# Oil Volatility Risk

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**Abstract**

An increase in oil price volatility predicts a decline in economic growth, controlling for market volatility and business cycle variables. At the same time, oil inventories increase and oil consumption falls. High oil uncertainty further negatively affects equity prices, with a differential impact across economic sectors. We develop a two-sector production model to explain the empirical evidence. 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. Due to this precautionary savings motive, aggregate growth goes down and asset prices fall.

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# 1 Introduction

Recent literature has documented that aggregate uncertainty risks matter for the macroeconomy and financial markets.[1] In this paper we consider a component of economic uncertainty associated with the volatility of oil prices, and show that it has a separate significant effect on real activity and asset valuations. Empirically, high oil price volatility predicts a persistent decline in future economic growth, controlling for typical financial and macroeconomic uncertainty and business cycle variables. At the same time, a rise in oil volatility increases oil inventories and dampens consumption of oil, in line with a precautionary savings motive. Consistent with a negative impact on cash flows, industries sensitive to oil as an input (e.g., durable-good producers) have a large negative exposure to oil volatility, while the exposures of oil producers are even positive. We develop a two-sector production model which features a real option mechanism for oil inventories to jointly explain the aggregate economy, oil sector, and asset price evidence.

Our benchmark evidence relies on implied volatility measures constructed from option price data in oil and equity markets. Using predictive regression analysis, we find that an increase in oil volatility is associated with a decline in current and future real economic activity (consumption, output, investment, employment), a reduction in the consumption of oil, and an increase in oil inventories, controlling for current growth rates, oil returns, and the market variance. Quantitatively, the impact of oil volatility is quite large, significant at several quarter horizons, and extends beyond the effects of market and other considered aggregate volatility measures. 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.

[1] Ramey and Ramey (1995), Fernandez-Villaverde, Guerrón-Quintana, Rubio-Ramirez, and Uribe (2011), Bansal, Kiku, Shaliastovich, and Yaron (2014), Bloom (2014), Gilchrist, Sim, and Zakrajsek (2014), Basu and Bundick (2017) 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.

We supplement the regression analysis with VAR-based impulse response evidence. We first consider a Cholesky-based identification under a "conservative" ordering, in which shocks to the corresponding macro variable, oil prices, and equity volatility are assumed to be "exogenous" to oil volatility, and thus are being controlled for when identifying the response to a pure oil volatility shock. The impulse response evidence confirms a significant role of oil volatility for the endogenous macroeconomic variables, above and beyond equity volatility. To guard against potential concerns about identification, we consider an alternative, economically-motivated approach based on using sign restrictions (following Faust 1998, Canova and De Nicoló 2002, and Uhlig 2005) to identify underlying oil uncertainty shocks. Specifically, we argue that a pure oil uncertainty shock leads to a simultaneous increase in oil price volatility, oil inventory, and oil prices. Indeed, our theoretical model shows that this set of sign restrictions distinguishes oil uncertainty shocks from other factors, such as macroeconomic volatility, oil supply, or sentiment shocks. We find that the effects of oil uncertainty shocks identified through sign restrictions are in line, and even larger than those under the traditional orthogonalization schemes.

Finally, we show that a rise in oil uncertainty has an adverse impact on asset valuations, and the effects are different across economic sectors. Aggregate market prices drop at times of high oil uncertainty, consistent with an adverse impact of oil volatility on future cash flows. Among the economic sectors, the effects of oil volatility are most pronounced for durable-good producing industries. On the other hand, industries which are involved in the production of oil and oil-related products have a positive stock return exposure to oil volatility. Consistent with these results and in line with Bernanke (1983), we find that oil uncertainty has a large and significant negative effect on measures of production output in durable industries, compared with nondurable industries and oil mining.

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, investments, and employment 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 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. Ferderer (1996), Bredin, Elder, and Fountas (2010), Elder and Serletis (2010) and Jo (2014) confirm these predictions empirically using parametric GARCH or stochastic volatility VAR models, and show that an increase in oil price volatility is negatively related to real economic activity. Our results corroborate and extend the empirical findings in this literature. First, we provide a comprehensive analysis of the effects of oil price uncertainty on a variety of aggregate and sectoral quantity and asset price data, using model-free measures of oil price uncertainty (both from option prices and from high-frequency data). Second, we focus on isolating the impact of oil price uncertainty from other measures of financial, economic, and policy uncertainty. Third, we provide novel evidence for the role of oil uncertainty for oil quantity data, and in particular oil inventories, which is at the heart of our economic mechanism. Fourth, we document the impact of oil volatility on asset markets and in the cross-section of portfolios. Finally, we develop an economic model which can jointly rationalize the aggregate, oil-sector, and asset-price evidence.

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

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

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 (Hitzemann 2016; Casassus, Collin-Dufresne, and Routledge 2018; Ready 2018). Our paper is the first to investigate the effect of oil-related supply uncertainty shocks in such general equilibrium type of model.

More broadly, we contribute to a macroeconomic literature that identifies uncertainty shocks as a main driver of macroeconomic variables and as a source of business cycle fluctuations (e.g., Christiano, Motto, and Rostagno 2014; Ludvigson, Ma, and Ng 2016; Bloom et al. 2018). 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. 2018).[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 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

[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 2013, David 2018), 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 2015).

