth | -0.49 | -0.35 | 0.19 |
| GDP growth | -0.55 | -0.40 | 0.29 |
| Investment growth | -0.49 | -0.37 | 0.20 |
| Employment growth | -0.55 | -0.49 | 0.08 |
| TFP growth | -0.30 | -0.17 | 0.28 |
| | | | |
| Excess equity return | -0.30 | -0.57 | 0.04 |
| Excess oil return | -0.21 | -0.15 | 1.00 |
| Equity IV | 0.57 | 1.00 | -0.15 |
| | | | |
| Oil consumption growth | -0.36 | -0.12 | 0.20 |
| Oil production growth | -0.14 | -0.15 | -0.17 |
| Oil inventory growth | 0.03 | -0.04 | -0.38 |
| | | | |
| | *1990-2014 sample excluding 2006Q3-2008Q4* | | |
| Consumption growth | -0.43 | -0.23 | 0.06 |
| Output growth | -0.44 | -0.27 | 0.08 |
| Investment growth | -0.42 | -0.30 | 0.06 |
| Employment growth | -0.47 | -0.41 | -0.09 |
| TFP growth | -0.21 | -0.07 | 0.18 |
| | | | |
| Excess equity return | -0.15 | -0.50 | -0.17 |
| Excess oil return | 0.03 | 0.03 | 1.00 |
| Equity IV | 0.49 | 1.00 | 0.03 |
| | | | |
| Oil consumption growth | -0.37 | 0.00 | 0.14 |
| Oil production growth | -0.09 | -0.12 | -0.30 |
| Oil inventory growth | -0.10 | -0.14 | -0.30 |

The table reports correlations between volatility measures, oil returns, and aggregate economic and asset-price variables. Variance measures correspond to the implied variances computed from the equity and oil option prices. The top panel uses quarterly data from 1990 to 2014, and the bottom panel excludes 2006Q3-2008Q4 episode.

Table 3: **Macroeconomic Predictability Evidence**

| | Lag growth | | Oil Var | | Equity Var | | Oil Return | | Adj. $R^2$ |
|---|---|---|---|---|---|---|---|---|---|
| *Consumption growth:* | | | | | | | | | |
| 0q ahead | 0.41 | (0.09) | -4.23 | (0.77) | -1.50 | (3.18) | 0.05 | (0.14) | 0.39 |
| 1q ahead | 0.38 | (0.13) | -3.49 | (0.93) | -3.35 | (4.10) | -0.38 | (0.20) | 0.35 |
| 2q ahead | 0.42 | (0.13) | -1.83 | (1.17) | -2.33 | (4.00) | -0.23 | (0.19) | 0.34 |
| 3q ahead | 0.46 | (0.13) | -0.80 | (0.93) | -1.62 | (3.50) | -0.11 | (0.15) | 0.36 |
| 4q ahead | 0.41 | (0.15) | -0.85 | (0.86) | -0.89 | (3.40) | -0.17 | (0.15) | 0.30 |
| *GDP growth:* | | | | | | | | | |
| 0q ahead | 0.24 | (0.09) | -6.80 | (1.36) | -5.97 | (5.81) | 0.61 | (0.27) | 0.36 |
| 1q ahead | 0.27 | (0.10) | -6.13 | (1.74) | 1.91 | (9.76) | -0.28 | (0.33) | 0.21 |
| 2q ahead | 0.32 | (0.07) | -2.44 | (1.19) | -2.30 | (7.20) | -0.34 | (0.30) | 0.20 |
| 3q ahead | 0.27 | (0.11) | -1.35 | (1.24) | -1.79 | (5.81) | -0.24 | (0.26) | 0.13 |
| 4q ahead | 0.27 | (0.12) | -1.06 | (1.41) | 0.36 | (5.26) | -0.37 | (0.25) | 0.12 |
| *Investment growth:* | | | | | | | | | |
| 0q ahead | 0.29 | (0.11) | -29.78 | (5.71) | -35.47 | (38.05) | 1.87 | (1.22) | 0.30 |
| 1q ahead | 0.25 | (0.09) | -31.58 | (10.93) | -6.66 | (51.77) | -0.53 | (1.84) | 0.23 |
| 2q ahead | 0.21 | (0.08) | -19.68 | (7.67) | -21.21 | (43.03) | 0.23 | (1.87) | 0.20 |
| 3q ahead | 0.18 | (0.10) | -11.04 | (6.63) | -19.52 | (33.74) | 0.17 | (1.68) | 0.11 |
| 4q ahead | 0.16 | (0.11) | -4.93 | (6.47) | -12.51 | (27.40) | -0.63 | (1.36) | 0.04 |
| *Employment growth:* | | | | | | | | | |
| 0q ahead | 0.80 | (0.06) | -2.88 | (0.90) | -4.79 | (3.26) | 0.08 | (0.11) | 0.85 |
| 1q ahead | 0.78 | (0.07) | -2.22 | (0.74) | -4.15 | (3.68) | 0.29 | (0.15) | 0.84 |
| 2q ahead | 0.70 | (0.10) | -2.47 | (0.78) | -4.76 | (4.59) | 0.20 | (0.19) | 0.75 |
| 3q ahead | 0.64 | (0.12) | -1.85 | (0.84) | -6.23 | (4.72) | 0.09 | (0.18) | 0.64 |
| 4q ahead | 0.57 | (0.13) | -1.51 | (0.94) | -6.00 | (4.55) | 0.02 | (0.18) | 0.53 |
| *TFP growth:* | | | | | | | | | |
| 0q ahead | 0.05 | (0.09) | -19.23 | (7.03) | 4.29 | (22.63) | 3.14 | (1.26) | 0.10 |
| 1q ahead | 0.14 | (0.09) | -9.89 | (8.57) | 30.03 | (36.64) | -1.96 | (1.77) | -0.00 |
| 2q ahead | 0.15 | (0.07) | -1.69 | (5.10) | 36.77 | (25.11) | -1.40 | (1.32) | 0.03 |
| 3q ahead | 0.10 | (0.08) | 2.40 | (4.96) | 33.34 | (20.04) | -0.75 | (1.00) | 0.03 |
| 4q ahead | 0.10 | (0.09) | 2.82 | (5.62) | 35.63 | (17.59) | -1.28 | (0.81) | 0.08 |
| *Utilization-adjusted TFP growth:* | | | | | | | | | |
| 0q ahead | -0.01 | (0.09) | 2.94 | (9.08) | 45.13 | (26.27) | 2.23 | (1.50) | -0.00 |
| 1q ahead | -0.01 | (0.08) | 12.02 | (9.43) | 49.29 | (39.03) | -2.68 | (1.32) | 0.08 |
| 2q ahead | 0.00 | (0.06) | 9.80 | (6.30) | 58.30 | (21.21) | -1.76 | (0.74) | 0.17 |
| 3q ahead | 0.05 | (0.04) | 3.36 | (4.93) | 61.70 | (21.02) | -0.94 | (0.78) | 0.16 |
| 4q ahead | 0.02 | (0.05) | -0.10 | (4.74) | 55.68 | (19.35) | -1.09 | (0.65) | 0.12 |

The table reports predictability evidence for future real consumption, GDP, investment, employment, and TFP growth by their own lag, oil variance, equity variance, and oil return. Variance measures correspond to the implied variances computed from the equity and oil option prices. Newey-West standard errors are in parentheses. Data are quarterly from 1990Q1 to 2014Q1.

Table 4: **Oil Predictability Evidence**

| | Lag growth | | Oil Var | | Equity Var | | Oil Return | | Adj. $R^2$ |
|---|---|---|---|---|---|---|---|---|---|
| *Oil Consumption Growth:* | | | | | | | | | |
| 0q ahead | -0.27 | (0.10) | -15.80 | (4.76) | 19.80 | (14.64) | 0.96 | (0.92) | 0.21 |
| 1q ahead | -0.23 | (0.10) | -7.59 | (5.23) | -23.32 | (16.21) | -2.30 | (0.86) | 0.24 |
| 2q ahead | -0.16 | (0.09) | -2.22 | (3.99) | -16.91 | (13.60) | -0.54 | (0.35) | 0.10 |
| 3q ahead | 0.01 | (0.05) | 1.57 | (2.66) | -20.49 | (8.53) | -0.32 | (0.32) | 0.07 |
| 4q ahead | -0.00 | (0.05) | 0.93 | (2.21) | -17.14 | (8.02) | -0.45 | (0.30) | 0.07 |
| *Oil Production Growth:* | | | | | | | | | |
| 0q ahead | -0.01 | (0.14) | -5.22 | (5.44) | -9.50 | (14.76) | -1.23 | (0.99) | 0.05 |
| 1q ahead | 0.13 | (0.09) | -0.33 | (3.81) | 7.51 | (9.72) | 1.58 | (0.65) | 0.05 |
| 2q ahead | 0.04 | (0.05) | -2.32 | (1.83) | 9.57 | (8.07) | 1.24 | (0.35) | 0.08 |
| 3q ahead | 0.06 | (0.05) | -0.24 | (1.25) | 0.86 | (7.26) | 0.59 | (0.26) | -0.00 |
| 4q ahead | 0.01 | (0.05) | 0.44 | (1.01) | -0.11 | (5.96) | 0.55 | (0.23) | -0.00 |
| *Oil Inventory Growth:* | | | | | | | | | |
| 0q ahead | 0.13 | (0.09) | 1.84 | (2.94) | -10.15 | (14.32) | -2.33 | (0.47) | 0.16 |
| 1q ahead | 0.16 | (0.09) | 4.01 | (2.30) | 3.09 | (12.05) | 0.19 | (0.60) | 0.00 |
| 2q ahead | 0.05 | (0.07) | 0.73 | (2.54) | 6.10 | (9.50) | -0.02 | (0.42) | -0.03 |
| 3q ahead | 0.01 | (0.05) | 0.41 | (1.61) | 0.35 | (7.65) | -0.36 | (0.36) | -0.03 |
| 4q ahead | -0.03 | (0.04) | -0.44 | (1.43) | 2.96 | (7.32) | 0.03 | (0.28) | -0.04 |

The table reports predictability evidence for future oil production, consumption, and inventory growth by their own lag, oil variance, equity variance, and oil return. Variance measures correspond to the implied variances computed from the equity and oil option prices. Newey-West standard errors are in parentheses. Data are quarterly from 1990Q1 to 2014Q1.

Table 5: **Predictability Evidence Controlling for Policy Uncertainty**

| | Lag growth | | Oil Var | | Policy Unc | | Oil Return | | Adj. $R^2$ |
|---|---|---|---|---|---|---|---|---|---|
| *Consumption Growth:* | | | | | | | | | |
| 0q ahead | 0.33 | (0.10) | -3.67 | (0.65) | -28.44 | (7.84) | 0.06 | (0.15) | 0.44 |
| 1q ahead | 0.32 | (0.13) | -3.78 | (0.97) | -16.24 | (8.98) | -0.37 | (0.19) | 0.37 |
| 4q ahead | 0.37 | (0.17) | -0.82 | (0.89) | -10.71 | (10.54) | -0.17 | (0.15) | 0.31 |
| *GDP Growth:* | | | | | | | | | |
| 0q ahead | 0.21 | (0.10) | -6.86 | (1.57) | -31.73 | (12.76) | 0.60 | (0.27) | 0.38 |
| 1q ahead | 0.22 | (0.11) | -5.47 | (1.47) | -21.77 | (16.42) | -0.27 | (0.33) | 0.22 |
| 4q ahead | 0.25 | (0.12) | -0.88 | (1.17) | -6.63 | (10.60) | -0.37 | (0.25) | 0.13 |
| *Investment Growth:* | | | | | | | | | |
| 0q ahead | 0.29 | (0.12) | -35.34 | (7.26) | -1.38 | (74.71) | 1.93 | (1.25) | 0.30 |
| 1q ahead | 0.25 | (0.10) | -30.96 | (10.86) | -45.40 | (90.92) | -0.54 | (1.86) | 0.23 |
| 4q ahead | 0.16 | (0.11) | -8.38 | (6.50) | 45.75 | (55.82) | -0.59 | (1.34) | 0.05 |
| *Employment Growth:* | | | | | | | | | |
| 0q ahead | 0.81 | (0.07) | -3.52 | (1.10) | -1.62 | (4.75) | 0.09 | (0.11) | 0.85 |
| 1q ahead | 0.80 | (0.07) | -2.70 | (0.85) | -1.06 | (6.62) | 0.30 | (0.16) | 0.84 |
| 4q ahead | 0.61 | (0.13) | -2.41 | (1.05) | 7.67 | (7.97) | 0.04 | (0.19) | 0.53 |
| *Oil Consumption Growth:* | | | | | | | | | |
| 0q ahead | -0.28 | (0.11) | -11.35 | (4.64) | -33.96 | (31.06) | 0.92 | (0.90) | 0.20 |
| 1q ahead | -0.27 | (0.11) | -9.56 | (4.56) | -65.25 | (24.18) | -2.27 | (0.81) | 0.25 |
| 4q ahead | -0.03 | (0.05) | -1.30 | (2.42) | -22.57 | (13.92) | -0.41 | (0.30) | 0.02 |
| *Oil Production Growth:* | | | | | | | | | |
| 0q ahead | -0.01 | (0.14) | -5.79 | (4.82) | -27.26 | (26.26) | -1.23 | (0.97) | 0.05 |
| 1q ahead | 0.11 | (0.08) | 1.88 | (2.94) | -30.10 | (25.54) | 1.53 | (0.65) | 0.06 |
| 4q ahead | 0.00 | (0.05) | 0.90 | (0.94) | -13.73 | (14.64) | 0.54 | (0.23) | 0.01 |
| *Oil Inventory Growth:* | | | | | | | | | |
| 0q ahead | 0.13 | (0.09) | 0.44 | (2.24) | -7.75 | (26.14) | -2.32 | (0.45) | 0.15 |
| 1q ahead | 0.16 | (0.09) | 4.37 | (2.39) | 3.88 | (30.65) | 0.18 | (0.58) | 0.00 |
| 4q ahead | -0.03 | (0.04) | 0.42 | (1.56) | -10.37 | (25.20) | 0.01 | (0.27) | -0.04 |

The table reports predictability evidence for future growth in macroeconomic and oil sectors by its own lag, oil variance, policy uncertainty, and oil return. Variance measures correspond to the implied variances computed from the oil option prices, and policy uncertainty measure. Newey-West standard errors are in parentheses. Data are quarterly from 1990Q1 to 2014Q1.

Table 6: **Predictability Evidence Controlling for Macroeconomic Variance**

| | Lag growth | | Oil Var | | Macro Var | | Oil Return | | Adj. $R^2$ |
|---|---|---|---|---|---|---|---|---|---|
| *Consumption Growth:* | | | | | | | | | |
| 0q ahead | 0.40 | (0.08) | -4.57 | (0.63) | -0.94 | (0.56) | 0.02 | (0.15) | 0.40 |
| 1q ahead | 0.39 | (0.13) | -4.00 | (0.95) | -0.02 | (0.54) | -0.37 | (0.20) | 0.35 |
| 4q ahead | 0.43 | (0.15) | -0.88 | (0.91) | 0.45 | (0.58) | -0.15 | (0.14) | 0.30 |
| *GDP Growth:* | | | | | | | | | |
| 0q ahead | 0.20 | (0.09) | -8.11 | (1.54) | -1.81 | (1.03) | 0.55 | (0.26) | 0.37 |
| 1q ahead | 0.26 | (0.11) | -5.86 | (1.56) | -0.03 | (0.94) | -0.28 | (0.34) | 0.21 |
| 4q ahead | 0.27 | (0.13) | -0.91 | (1.37) | 0.36 | (1.08) | -0.36 | (0.24) | 0.12 |
| *Investment Growth:* | | | | | | | | | |
| 0q ahead | 0.29 | (0.11) | -35.82 | (7.66) | -2.41 | (5.74) | 1.82 | (1.27) | 0.30 |
| 1q ahead | 0.25 | (0.10) | -32.55 | (11.90) | 0.03 | (4.42) | -0.52 | (1.92) | 0.22 |
| 4q ahead | 0.17 | (0.11) | -5.75 | (6.53) | 6.20 | (5.52) | -0.38 | (1.40) | 0.06 |
| *Employment Growth:* | | | | | | | | | |
| 0q ahead | 0.80 | (0.07) | -3.72 | (1.13) | -0.51 | (0.46) | 0.07 | (0.12) | 0.85 |
| 1q ahead | 0.82 | (0.08) | -2.59 | (0.84) | 0.32 | (0.48) | 0.32 | (0.17) | 0.84 |
| 4q ahead | 0.67 | (0.14) | -1.52 | (1.02) | 1.65 | (0.96) | 0.11 | (0.19) | 0.54 |
| *Oil Consumption Growth:* | | | | | | | | | |
| 0q ahead | -0.27 | (0.10) | -12.40 | (4.22) | 2.33 | (2.18) | 1.02 | (0.89) | 0.19 |
| 1q ahead | -0.26 | (0.12) | -11.72 | (4.74) | 1.03 | (1.70) | -2.20 | (0.84) | 0.21 |
| 4q ahead | -0.03 | (0.06) | -2.06 | (2.39) | 2.26 | (0.97) | -0.30 | (0.27) | 0.03 |
| *Oil Production Growth:* | | | | | | | | | |
| 0q ahead | -0.02 | (0.14) | -7.11 | (4.66) | -3.42 | (1.61) | -1.36 | (0.97) | 0.06 |
| 1q ahead | 0.12 | (0.09) | 0.78 | (2.91) | -0.81 | (1.28) | 1.52 | (0.66) | 0.05 |
| 4q ahead | -0.00 | (0.05) | 0.25 | (1.13) | -1.49 | (1.10) | 0.47 | (0.23) | 0.01 |
| *Oil Inventory Growth:* | | | | | | | | | |
| 0q ahead | 0.13 | (0.09) | 0.22 | (2.30) | 1.02 | (1.96) | -2.28 | (0.47) | 0.15 |
| 1q ahead | 0.16 | (0.09) | 4.56 | (2.28) | 1.05 | (1.91) | 0.22 | (0.59) | 0.00 |
| 4q ahead | -0.03 | (0.04) | 0.11 | (1.39) | 1.11 | (1.47) | 0.06 | (0.28) | -0.03 |

The table reports predictability evidence for future growth in macroeconomic and oil sectors by its own lag, oil variance, macroeconomic variance, and oil return. Variance measures correspond to the implied variances computed from the oil option prices, and the conditional variance of aggregate consumption. Newey-West standard errors are in parentheses. Data are quarterly from 1990Q1 to 2014Q1.

Table 7: **Asset Pricing Evidence**

| | OilVar | | EquityVar | | Oil Return | | Market Return | | Adj. $R^2$ |
|---|---|---|---|---|---|---|---|---|---|
| | | | | *1990-2014 sample* | | | | | |
| durables | -0.36 | (0.13) | -0.25 | (0.84) | 0.01 | (0.03) | 1.31 | (0.09) | 0.79 |
| non-durables | 0.11 | (0.12) | 0.11 | (0.59) | -0.08 | (0.01) | 0.87 | (0.04) | 0.84 |
| oil producers | 0.46 | (0.33) | -3.38 | (1.17) | 0.09 | (0.04) | 0.34 | (0.11) | 0.35 |
| | | | | *1990-2014 sample, excluding 2006Q3-2008Q4* | | | | | |
| durables | -0.45 | (0.18) | -0.34 | (0.90) | 0.04 | (0.04) | 1.33 | (0.10) | 0.77 |
| non-durables | 0.22 | (0.11) | -0.25 | (0.55) | -0.09 | (0.01) | 0.86 | (0.04) | 0.85 |
| oil producers | 0.15 | (0.17) | -3.01 | (0.99) | 0.11 | (0.03) | 0.38 | (0.09) | 0.39 |

The table reports the exposures of portfolio equity returns in durable, non-durable, and oil producing sectors to oil and equity volatilities, and oil and market returns. Variance measures correspond to the implied variances computed from the equity and oil option prices. The top panel uses quarterly data from 1990Q1 to 2014Q4, and the bottom panel excludes 2006Q3-2008Q4 episode. Newey-West standard errors are in parentheses.

Table 8: **Sectoral Predictability Evidence**

| | Lag growth | | Oil Var | | Equity Var | | Oil Return | | Adj. $R^2$ |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Industrial Production Growth: | | | | | |
| *Aggregate:* | | | | | | | | | |
| 0q ahead | 0.59 | (0.10) | -0.09 | (0.02) | -0.15 | (0.14) | 0.01 | (0.00) | 0.61 |
| 1q ahead | 0.55 | (0.14) | -0.10 | ( 0.03) | -0.08 | (0.10) | 0.00 | (0.01) | 0.58 |
| 4q ahead | 0.31 | (0.16) | -0.00 | (0.03) | -0.11 | (0.09) | -0.00 | (0.01) | 0.15 |
| *Durable consumer goods:* | | | | | | | | | |
| 0q ahead | 0.25 | (0.09) | -0.31 | (0.05) | -0.32 | (0.48) | -0.00 | (0.01) | 0.27 |
| 1q ahead | 0.20 | (0.12) | -0.40 | (0.11) | 0.24 | (0.36) | 0.02 | (0.03) | 0.27 |
| 4q ahead | 0.16 | (0.13) | 0.02 | (0.07) | -0.02 | (0.21) | -0.01 | (0.01) | 0.03 |
| *Durable manufacturing, motor vehicles:* | | | | | | | | | |
| 0q ahead | 0.21 | (0.08) | -0.53 | (0.14) | -0.66 | (1.08) | -0.01 | (0.03) | 0.16 |
| 1q ahead | 0.15 | (0.11) | -0.82 | (0.24) | 0.89 | (0.78) | 0.04 | (0.07) | 0.21 |
| 4q ahead | 0.09 | (0.08) | 0.08 | (0.08) | 0.24 | (0.38) | -0.02 | (0.02) | -0.01 |
| *Nondurable consumer goods:* | | | | | | | | | |
| 0q ahead | 0.11 | (0.12) | 0.00 | (0.02) | -0.18 | (0.08) | 0.00 | (0.00) | 0.03 |
| 1q ahead | 0.06 | (0.12) | -0.01 | (0.02) | -0.30 | (0.08) | -0.00 | (0.00) | 0.14 |
| 4q ahead | 0.14 | (0.09) | -0.00 | (0.01) | -0.16 | (0.05) | -0.00 | (0.00) | 0.16 |
| *Mining, crude oil:* | | | | | | | | | |
| 0q ahead | 0.38 | (0.10) | 0.18 | (0.09) | -0.38 | (0.31) | -0.01 | (0.01) | 0.12 |
| 1q ahead | 0.33 | (0.12) | 0.01 | (0.05) | 0.44 | (0.28) | -0.01 | (0.01) | 0.12 |
| 4q ahead | 0.19 | (0.17) | -0.00 | (0.04) | 0.33 | (0.19) | -0.00 | (0.01) | 0.09 |
| | | | | Earnings Growth: | | | | | |
| *Aggregate:* | | | | | | | | | |
| 0q ahead | 0.26 | (0.10) | -0.66 | (1.06) | -1.99 | (2.53) | 0.34 | (0.14) | 0.23 |
| 1q ahead | 0.19 | (0.12) | 0.75 | (0.50) | -4.96 | (3.41) | 0.26 | (0.11) | 0.16 |
| 4q ahead | 0.01 | (0.09) | 0.55 | (0.44) | -1.57 | (1.93) | 0.09 | (0.05) | -0.01 |
| *Durables:* | | | | | | | | | |
| 0q ahead | 0.05 | (0.11) | -2.36 | (0.45) | 1.63 | (2.69) | 0.15 | (0.11) | 0.15 |
| 1q ahead | 0.09 | (0.08) | -0.26 | (0.54) | -5.96 | (2.27) | -0.18 | (0.12) | 0.09 |
| 4q ahead | -0.01 | (0.06) | 0.01 | (0.27) | -2.75 | (1.72) | 0.02 | (0.04) | 0.02 |
| *Nondurables:* | | | | | | | | | |
| 0q ahead | 0.12 | (0.11) | 0.33 | (0.94) | -3.77 | (2.34) | 0.24 | (0.12) | 0.09 |
| 1q ahead | 0.08 | (0.11) | 1.33 | (0.52) | -5.40 | (2.64) | 0.18 | (0.06) | 0.08 |
| 4q ahead | -0.04 | (0.05) | 0.63 | (0.26) | -2.00 | (1.38) | 0.07 | (0.04) | -0.00 |
| *Oil producers:* | | | | | | | | | |
| 0q ahead | 0.23 | (0.09) | 1.12 | (1.33) | -7.59 | (3.30) | 0.12 | (0.16) | 0.11 |
| 1q ahead | 0.16 | (0.08) | 0.14 | (0.57) | -6.85 | (3.03) | 0.57 | (0.09) | 0.33 |
| 4q ahead | 0.01 | (0.08) | 0.32 | (0.46) | -5.48 | (2.13) | 0.20 | (0.08) | 0.15 |

The table reports predictability evidence for future industrial production and earnings growth for the aggregate economy, and durable, nondurable, and oil sectors. Variance measures correspond to the implied variances computed from the equity and oil option prices. Newey-West standard errors are in parentheses. Data are quarterly from 1990Q1 to 2014Q1.

Table 9: **Model Parameters**

| Parameter | | Value |
|---|---|---|
| Subjective discount factor | $\beta$ | 0.97 |
| Risk aversion | $\gamma$ | 10 |
| Intertemporal elasticity of substitution | $\psi$ | 2 |
| Oil share of production | $\iota$ | 0.022 |
| Elasticity of substitution between oil and capital | $o$ | 0.225 |
| General macroeconomy | | |
| Capital share | $\alpha$ | 0.34 |
| Depreciation rate of capital | $\delta$ | 0.06 |
| Average growth rate | $\mu$ | 1.8% |
| Capital adjustment costs | $\xi$ | 3.1 |
| Share of final goods in consumption | $\tau$ | 0.205 |
| Elasticity of substitution between leisure and consumption goods | $\xi_L$ | 0.9 |
| Volatility of productivity risk | $\sigma_A$ | 3.35% |
| Autocorrelation of expected growth | $\phi$ | 0.8 |
| Volatility of long-run risk | $\sigma_x$ | $0.1\sigma_A$ |
| Mean-reversion of volatility of macro productivity | $\rho_w$ | 0.987 |
| Volatility of volatility of macro productivity | $\sigma_w$ | 1% |
| Oil sector | | |
| Oil inventory costs | $\omega$ | 0.1 |
| Oil stock-out costs | $\pi$ | 0.00003 |
| Average oil production rate | $\eta$ | 0.16 |
| Mean-reversion of oil productivity | $\chi$ | 0.87 |
| Volatility of oil productivity | $\sigma_\kappa$ | 6.63% |
| Mean-reversion of oil production volatility | $\rho_v$ | 0.8 |
| Volatility of oil production volatility | $\sigma_v$ | 46.48% |

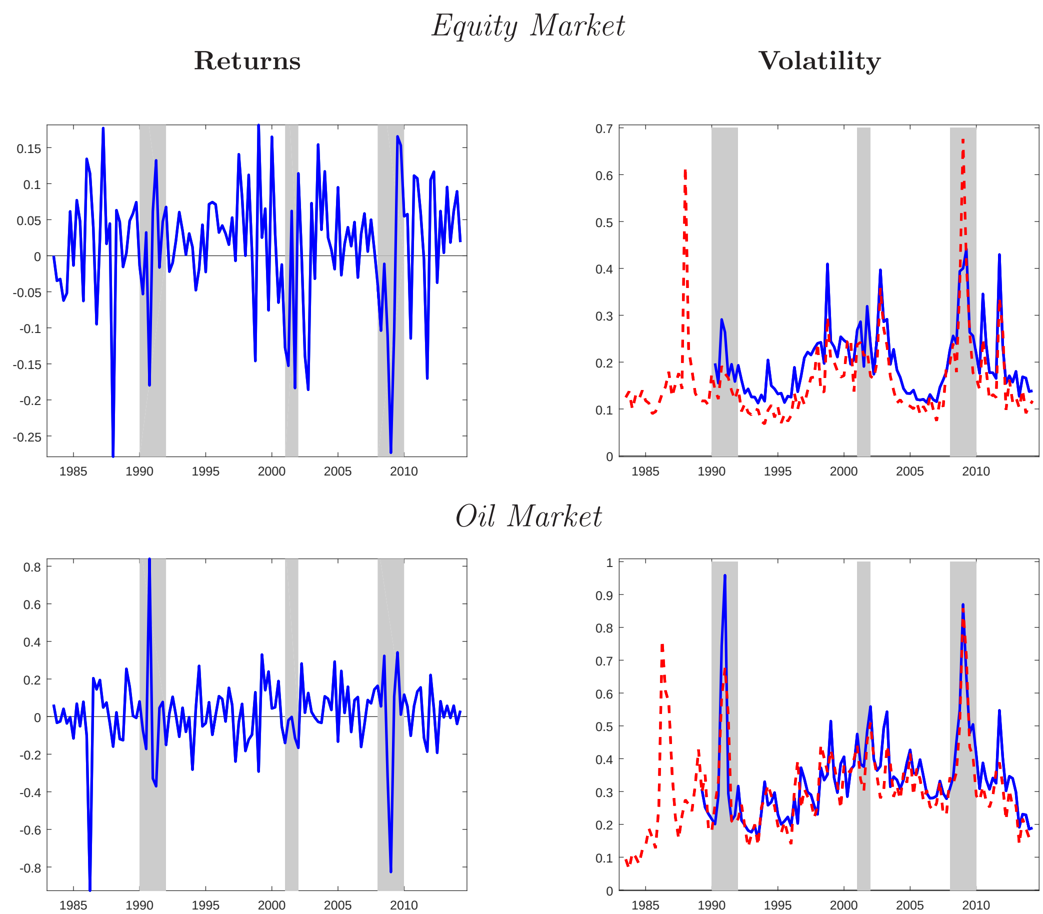
The table reports the parameters of the calibrated model. Parameters describing the household's preferences as well as the general structure and the oil sector are set according to the literature. The capital adjustment cost parameter, the oil stock-out cost parameter, the oil share parameter, and the parameters describing the volatility of oil supply are calibrated to match the moments in the first panel of Table 10. All parameters are annualized.

Table 10: **Moments**

| Calibrated Moments | | |
|---|---|---|
| Statistic | Data | Model |
| Relative volatility of general consumption and output | | |
| $\sigma(\Delta c)/\sigma(\Delta y)$ | 0.62 | 0.62 |
| Oil inventory-production ratio | | |
| $\mathbb{E}[S/E]$ | 0.29 | 0.28 |
| Oil input relative to general consumption | | |
| $\mathbb{E}[P * J/C]$ | 0.04 | 0.04 |
| Oil price volatility | | |
| $\sigma(p_t)$ [%] | 34.38 | 34.44 |
| Oil price vol of vol | | |
| $\sigma(\sigma_t(p))$ [%] | 13.58 | 14.90 |
| Oil price vol autocorrelation | | |
| $\rho(\sigma_{t-1}(p), \sigma_t(p))$ [%] | 0.59 | 0.61 |
| Price and Quantity Moments | | |
| Statistic | Data | Model |
| Investment-output ratio | | |
| $\mathbb{E}[I/Y]$ [%] | 15.88 | 23.40 |
| Relative volatility of general investment and output | | |
| $\sigma(\Delta i)/\sigma(\Delta y)$ | 5.14 | 2.20 |
| Relative volatility of oil inventories and oil production | | |
| $\sigma(\Delta s)/\sigma(\Delta e)$ | 0.92 | 0.98 |
| Equity risk premium | | |
| $\mathbb{E}[r^{LEV}_{ex,t+1}]$ [%] | 6.21 | 2.07 |
| Equity volatility | | |
| $\sigma[r^{LEV}_{ex,t+1}]$ [%] | 20.08 | 6.18 |
| Risk-free rate | | |
| $\mathbb{E}[r^f_t]$ [%] | 1.23 | 2.78 |
| Volatility of risk-free rate | | |
| $\sigma(r^f_t)$ [%] | 1.04 | 0.87 |

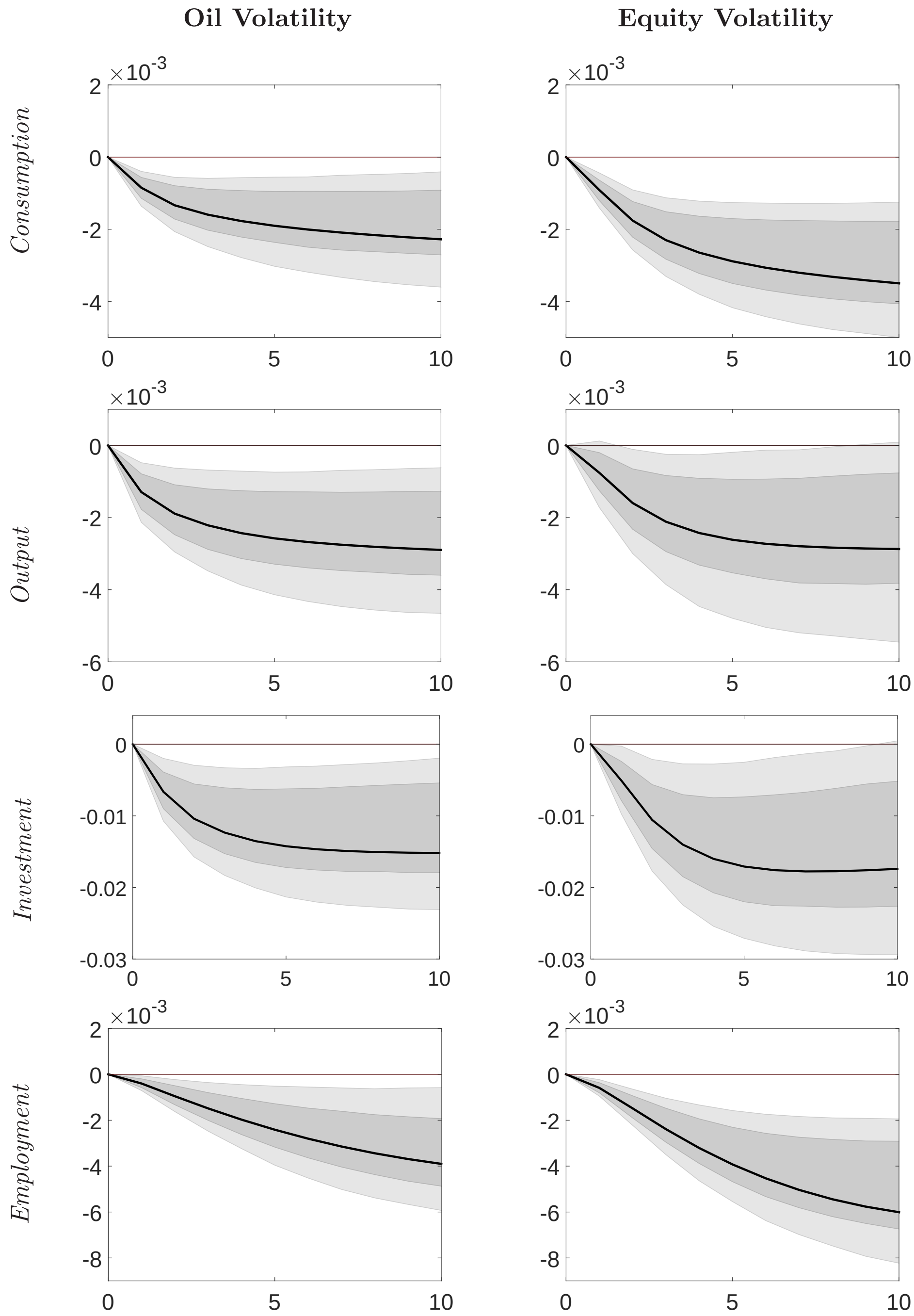
The table reports the moments that the model is explicitly calibrated to, as well as other price and quantity moments. The empirical moments correspond to the summary statistics in Table 1. We simulate the model on a quarterly basis and aggregate moments to an annual frequency.

Figure 1: **Excess Return and Volatility in Oil and Equity Markets**



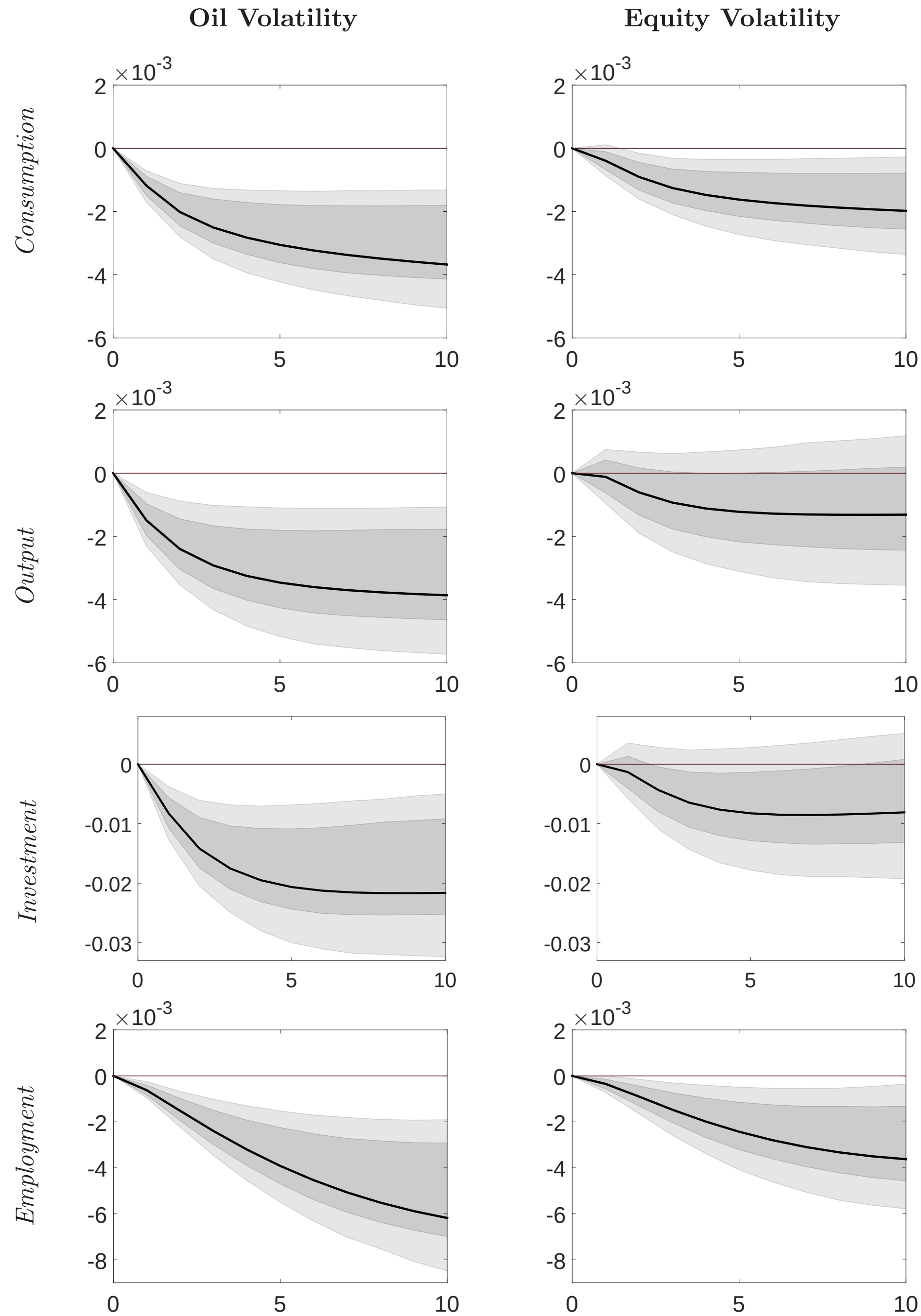

The figure shows the excess returns (left panels) and volatilities (right panels) in equity and oil markets. Implied volatilities (solid line) are constructed from the equity and oil option data, and realized volatilities (dashed line) are based on daily return data. The volatilities are expressed in annualized standard deviation units.

Figure 2: **Impulse Response of Macro Series to Volatility**



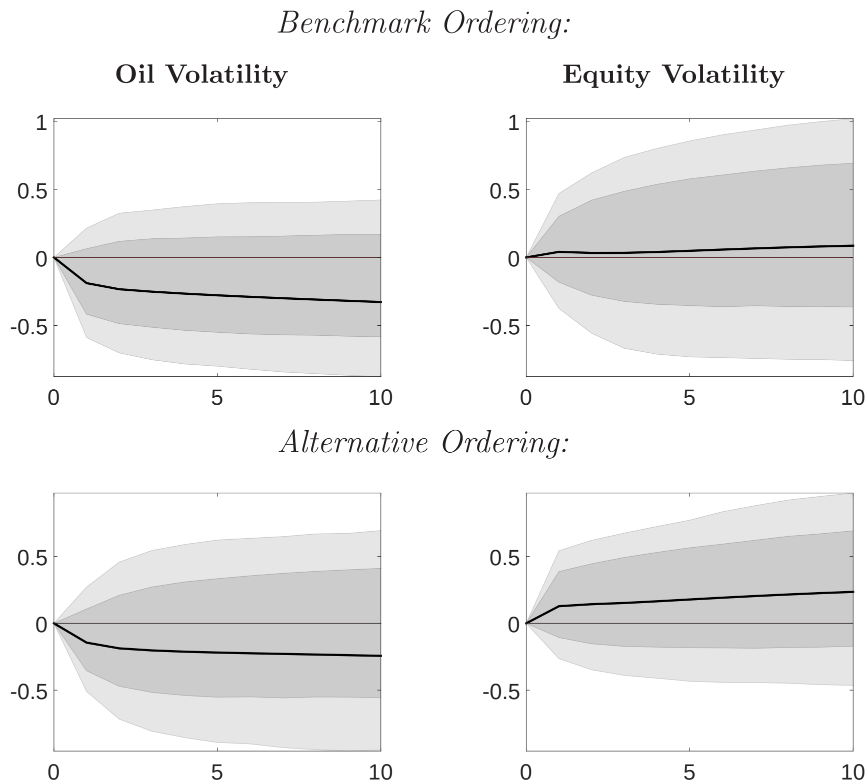

The figure shows the cumulative impulse response of future consumption, output, investment, and employment growth to implied oil volatility (left panels) and equity volatility (right panels). The impulse responses are based on a lower-triangular Cholesky decomposition of a VAR(1) fitted to the corresponding macroeconomic series, oil return, market variance, oil variance, risk-free rate, and the market-price-dividend ratio, in that order. Light and dark gray regions indicate 90% and 68% confidence intervals computed by block-bootstrap. Data are quarterly from 1990Q1 to 2014Q1.

Figure 3: **Impulse Response of Macro Series to Volatility: Alternative Ordering**



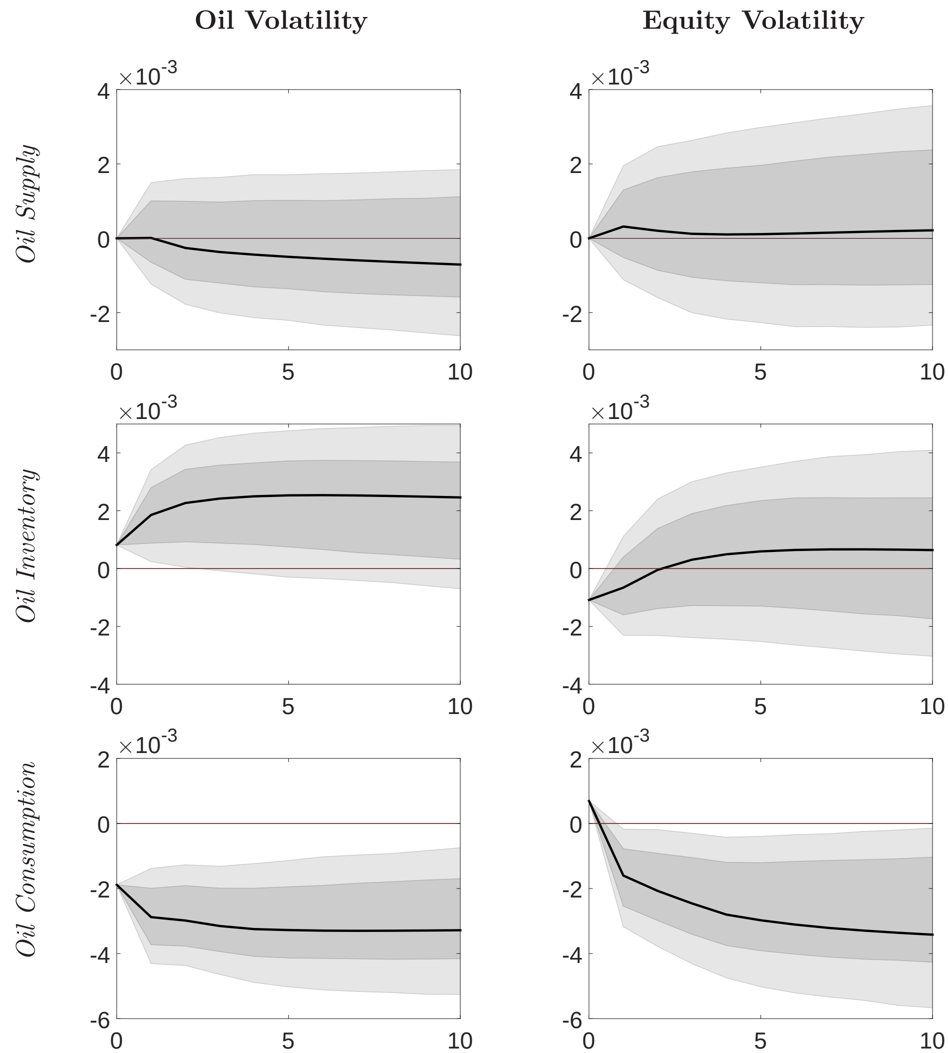

The figure shows the cumulative impulse response of future consumption, output, investment, and employment growth to implied oil volatility (left panels) and equity volatility (right panels). The impulse responses are based on a lower-triangular Cholesky decomposition of a VAR(1) fitted to the corresponding macroeconomic series, oil return, oil variance, market variance, risk-free rate, and the market-price-dividend ratio, in that order. Light and dark gray regions indicate 90% and 68% confidence intervals computed by block-bootstrap. Data are quarterly from 1990Q1 to 2014Q1.

Figure 4: **Impulse Response of TFP to Volatility**



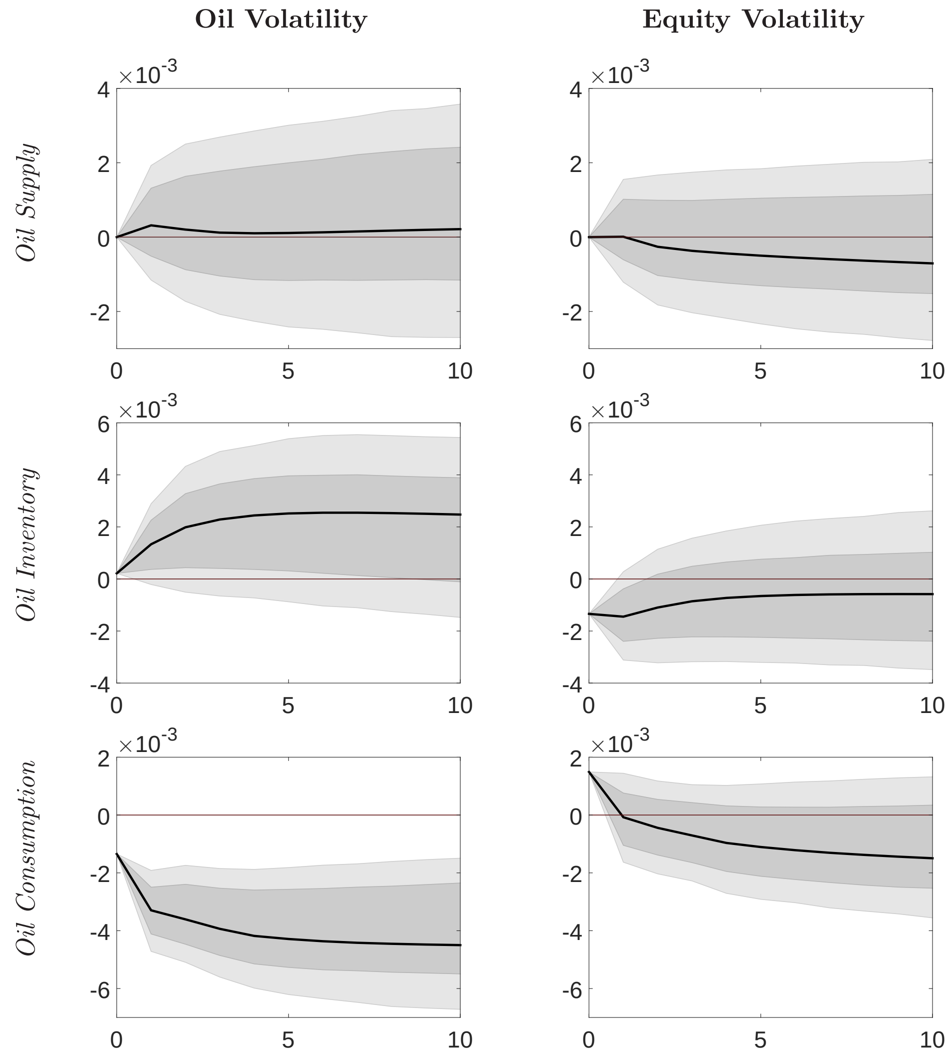

The figure shows the cumulative impulse response of future TFP growth to implied oil volatility (left panels) and equity volatility (right panels). The impulse responses are based on a lower-triangular Cholesky decomposition of a VAR(1) fitted to the TFP growth, oil return, market variance, oil variance, risk-free rate, and the market-price-dividend ratio (benchmark ordering) and the TFP growth, oil return, oil variance, market variance, risk-free rate, and the market-price-dividend ratio (Alternative ordering). Light and dark gray regions indicate 90% and 68% confidence intervals computed by block-bootstrap. Data are quarterly from 1990Q1 to 2014Q1.

Figure 5: **Impulse Response of Oil Series to Volatility**



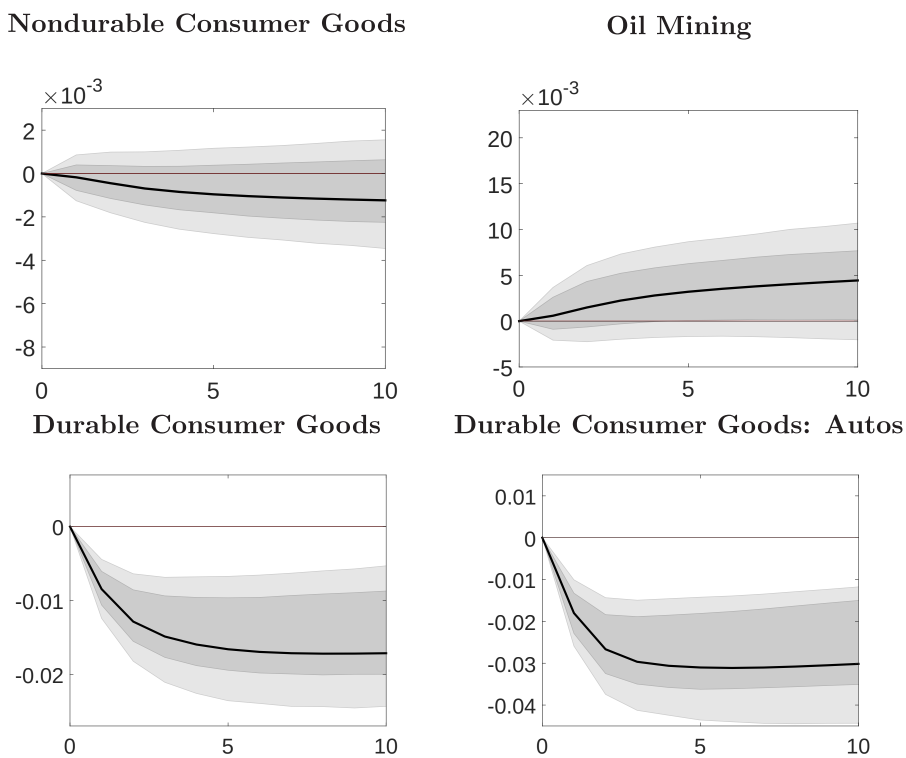

The figure shows the cumulative impulse response of future oil supply, oil inventory, and oil consumption growth to implied oil volatility (left panels) and equity volatility (right panels). The impulse responses are based on a lower-triangular Cholesky decomposition of a VAR(1) fitted to: 1) oil supply growth, oil return, market variance, oil variance, risk-free rate, and the market-price-dividend ratio (top panel); 2) oil supply growth, oil return, market variance, oil variance, oil inventory or oil consumption growth, risk-free rate, the market-price-dividend ratio (middle and bottom panels). Light and dark gray regions indicate 90% and 68% confidence intervals computed by block-bootstrap. Data are quarterly from 1990Q1 to 2014Q1.

Figure 6: **Impulse Response of Oil Series to Volatility: Alternative Ordering**



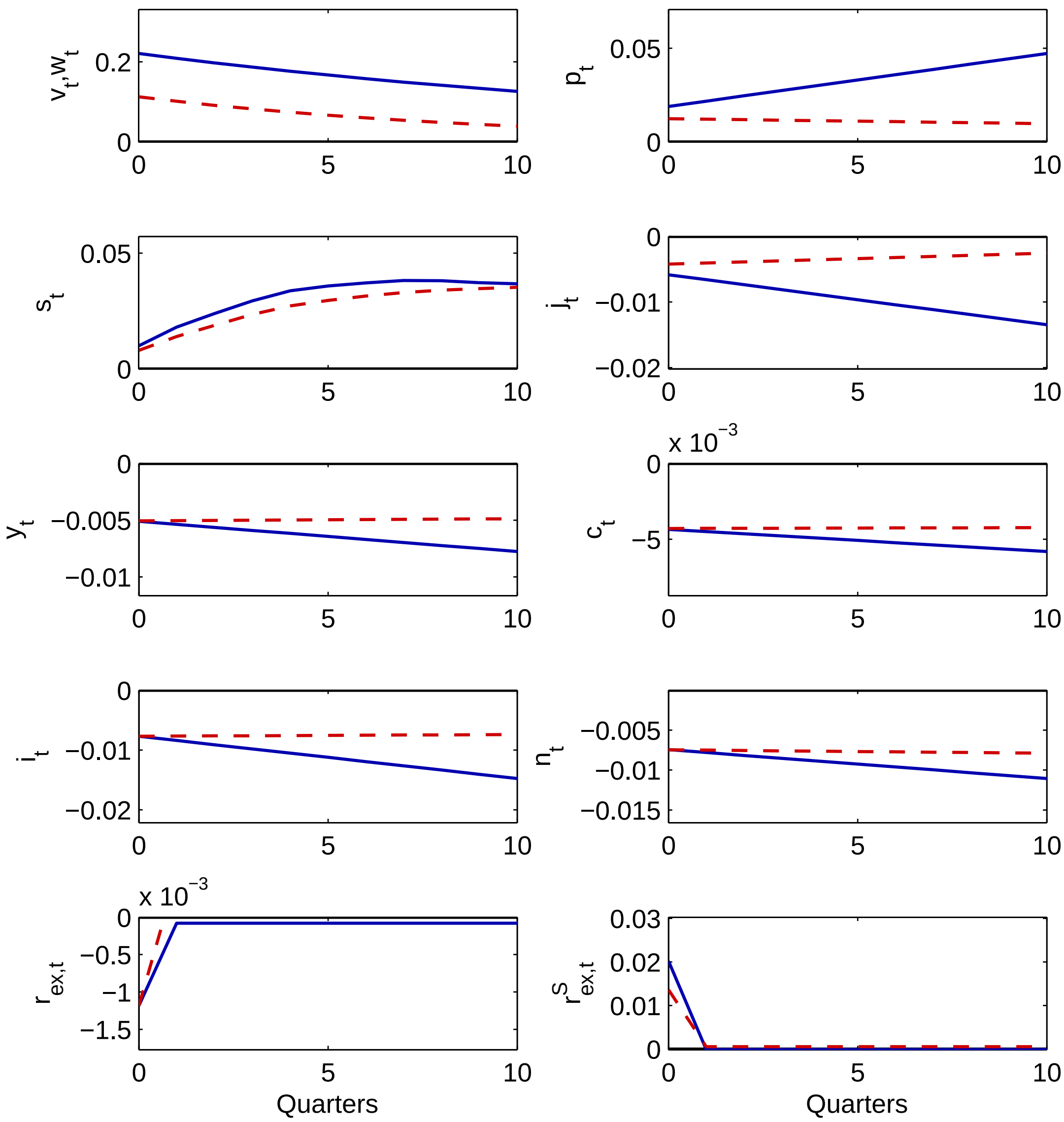

The figure shows the cumulative impulse response of future oil supply, oil inventory, and oil consumption growth to implied oil volatility (left panels) and equity volatility (right panels). The impulse responses are based on a lower-triangular Cholesky decomposition of a VAR(1) fitted to: 1) oil supply growth, oil return, oil variance, market variance, risk-free rate, and the market-price-dividend ratio (top panel); 2) oil supply growth, oil return, oil variance, market variance, oil inventory or oil consumption growth, risk-free rate, the market-price-dividend ratio (middle and bottom panels). Light and dark gray regions indicate 90% and 68% confidence intervals computed by block-bootstrap. Data are quarterly from 1990Q1 to 2014Q1.

Figure 7: **Impulse Response of Sectors to Oil Volatility**



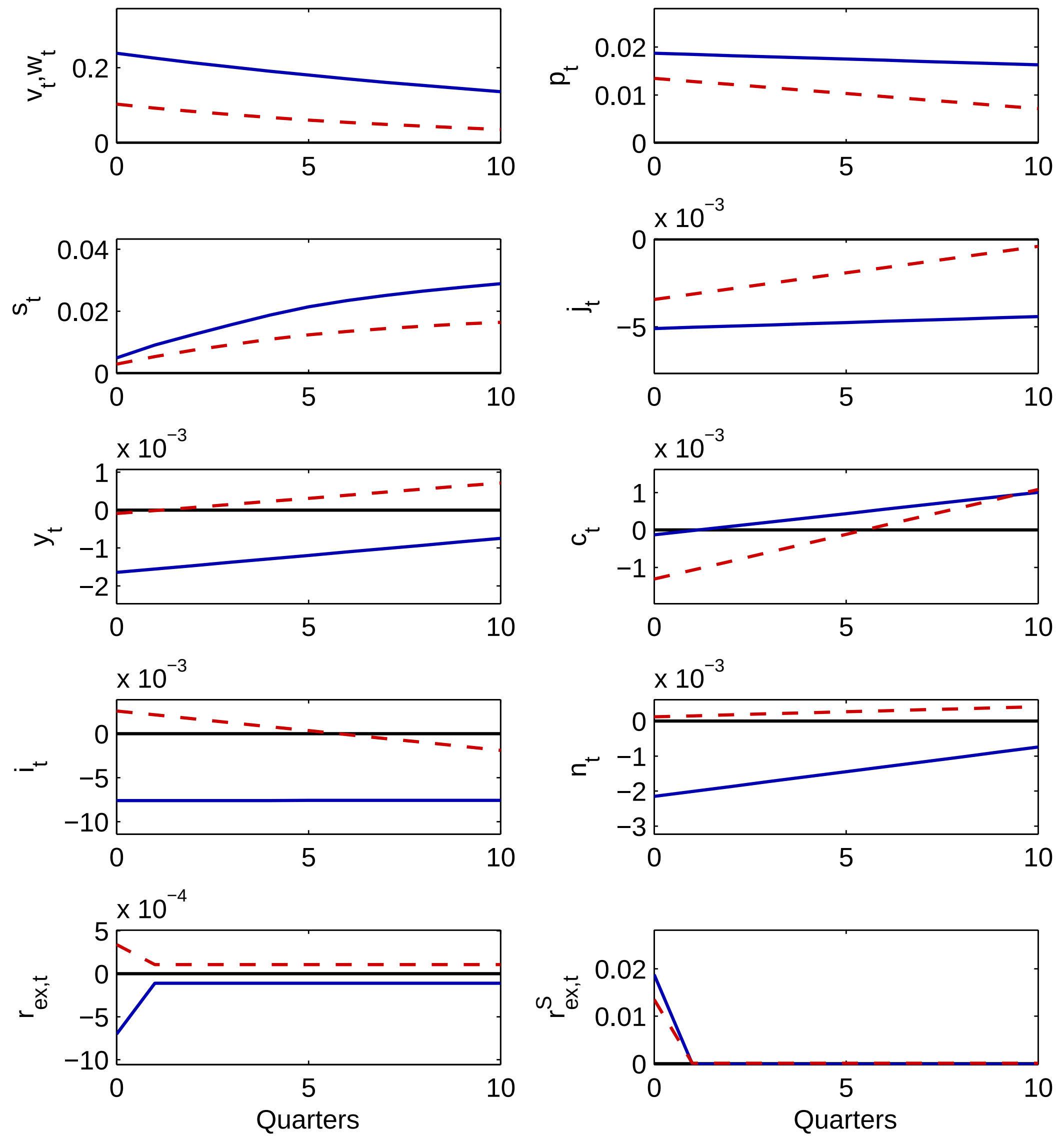

The figure shows the cumulative impulse response of future industrial production growth in non-durable consumer goods, oil mining, durable consumer goods, and auto sectors to oil volatility shock. The impulse responses are based on a lower-triangular Cholesky decomposition of a VAR(1) fitted to the sectoral industrial production growth, oil return, market variance, oil variance, risk-free rate, and the market-price-dividend ratio, in that order. Light and dark gray regions indicate 90% and 68% confidence intervals computed by block-bootstrap. Data are quarterly from 1990Q1 to 2014Q1.

Figure 8: **Model-Based Impulse Responses for Oil and Macro Volatility Shocks: Benchmark Calibration**



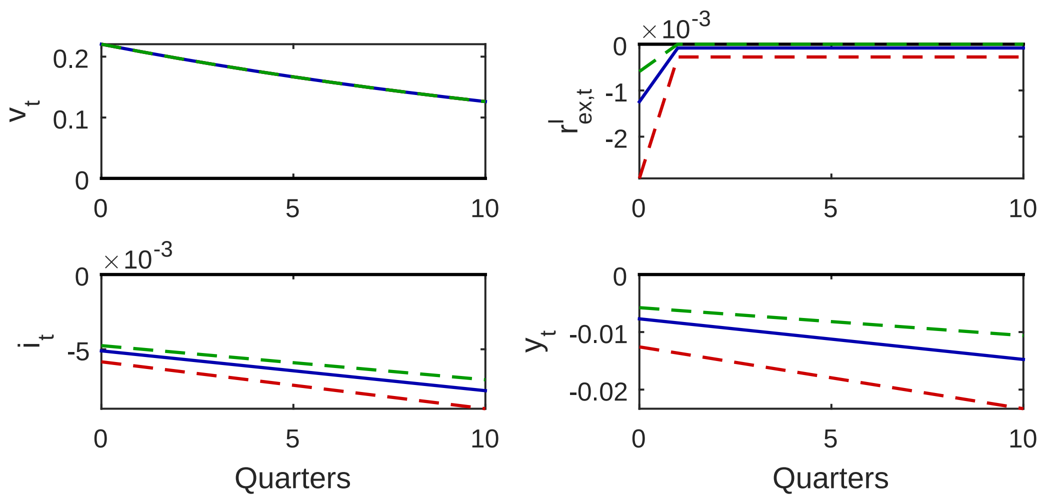

The figure shows model-based impulse response functions for the benchmark calibration. The blue solid lines stand for a one-standard deviation shock to oil production volatility $v_t$, the red dashed lines for a one-standard deviation shock to the volatility of macroeconomic productivity $w_t$.

Figure 9: **Model-Based Impulse Responses for Oil and Macro Volatility Shocks: Low Capital Adjustment Costs**




The figure shows model-based impulse response functions for a calibration with more flexible capital adjustments in the macro sector. The capital adjustment cost parameter $\xi$ is set to 10.1, while all other parameters are in line with the benchmark model calibration. The blue solid lines stand for a one-standard deviation shock to oil production volatility $v_t$, the red dashed lines for a one-standard deviation shock to the volatility of macroeconomic productivity $w_t$.

Figure 10: **Model-Based Impulse Responses for Different Oil Input Sensitivities**




The figure shows model-based impulse response functions for a one-standard deviation shock to oil production volatility. The impulse responses are calculated based on the benchmark model calibration parameters, but for different levels of oil elasticity $o$. The blue solid lines stand for the benchmark calibration with $o = 0.225$, the red dashed lines for $o = 0.15$, and $o = 0.3$ for the green dashed lines.

# A Appendix

## A.1 Oil Volatility Measure

We obtain daily data on futures and option prices on the WTI light sweet crude oil from Commodity Research Bureau. The WTI crude oil contracts have the longest history of option and futures prices available compared to other oil contracts, such as Brent, and are used most often in the literature (see e.g. Christoffersen and Pan (2014)). Oil options are written on oil futures contracts. Both oil options and futures are traded on the CME and are American style. We convert American option prices to European options following Barone-Adesi and Whaley (1987).[14] To ensure sufficient liquidity, we use out-of-the money put and call options with at least 15 days and at most 8 months to expiry. We further exclude options violating standard no-arbitrage conditions, and those with a price below five times the minimum tick value. We truncate upper and lower strike prices at $K_t = F_{t,T} \cdot exp\{\pm 6\sigma(T-t)\}$.[15] We compute the 30-day model-free option implied volatility following Bakshi et al. (2003).

Our crude oil volatility measure tracks very closely the crude oil volatility index (OVX) traded on the CME exchange. The OVX index is based on options on the United States Oil Fund, and is available from 2007. For the overlapping period, the correlation between our measure and the OVX is 99.1%.

[14] This is similar to Trolle and Schwartz (2009) or Christoffersen and Pan (2014)

[15] Jiang and Tian (2005) find that the truncation error can be ignored if the truncation points are more than two standard deviations away from the forward price. We also try using alternative truncation points at $10\sigma$, and the difference is negligible.

## A.2 Firms' First Order Conditions

**Final goods producer** Without loss of generality, consider (3.5) at time 0 and add the Lagrange multiplier $Q_t^I$ for the resource constraint (3.3):

$$\max_{I_t, K_{t+1}, N_t, J_t} \mathbb{E}_0 \sum_{t=0}^{\infty} M_t (Y_t - I_t - P_t J_t - W_t^N N_t \\ - Q_t^I (K_{t+1} - (1-\delta) K_t - I_t + G_t K_t)). \tag{A.1}$$

Setting the derivative with respect to $I_t$ to zero yields

$$Q_t^I = \frac{1}{1 - G_t'}. \tag{A.2}$$

Setting the derivative with respect to $K_{t+1}$ to zero, we obtain

$$\mathbb{E}_t \left[ M_{t+1} \frac{\alpha(1-\iota) \frac{Y_{t+1}}{K_{t+1}^{\frac{1}{o}} Z_{t+1}^{1-\frac{1}{o}}} + ((1-\delta) + G_{t+1}{}' \frac{I_{t+1}}{K_{t+1}} - G_{t+1}) Q_{t+1}^I}{Q_t^I} \right] = 1. \tag{A.3}$$

Setting the derivative with respect to $N_t$ to zero, we have

$$W_t^N = \frac{\partial Y_t}{\partial N_t} = (1-\alpha) \frac{Y_t}{N_t}. \tag{A.4}$$

Finally, we set the derivative with respect to $J_t$ to zero and get

$$P_t = \frac{\partial Y_t}{\partial J_t} = \alpha \iota \frac{Y_t}{J_t^{\frac{1}{o}} Z_t^{1-\frac{1}{o}}}. \tag{A.5}$$

**Oil Producer** Without loss of generality, consider (3.10) at time 0 and add the Lagrange multiplier $Q_t^S$ for the resource constraint (3.8)

$$\max_{D_t, S_t} \mathbb{E}_0 \sum_{t=0}^{\infty} M_t (P_t D_t - Q_t^S (S_t - (1-\omega) S_{t-1} + \Pi_{t-1} A_{t-1} - E_t + D_t)). \tag{A.6}$$

Setting the derivative with respect to $D_t$ to zero, we get

$$P_t = Q_t^S. \tag{A.7}$$

Setting the derivative with respect to $S_t$ to zero yields

$$\mathbb{E}_t \left[ M_{t+1} \frac{(1 - \omega - \Pi_t')Q_{t+1}^S}{Q_t^S} \right] = 1. \tag{A.8}$$

## A.3 Appendix Tables and Figures

Table A.1: **Correlation Evidence: 1983-2014 Sample**

| | Oil RV | Equity RV | Oil return |
|---|---|---|---|
| | *1983-2014 sample* | | |
| Consumption growth | -0.43 | -0.37 | 0.14 |
| Output growth | -0.52 | -0.42 | 0.19 |
| Investment growth | -0.51 | -0.30 | 0.13 |
| Employment growth | -0.55 | -0.44 | 0.04 |
| TFP growth | -0.26 | -0.23 | 0.19 |
| | | | |
| Excess equity return | -0.21 | -0.55 | 0.00 |
| Excess oil return | -0.36 | -0.31 | 1.00 |
| Equity RV | 0.55 | 1 | -0.31 |
| | | | |
| Oil consumption growth | -0.13 | -0.16 | 0.17 |
| Oil production growth | -0.08 | -0.13 | -0.08 |
| Oil inventory growth | 0.20 | 0.16 | -0.32 |
| | *1983-2014 sample, excluding 2006Q3-2008Q4* | | |
| Consumption growth | -0.36 | -0.24 | 0.04 |
| Output growth | -0.40 | -0.15 | 0.02 |
| Investment growth | -0.46 | -0.12 | 0.02 |
| Employment growth | -0.49 | -0.32 | -0.09 |
| TFP growth | -0.16 | -0.02 | 0.10 |
| | | | |
| Excess equity return | -0.04 | -0.49 | -0.15 |
| Excess oil return | -0.19 | 0.00 | 1.00 |
| Equity RV | 0.27 | 1.00 | 0.00 |
| | | | |
| Oil consumption growth | -0.09 | -0.10 | 0.13 |
| Oil production growth | -0.05 | -0.10 | -0.15 |
| Oil inventory growth | 0.13 | 0.04 | -0.25 |

The table reports correlations between volatility measures, oil returns, and aggregate economic and asset-price variables. Variance measures correspond to the realized variances computed from the equity and oil prices. The realized oil and equity variances are constructed from the oil and equity realized returns, respectively. The top panel uses quarterly data from 1983 to 2014, and the bottom panel excludes 2006Q3-2008Q4 episode.

Table A.2: **Predictability Evidence: 1984-2014 Sample**

| | Lag growth | | Oil Var | | Equity Var | | Oil Return | | Adj. $R^2$ |
|---|---|---|---|---|---|---|---|---|---|
| *Consumption Growth:* | | | | | | | | | |
| 0q ahead | 0.45 | (0.08) | -3.29 | (1.47) | -2.20 | (2.16) | -0.02 | (0.12) | 0.35 |
| 1q ahead | 0.47 | (0.09) | -3.56 | (1.68) | -0.32 | (3.29) | -0.46 | (0.19) | 0.35 |
| 4q ahead | 0.44 | (0.12) | -0.67 | (1.39) | -0.72 | (2.65) | -0.23 | (0.13) | 0.33 |
| *GDP Growth:* | | | | | | | | | |
| 0q ahead | 0.24 | (0.07) | -6.63 | (3.34) | -5.40 | (8.05) | 0.15 | (0.29) | 0.28 |
| 1q ahead | 0.26 | (0.09) | -4.04 | (2.04) | -7.46 | (2.84) | -0.36 | (0.28) | 0.20 |
| 4q ahead | 0.27 | (0.10) | -1.07 | (1.41) | -1.02 | (1.43) | -0.33 | (0.22) | 0.15 |
| *Investment Growth:* | | | | | | | | | |
| 0q ahead | 0.20 | (0.10) | -49.00 | (13.08) | 2.78 | (29.59) | -0.16 | (1.38) | 0.25 |
| 1q ahead | 0.14 | (0.08) | -26.03 | (9.67) | -72.29 | (12.87) | -1.24 | (1.18) | 0.27 |
| 4q ahead | 0.11 | (0.09) | -3.06 | (7.05) | -23.77 | (9.50) | -0.54 | (1.10) | 0.05 |
| *Employment Growth:* | | | | | | | | | |
| 0q ahead | 0.81 | (0.05) | -3.62 | (1.11) | -2.56 | (2.31) | -0.04 | (0.10) | 0.86 |
| 1q ahead | 0.81 | (0.07) | -1.82 | (1.23) | -3.82 | (1.98) | 0.16 | (0.13) | 0.85 |
| 4q ahead | 0.63 | (0.13) | -0.33 | (1.74) | -3.78 | (2.63) | -0.03 | (0.16) | 0.56 |
| *Oil Consumption Growth:* | | | | | | | | | |
| 0q ahead | -0.27 | (0.10) | -7.16 | (6.33) | -3.95 | (6.75) | 1.18 | (0.64) | 0.10 |
| 1q ahead | -0.19 | (0.09) | -9.22 | (6.28) | -12.80 | (9.70) | -2.70 | (0.78) | 0.18 |
| 4q ahead | -0.02 | (0.04) | -1.55 | (2.98) | -5.40 | (8.34) | -0.60 | (0.24) | 0.03 |
| *Oil Production Growth:* | | | | | | | | | |
| 0q ahead | -0.08 | (0.09) | -2.83 | (5.99) | -15.98 | (4.62) | -1.33 | (1.00) | 0.03 |
| 1q ahead | -0.08 | (0.09) | -6.23 | (6.38) | -2.57 | (8.50) | 0.13 | (0.81) | -0.01 |
| 4q ahead | -0.07 | (0.04) | -3.54 | (1.81) | 5.76 | (3.13) | 0.39 | (0.21) | 0.05 |
| *Oil Inventory Growth:* | | | | | | | | | |
| 0q ahead | 0.03 | (0.07) | 1.75 | (7.44) | 7.85 | (9.63) | -1.51 | (0.78) | 0.05 |
| 1q ahead | 0.07 | (0.08) | 9.46 | (6.07) | -6.25 | (8.95) | 0.59 | (0.66) | -0.00 |
| 4q ahead | -0.06 | (0.03) | 1.05 | (2.15) | -2.08 | (2.82) | -0.06 | (0.25) | -0.01 |

The table reports predictability evidence for future growth in macroeconomic aggregate and oil variables by their own lag, oil variance, equity variance, and oil return. Variance measures correspond to the realized variances computed from the equity and oil prices. Newey-West standard errors are in parentheses. Data are quarterly from 1984Q2 to 2014Q1.

Table A.3: **Predictability Evidence: 1984-2014 Sample, Continuous Oil Variation**

| | Lag growth | | Oil Var | | Equity Var | | Oil Return | | Adj. $R^2$ |
|---|---|---|---|---|---|---|---|---|---|
| *Consumption Growth:* | | | | | | | | | |
| 0q ahead | 0.46 | (0.08) | -6.13 | (2.86) | -2.58 | (2.00) | 0.03 | (0.13) | 0.35 |
| 1q ahead | 0.47 | (0.09) | -6.34 | (2.92) | -0.82 | (3.40) | -0.41 | (0.19) | 0.35 |
| 4q ahead | 0.43 | (0.12) | -2.08 | (2.51) | -0.56 | (2.45) | -0.23 | (0.13) | 0.33 |
| *GDP Growth:* | | | | | | | | | |
| 0q ahead | 0.27 | (0.08) | -10.20 | (5.60) | -6.67 | (8.26) | 0.27 | (0.30) | 0.26 |
| 1q ahead | 0.28 | (0.09) | -6.56 | (3.79) | -8.10 | (2.72) | -0.30 | (0.27) | 0.19 |
| 4q ahead | 0.26 | (0.09) | -4.17 | (2.35) | -0.55 | (1.15) | -0.33 | (0.21) | 0.16 |
| *Investment Growth:* | | | | | | | | | |
| 0q ahead | 0.23 | (0.11) | -71.38 | (22.73) | -9.03 | (34.19) | 0.78 | (1.34) | 0.20 |
| 1q ahead | 0.19 | (0.07) | -24.03 | (21.81) | -82.01 | (13.78) | -0.69 | (1.30) | 0.25 |
| 4q ahead | 0.11 | (0.08) | -11.03 | (11.89) | -22.45 | (7.24) | -0.54 | (1.11) | 0.05 |
| *Employment Growth:* | | | | | | | | | |
| 0q ahead | 0.82 | (0.06) | -4.95 | (1.72) | -3.52 | (2.74) | 0.04 | (0.09) | 0.85 |
| 1q ahead | 0.80 | (0.06) | -3.97 | (1.95) | -3.88 | (1.85) | 0.18 | (0.13) | 0.85 |
| 4q ahead | 0.61 | (0.12) | -3.26 | (2.90) | -3.25 | (2.21) | -0.05 | (0.15) | 0.56 |
| *Oil Consumption Growth:* | | | | | | | | | |
| 0q ahead | -0.27 | (0.10) | -14.64 | (12.09) | -4.30 | (6.07) | 1.27 | (0.61) | 0.11 |
| 1q ahead | -0.20 | (0.09) | -17.17 | (11.08) | -13.91 | (9.48) | -2.57 | (0.76) | 0.18 |
| 4q ahead | -0.03 | (0.04) | -5.29 | (5.74) | -4.72 | (7.52) | -0.60 | (0.25) | 0.04 |
| *Oil Production Growth:* | | | | | | | | | |
| 0q ahead | -0.08 | (0.09) | 0.66 | (10.52) | -18.57 | (4.68) | -1.23 | (0.96) | 0.02 |
| 1q ahead | -0.08 | (0.09) | -12.13 | (11.57) | -2.98 | (8.01) | 0.22 | (0.78) | -0.00 |
| 4q ahead | -0.06 | (0.04) | -5.90 | (4.54) | 5.13 | (3.24) | 0.45 | (0.20) | 0.04 |
| *Oil Inventory Growth:* | | | | | | | | | |
| 0q ahead | 0.03 | (0.07) | 2.49 | (13.23) | 8.34 | (8.59) | -1.54 | (0.76) | 0.05 |
| 1q ahead | 0.07 | (0.08) | 9.68 | (11.73) | -2.13 | (10.27) | 0.39 | (0.58) | -0.02 |
| 4q ahead | -0.06 | (0.03) | 2.83 | (5.43) | -2.28 | (2.54) | -0.06 | (0.25) | -0.01 |

The table reports predictability evidence for future growth in macroeconomic aggregate and oil variables by their own lag, oil variance, equity variance, and oil return. Variance measures correspond to the realized equity variance computed from the equity prices, and the continuous variation computed in oil prices. Newey-West standard errors are in parentheses. Data are quarterly from 1984Q2 to 2014Q1.

Table A.4: **Predictability Evidence, Excluding 2006Q3-2008Q4**

| | Lag growth | | Oil Var | | Equity Var | | Oil Return | | Adj. $R^2$ |
|---|---|---|---|---|---|---|---|---|---|
| *Consumption Growth:* | | | | | | | | | |
| 0q ahead | 0.36 | (0.10) | -4.74 | (0.72) | -1.28 | (3.81) | 0.06 | (0.19) | 0.29 |
| 1q ahead | 0.28 | (0.11) | -3.51 | (0.93) | -0.60 | (3.68) | -0.42 | (0.23) | 0.24 |
| 4q ahead | 0.24 | (0.10) | -1.54 | (0.64) | 2.99 | (2.81) | -0.17 | (0.14) | 0.14 |
| *GDP Growth:* | | | | | | | | | |
| 0q ahead | 0.16 | (0.11) | -6.34 | (1.15) | -5.51 | (7.99) | 0.30 | (0.30) | 0.19 |
| 1q ahead | 0.21 | (0.11) | -5.61 | (1.66) | 12.75 | (6.33) | -0.67 | (0.26) | 0.15 |
| 4q ahead | 0.11 | (0.06) | -2.60 | (0.75) | 7.71 | (3.68) | -0.25 | (0.16) | 0.06 |
| *Investment Growth:* | | | | | | | | | |
| 0q ahead | 0.16 | (0.11) | -31.49 | (5.83) | -45.77 | (53.32) | 1.40 | (1.57) | 0.18 |
| 1q ahead | 0.20 | (0.12) | -23.65 | (7.27) | 36.74 | (38.42) | -3.72 | (1.34) | 0.10 |
| 4q ahead | 0.01 | (0.04) | -10.15 | (4.43) | 28.57 | (22.32) | -0.78 | (0.77) | -0.02 |
| *Employment Growth:* | | | | | | | | | |
| 0q ahead | 0.70 | (0.07) | -3.08 | (1.29) | -11.69 | (9.56) | -0.03 | (0.17) | 0.71 |
| 1q ahead | 0.74 | (0.05) | -1.95 | (0.58) | 0.62 | (3.02) | 0.09 | (0.16) | 0.61 |
| 4q ahead | 0.45 | (0.08) | -2.55 | (0.87) | 2.58 | (5.30) | -0.04 | (0.14) | 0.32 |
| *Oil Consumption Growth:* | | | | | | | | | |
| 0q ahead | -0.27 | (0.10) | -17.85 | (4.44) | 31.61 | (11.36) | 0.98 | (1.10) | 0.24 |
| 1q ahead | -0.28 | (0.10) | -5.97 | (4.66) | -14.08 | (14.31) | -2.73 | (0.98) | 0.27 |
| 4q ahead | -0.06 | (0.03) | 0.65 | (1.53) | -8.89 | (6.43) | -0.48 | (0.20) | 0.08 |
| *Oil Production Growth:* | | | | | | | | | |
| 0q ahead | -0.01 | (0.13) | -3.10 | (4.99) | -9.15 | (14.37) | -1.82 | (1.08) | 0.07 |
| 1q ahead | 0.11 | (0.10) | 1.33 | (2.96) | 11.80 | (9.02) | 1.16 | (0.83) | 0.00 |
| 4q ahead | 0.04 | (0.05) | -0.10 | (1.05) | 3.36 | (7.01) | 0.71 | (0.26) | 0.00 |
| *Oil Inventory Growth:* | | | | | | | | | |
| 0q ahead | 0.12 | (0.09) | 1.43 | (2.99) | -11.32 | (16.70) | -2.01 | (0.60) | 0.09 |
| 1q ahead | 0.15 | (0.09) | 2.63 | (1.91) | -6.84 | (9.50) | 0.47 | (0.66) | -0.02 |
| 4q ahead | -0.03 | (0.04) | -0.42 | (1.54) | -3.30 | (7.20) | -0.06 | (0.31) | -0.04 |

The table reports predictability evidence for future growth in macroeconomic aggregate and oil variables by their own lag, oil variance, equity variance, and oil return. Variance measures correspond to the implied variances computed from the equity and oil option prices. Newey-West standard errors are in parentheses. Data are quarterly from 1990Q1 to 2014Q1, excluding 2006Q3-2008Q4 period.

Table A.5: **Predictability Evidence with Additional Asset-Price Controls**

| | Lag growth | | Oil Var | | Equity Var | | Oil Return | | Adj. $R^2$ |
|---|---|---|---|---|---|---|---|---|---|
| *Consumption Growth:* | | | | | | | | | |
| 0q ahead | 0.22 | (0.10) | -3.84 | (0.81) | -1.65 | (3.43) | 0.04 | (0.15) | 0.46 |
| 1q ahead | 0.19 | (0.12) | -3.66 | (0.97) | -3.71 | (3.57) | -0.41 | (0.16) | 0.41 |
| 4q ahead | 0.31 | (0.15) | -0.88 | (0.94) | -0.54 | (3.41) | -0.20 | (0.14) | 0.36 |
| *GDP Growth:* | | | | | | | | | |
| 0q ahead | 0.13 | (0.08) | -6.18 | (1.40) | -6.96 | (5.93) | 0.54 | (0.23) | 0.41 |
| 1q ahead | 0.18 | (0.11) | -6.03 | (1.84) | 0.67 | (10.87) | -0.29 | (0.30) | 0.22 |
| 4q ahead | 0.22 | (0.11) | -1.00 | (1.53) | -0.22 | (5.81) | -0.39 | (0.26) | 0.14 |
| *Investment Growth:* | | | | | | | | | |
| 0q ahead | 0.27 | (0.10) | -26.66 | (7.30) | -40.43 | (37.15) | 1.66 | (1.25) | 0.31 |
| 1q ahead | 0.20 | (0.10) | -31.08 | (12.35) | -10.27 | (54.69) | -0.73 | (1.72) | 0.25 |
| 4q ahead | 0.12 | (0.10) | -6.13 | (8.12) | -17.15 | (31.21) | -0.73 | (1.34) | 0.13 |
| *Employment Growth:* | | | | | | | | | |
| 0q ahead | 0.84 | (0.07) | -2.37 | (1.06) | -4.95 | (3.09) | 0.08 | (0.11) | 0.86 |
| 1q ahead | 0.84 | (0.08) | -1.72 | (0.98) | -4.19 | (3.66) | 0.30 | (0.15) | 0.85 |
| 4q ahead | 0.73 | (0.14) | -0.64 | (1.15) | -5.07 | (4.62) | 0.04 | (0.20) | 0.61 |
| *Oil Consumption Growth:* | | | | | | | | | |
| 0q ahead | -0.31 | (0.09) | -17.30 | (5.23) | 29.97 | (16.53) | 0.88 | (0.79) | 0.25 |
| 1q ahead | -0.27 | (0.10) | -8.01 | (4.65) | -17.13 | (15.16) | -2.40 | (0.84) | 0.25 |
| 4q ahead | -0.04 | (0.05) | 0.23 | (1.53) | -11.05 | (7.07) | -0.52 | (0.27) | 0.24 |
| *Oil Production Growth:* | | | | | | | | | |
| 0q ahead | -0.03 | (0.13) | -3.80 | (5.08) | -14.01 | (15.20) | -1.25 | (0.87) | 0.05 |
| 1q ahead | 0.11 | (0.09) | 0.28 | (4.37) | 6.29 | (9.79) | 1.51 | (0.65) | 0.03 |
| 4q ahead | -0.00 | (0.05) | 0.81 | (1.24) | -1.20 | (5.20) | 0.48 | (0.24) | 0.08 |
| *Oil Inventory Growth:* | | | | | | | | | |
| 0q ahead | 0.13 | (0.09) | 2.18 | (2.87) | -12.99 | (14.61) | -2.29 | (0.44) | 0.14 |
| 1q ahead | 0.16 | (0.09) | 4.39 | (2.44) | 2.64 | (12.20) | 0.18 | (0.60) | -0.03 |
| 4q ahead | -0.03 | (0.04) | -0.33 | (1.79) | 3.06 | (7.52) | 0.02 | (0.28) | -0.07 |

The table reports predictability evidence for future growth in macroeconomic aggregate and oil variables by their own lag, oil variance, equity variance, oil return, the market price-dividend ratio, real risk-free rate rate, and the term spread. Variance measures correspond to the implied variances computed from the equity and oil option prices. Newey-West standard errors are in parentheses. Data are quarterly from 1990Q1 to 2014Q1.

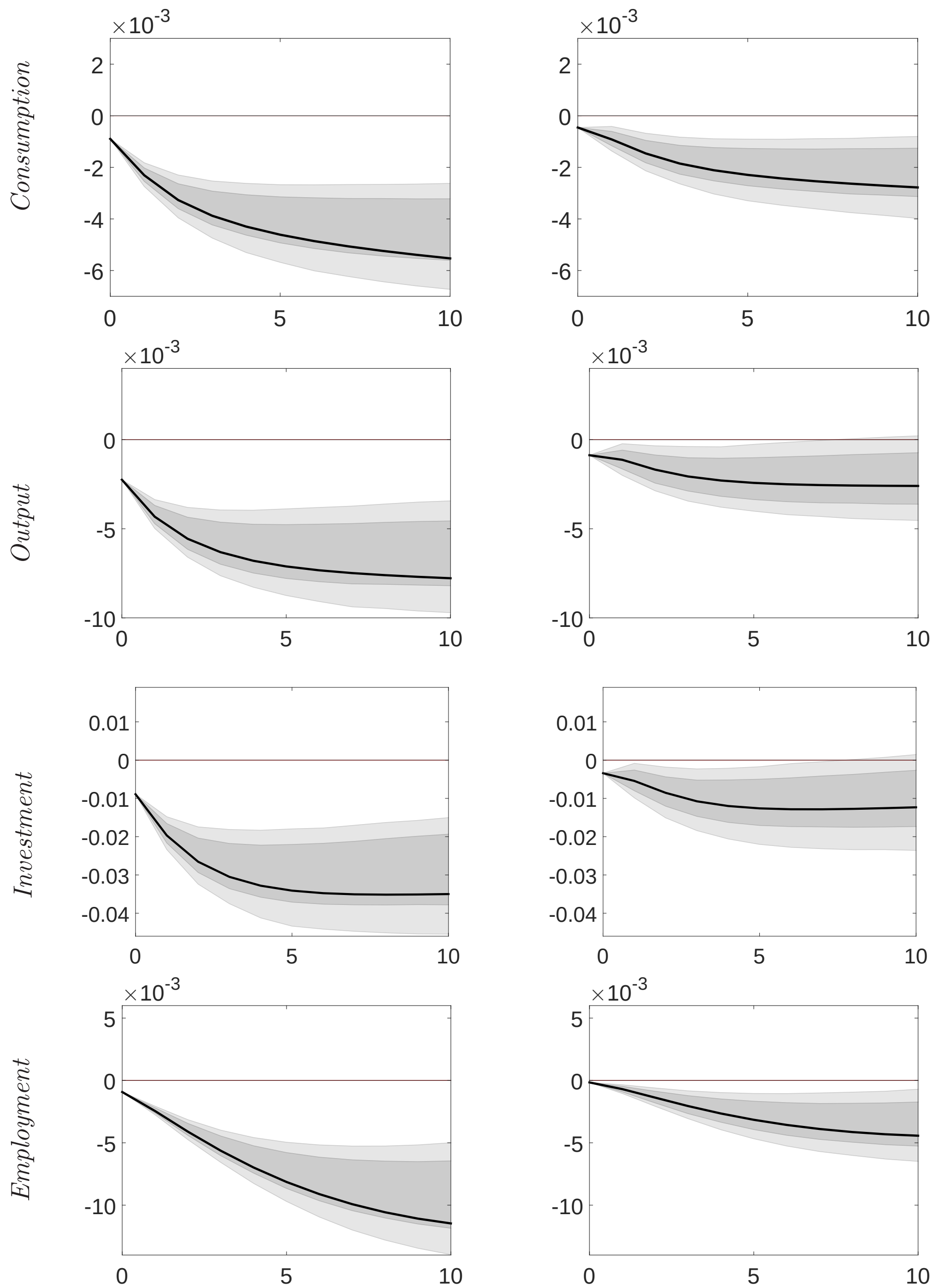
Table A.6: **Asset Pricing Evidence, 1983-2014 Sample**

| | OilVar | | EquityVar | | Oil Return | | Market Return | | Adj. $R^2$ |
|---|---|---|---|---|---|---|---|---|---|
| | | | | *1983-2014 sample* | | | | | |
| durables | -0.26 | (0.24) | -0.22 | (0.49) | -0.01 | (0.02) | 1.30 | (0.08) | 0.80 |
| non-durables | -0.09 | (0.21) | 0.27 | (0.29) | -0.07 | (0.02) | 0.91 | (0.04) | 0.84 |
| oil producers | 0.16 | (0.22) | -0.32 | (0.83) | 0.10 | (0.04) | 0.53 | (0.09) | 0.34 |
| | | | | *1983-2014 sample, excluding 2006Q3-2008Q4* | | | | | |
| durables | -0.19 | (0.26) | -0.27 | (0.53) | 0.00 | (0.03) | 1.30 | (0.08) | 0.78 |
| non-durables | -0.08 | (0.21) | 0.23 | (0.28) | -0.06 | (0.02) | 0.92 | (0.04) | 0.84 |
| oil producers | 0.00 | (0.20) | -2.44 | (0.78) | 0.10 | (0.03) | 0.46 | (0.08) | 0.44 |

The table reports the exposures of portfolio equity returns in durable, non-durable, and oil producing sectors to oil and equity volatilities, and oil and market returns. The top panel uses quarterly data from 1983 to 2014, and the bottom panel excludes 2006Q3-2008Q4 episode. Newey-West standard errors are in parentheses.

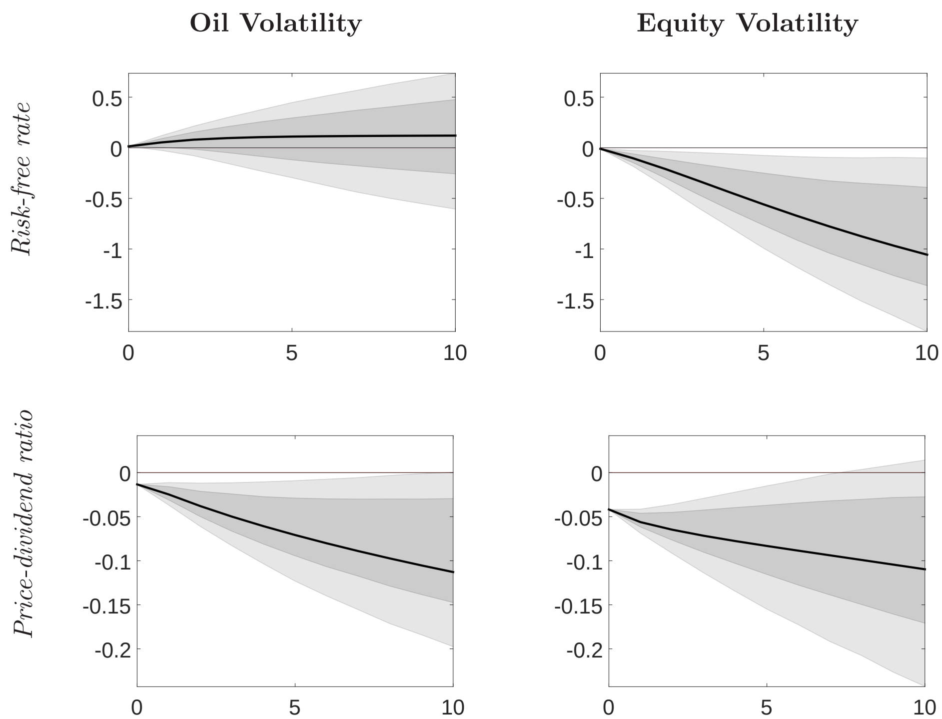
Figure A.1: **Impulse Response of Macro Series to Volatility: Exogenous Volatility**

**Oil Volatility** **Equity Volatility**



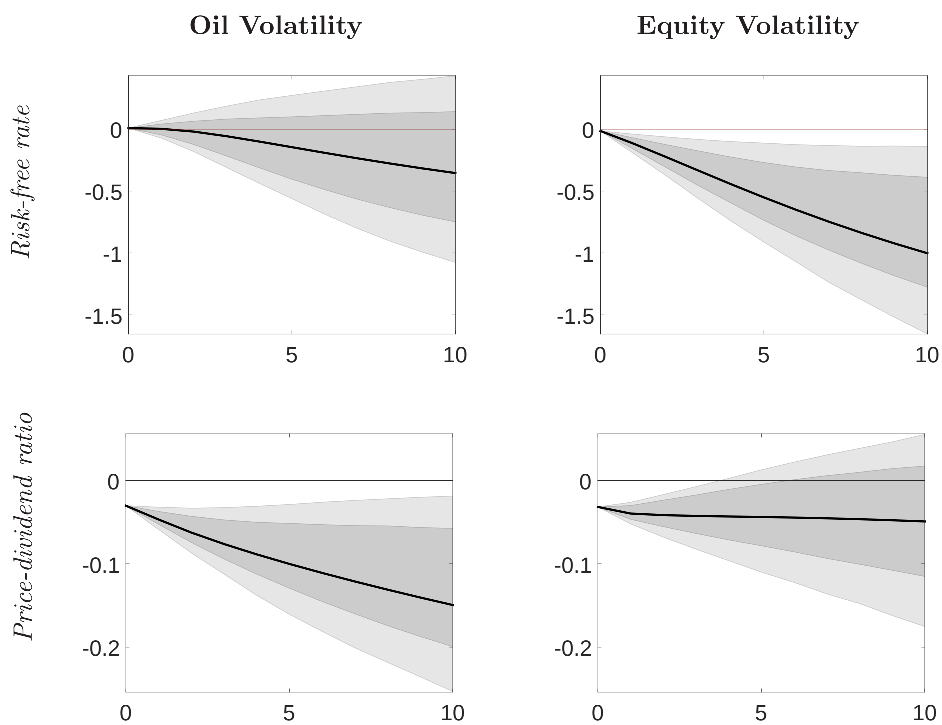

The figure shows the cumulative impulse response of future consumption, output, investment, and employment growth to implied oil volatility (left panels) and equity volatility (right panels). The impulse responses are based on a lower-triangular Cholesky decomposition of a VAR(1) fitted to the oil variance, market variance, corresponding macroeconomic series, oil return, risk-free rate, and the market-price-dividend ratio, in that order. Light and dark gray regions indicate 90% and 68% confidence intervals computed by block-bootstrap. Data are quarterly from 1990Q1 to 2014Q1.

Figure A.2: **Impulse Response of Asset Prices to Volatility**



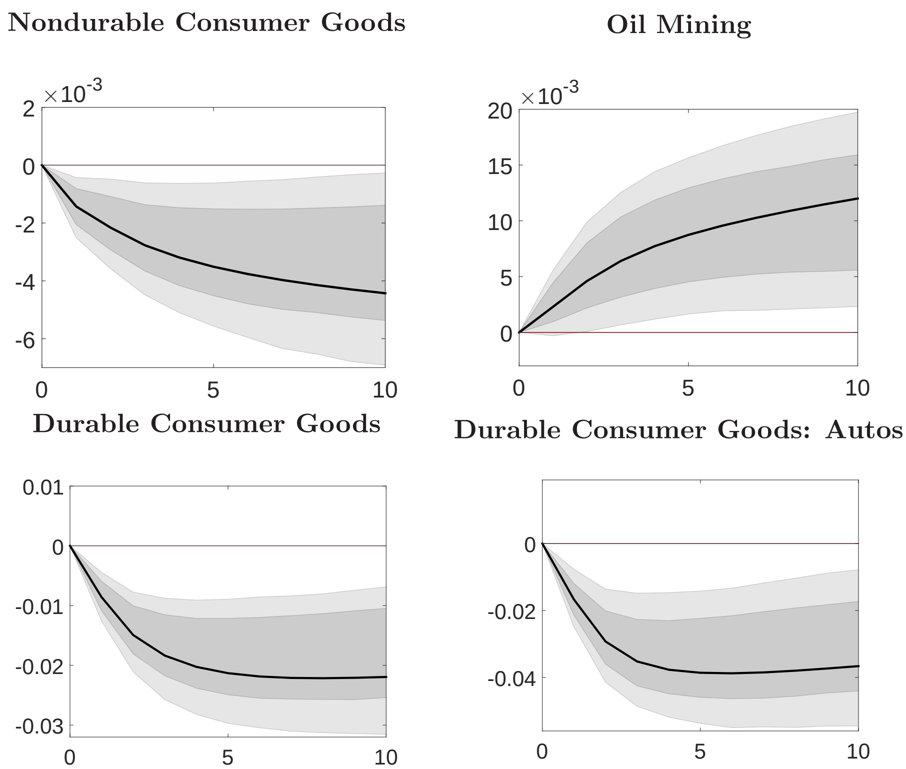

The figure shows the impulse response of future risk-free rates and market price-dividend ratio to implied oil volatility (left panels) and equity volatility (right panels). The impulse responses are based on a lower-triangular Cholesky decomposition of a VAR(1) fitted to the output growth, oil return, market variance, oil variance, risk-free rate, and the market-price-dividend ratio, in that order. Light and dark gray regions indicate 90% and 68% confidence intervals computed by block-bootstrap. Data are quarterly from 1990Q1 to 2014Q1.

Figure A.3: **Impulse Response of Asset Prices to Volatility: Alternative Ordering**




The figure shows the impulse response of future risk-free rates and market price-dividend ratio to implied oil volatility (left panels) and equity volatility (right panels). The impulse responses are based on a lower-triangular Cholesky decomposition of a VAR(1) fitted to the output growth, oil return, oil variance, market variance, risk-free rate, and the market-price-dividend ratio, in that order. Light and dark gray regions indicate 90% and 68% confidence intervals computed by block-bootstrap. Data are quarterly from 1990Q1 to 2014Q1.

Figure A.4: **Impulse Response of Sectors to Oil Volatility: Alternative Ordering**




The figure shows the cumulative impulse response of future industrial production growth in non-durable consumer goods, oil mining, durable consumer goods, and auto sectors to oil volatility shock. The impulse responses are based on a lower-triangular Cholesky decomposition of a VAR(1) fitted to the sectoral industrial production growth, oil return, market variance, oil variance, risk-free rate, and the market-price-dividend ratio, in that order. Light and dark gray regions indicate 90% and 68% confidence intervals computed by block-bootstrap. Data are quarterly from 1990Q1 to 2014Q1.

# References


Arellano, C., Y. Bai, and P. Kehoe (2012). Financial markets and fluctuations in uncertainty. *Working Paper*.

Baker, S. R., N. Bloom, and S. J. Davis (2013). Measuring economic policy uncertainty. Working paper.

Bakshi, G., N. Kapadia, and D. Madan (2003). Stock return charakteristics, skew laws, and the differential pricing of individual equity options. *The Review of Financial Studies 16*(1), 101–143.

Bansal, R., V. Khatchatrian, and A. Yaron (2005). Interpretable asset markets? *European Economic Review 49*, 531–560.

Bansal, R., D. Kiku, I. Shaliastovich, and A. Yaron (2014). Volatility, the macroeconomy, and asset prices. *Journal of Finance 69*, 2471–2511.

Bansal, R. and A. Yaron (2004). Risks for the long run: A potential resolution of asset pricing puzzles. *Journal of Finance 59*(4), 1481–1509.

Barone-Adesi, G. and R. E. Whaley (1987). Efficient analytic approximation of american option values. *Journal of Finance 42*(2), 301–320.

Basu, S. and B. Bundick (2012). Uncertainty shocks in a model of effective demand. *NBER Working Paper No. 18420*.

Basu, S., J. Fernald, and M. Kimball (2006). Are technology improvements contractionary? *American Economic Review 96*(5), 1418–48.

Bernanke, B. (1983). Irreversibility, uncertainty, and cyclical investment. *Quarterly Journal of Economics 98*, 85–106.

Bloom, N. (2014). Fluctuations in uncertainty. *Journal of Economic Perspectives 28*(2), 153–176.

Bloom, N., M. Floetotto, N. Jaimovich, I. Saporta-Eksten, and S. J. Terry (2014). Really uncertain business cycles. *Working Paper*.

Boldrin, M., L. J. Christiano, and J. D. M. Fisher (2001). Habit persistence, asset returns, and the business cycle. *American Economic Review 91*(1), 149–166.

Bollerslev, T. and V. Todorov (2011). Tails, fears and risk premia. *Journal of Finance 66*, 2165 – 211.

Casassus, J., P. Collin-Dufresne, and B. R. Routledge (2009). Equilibrium commodity prices with irreversible investment and non-linear technologies. *Working Paper*.

Chiang, I.-H. E., W. K. Hughen, and J. S. Sagi (2015). Estimating oil risk factors using information from equity and derivatives markets. *Journal of Finance 70*(2), 769–804.

Christiano, L. J., R. Motto, and M. Rostagno (2014). Risk shocks. *American Economic Review 104*(1), 27–65.

Christoffersen, P. and X. Pan (2014). Oil volatility risk and expected stock returns. *Working Paper*.

Cochrane, J. H. (1991). Production-based asset pricing and the link between stock returns and economic fluctuations. *Journal of Finance 46*(1), 209–237.

Cochrane, J. H. (1996). A cross-sectional test of an investment-based asset pricing model. *Journal of Political Economy 104*(3), 572–621.

Croce, M. M. (2014). Long-run productivity risk. a new hope for production-based asset pricing? *Journal of Monetary Economics 66*, 13–31.

Deaton, A. and G. Laroque (1992). On the behaviour of commodity prices. *Review of Economic Studies 59*(1), 1–23.

Dvir, E. and K. S. Rogoff (2009). Three epochs of oil. *Working Paper*.

Elder, J. and A. Serletis (2010). Oil price uncertainty. *Journal of Money, Credit and Banking 42*, 1138–59.

Epstein, L. G. and S. E. Zin (1991). Substitution, risk aversion, and the temporal behavior of consumption and asset returns: An empirical analysis. *Journal of Political Economy 99*(2), 263–286.

Eraker, B., I. Shaliastovich, and W. Wang (2015). Durable goods, inflation risk, and equilibrium asset prices. *The Review of Financial Studies*, forthcoming.

Fernandez-Villaverde, J., P. Guerrón-Quintana, J. F. Rubio-Ramirez, and M. Uribe (2011). Risk matters: The real effects of volatility shocks. *The American Economic Review 101*, 2530–2561.

Finn, M. G. (2000). Perfect competition and the effects of energy price increases on economic activity. *Journal of Money, Credit and Banking 32*(3), 400–416.

Gilchrist, S., J. Sim, and E. Zakrajsek (2014). Uncertainty, financial frictions and investment dynamics. *NBER Working Paper No. 20038*.

Gilchrist, S. and J. C. Williams (2005). Investment, capacity, and uncertainty: a putty–clay approach. *Review of Economic Dynamics 8*, 1–27.

Gomes, J., L. Kogan, and L. Zhang (2003). Equilibrium cross section of returns. *Journal of Political Economy 111*(4), 693–732.

Gomes, J. F., L. Kogan, and M. Yogo (2009). Durability of output and expected stock returns. *Journal of Political Economy 117*(5), 941–986.

Gorton, G. B., F. Hayashi, and K. G. Rouwenhorst (2012). The fundamentals of commodity futures returns. *Review of Finance 17*(1), 35–105.

Hitzemann, S. (2016). Macroeconomic fluctuations, oil supply shocks, and equilibrium oil futures prices. *Working Paper*.

Jermann, U. J. (1998). Asset pricing in production economies. *Journal of Monetary Economics 41*(2), 257–275.

Jiang, G. J. and Y. S. Tian (2005). The model-free implied volatility and its information content. *Review of Financial Studies 18*(4), 1305–1342.

Jo, S. (2014). The effects of oil price uncertainty on global real economic activity. *Journal of Money, Credit and Banking 46*(6), 1113–1135.

Jones, L., R. Manuelli, H. Siu, and E. Stacchetti (2005). Fluctuations in convex models of endogenous growth I: Growth effects. *Review of Economic Dynamics 8*, 780–804.

Kaldor, N. (1939). Speculation and economic stability. *Review of Economic Studies 7*(1), 1–27.

Kilian, L. (2008). Exogenous oil supply shocks: How big are they and how much do they matter for the u.s. economy? *Review of Economics and Statistics 90*(2), 216–240.

Kilian, L. (2009). Not all oil price shocks are alike: Disentangling demand and supply shocks in the crude oil market. *American Economic Review 99*(3), 1053–1069.

Kilian, L. (2014). Oil price shocks: Causes and consequences. *Annual Review of Resource Economics 6*(1), 133–154.

Kung, H. and L. Schmid (2014). Innovation, growth, and asset prices. *Journal of Finance forthcoming*.

Lettau, M., S. C. Ludvigson, and J. A. Wachter (2008). The declining equity premium: What role does macroeconomic risk play? *Review of Financial Studies 21*, 1653–1687.

Liu, H. and J. Miao (2015). Growth uncertainty, generalized disappointment aversion and production-based asset pricing. *Journal of Monetary Economics 69*, 70–89.

Ludvigson, S., S. Ma, and S. Ng (2016). Uncertainty and business cycles: Exogenous impulse or endogenous response? *Working Paper*.

Pindyck, R. S. (1991). Irreversibility, uncertainty, and investment. *Journal of Economic Literature 29*(3), 1110–1148.

Ramey, G. and V. Ramey (1995). Cross-country evidence on the link between volatility and growth. *American Economic Review 85*, 1138–1151.

Ready, R. C. (2014). Oil consumption, economic growth, and oil futures: A fundamental alternative to financialization. *Working Paper*.

Rotemberg, J. J. and M. Woodford (1996). Imperfect competition and the effects of energy price increases on economic activity. *Journal of Money, Credit and Banking 28*(4), 549–577.

Routledge, B. R., D. J. Seppi, and C. S. Spatt (2000). Equilibrium forward curves for commodities. *Journal of Finance 55*(3), 1297–1338.

Rouwenhorst, K. G. (1995). Asset pricing implications of equilibrium business cycle models. In T. Cooley (Ed.), *Frontiers of Business Cycle Research*, pp. 294–330. Princeton University Press.

Telser, L. G. (1958). Futures trading and the storage of cotton and wheat. *Journal of Political Economy 66*(3), 233–255.

Trolle, A. and E. Schwartz (2009). Unspanned stochastic volatility and the pricing of commodity derivatives. *Review of Financial Studies 22*, 4423–4461.

Williams, J. C. and B. D. Wright (1991). *Storage and Commodity Markets*. Cambridge University Press.

Working, H. (1948). Theory of the inverse carrying charge in futures markets. *American Journal of Agricultural Economics 30*(1), 1–28.

Working, H. (1949). The theory of price of storage. *American Economic Review 39*(6), 1254–1262.

Yogo, M. (2006). A consumption-based explanation of expected stock returns. *Journal of Finance 61*(2), 539–580.