Croce 2014 and 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 main empirical evidence for the effects of oil uncertainty on economic quantities and asset prices. We first consider a direct, statistical identification of oil uncertainty shocks based on the volatility of oil prices, controlling for the impact of other aggregate variables. In Section 2.4 we corroborate our main empirical findings using an alternative identification approach based on economically-motivated sign restrictions for the impact of oil uncertainty on economic fundamentals.

## 2.1 Data

In our empirical analysis we use data on important macroeconomic quantities related to the aggregate economy and the oil sector, data on equity returns, as well as option prices for crude oil and the market index. Our benchmark sample runs quarterly from 1990Q1 to 2014Q1 due to the availability of the options data; for robustness, we also consider realized instead of option-implied variances, which allows us to start a sample in the early 1980s.

The key object of our analysis is a measure of oil price uncertainty. We employ an ex-ante measure based on the 30-day model-free implied volatility constructed from oil option prices using similar methods as in Bakshi, Kapadia, and Madan (2003); see Appendix A.1 for details. We also compute realized oil price variation from squared daily oil returns over the quarter. To control for general macroeconomic or financial uncertainty in our analysis, we include several aggregate uncertainty measures. We use the volatility index VIX, constructed from the cross-section of S&P 500 index option prices, as a model-free estimate of the aggregate market volatility, and measures of other commodity price volatilities constructed from option prices in sugar, corn, gold, and copper markets. To capture aggregate economic uncertainty, we also use the Baker, Bloom, and Davis (2016) economic policy uncertainty index, as well as the stochastic volatility of real consumption growth constructed from an AR(1)-GARCH(1,1) filter to real consumption growth data.

We consider the effect of oil uncertainty shocks by analyzing aggregate macroeconomic data for the United States as a major oil-dependent economy. These data 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). Industrial production data for the aggregate economy and for different economic sectors is provided by the Federal Reserve Bank of St. Louis (FRED). We additionally collect the Total Factor Productivity (TFP) index which corresponds to the estimates of the Solow residual for the US economy, and the utilization-adjusted productivity measure proposed by Basu, Fernald, and Kimball (2006). All macroeconomic data are real and seasonally adjusted. The oil quantity data for our study come from the U.S. Energy Information Administration.[5] In line with the global nature of the oil market, we use oil data for the largest geographical coverage that is available. For oil production, worldwide quantities are available, and for oil inventories and consumption we can rely on data of total petroleum stocks and usage for the OECD countries. In terms of asset price data, we use crude oil futures from the Commodity Research Bureau (CRB). Equity return data for a broad market portfolio comes from CRSP. We further collect price and cash flow data for the equity portfolios of interest.

The key summary statistics for our data are reported in Table 1. The average aggregate growth measures range from 1% for TFP to 1.8% for investment. The volatilities of the

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

aggregate growth series are all around 1%, with the exception of real investment whose volatility is 6.1%. Oil-related growth measures are about twice as volatile as general consumption or output. Most of the macroeconomic variables are mildly persistent, except for the oil-related measures for which the autocorrelation coefficients are close to zero or even negative.

In terms of the asset-price moments, the sample equity risk premium is about 6.6%, while the average excess return on oil is 4%. The volatility of oil returns is almost 40%, more than double the volatility of market index returns. The implied oil volatility is also larger than the implied equity volatility, and is itself about 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, and 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. On the other hand, a rise in oil volatility can be associated with either sharp increases in the underlying oil 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 their share in the oil markets.

## 2.2 Oil Price Volatility and Aggregate Growth

We start the analysis by considering the contemporaneous correlations of the volatility measures with various aggregate economic fundamentals. As shown in the first panel of Table 2, all standard measures of real economic activity, such as consumption, GDP, investment, and employment growth, decline significantly at times of high oil price volatility. For example, the correlation between oil implied volatility and investment growth is -50%, and it is -55%

for both GDP and employment growth. The correlations are weaker and in fact positive for the growth rate of utilization-adjusted TFP.[6] Interestingly, the reported negative correlations for oil volatility are larger in absolute value than those for equity volatility: market volatility has a correlation of -40% with GDP and investment growth, and -50% with employment growth. The correlations are also much larger, in absolute value, than those for the change in oil prices themselves. The second panel of the table demonstrates that these findings are robust to excluding the recent financial crisis which features abnormally large volatility movements.

Our univariate correlation evidence is consistent with the literature that documents a strong negative relation of real economic activity and oil price volatility (see Ferderer 1996, Bredin, Elder, and Fountas 2010, Elder and Serletis 2010, and Jo 2014). However, the observed effects may be driven by other omitted factors, such as macroeconomic or financial uncertainty, which increase oil price volatility and depress economic growth. We make a first attempt of separating the effect of oil uncertainty from such other factors by including various related control variables. In addition, we also propose an alternative, economically motivated structural approach for identifying the underlying oil uncertainty shocks in Section 2.4.

To begin with, we extend our analysis to a multivariate setting by running contemporaneous and predictive regressions for the aggregate variables and report the results in Table 3. The regressions take the form

$$\frac{1}{h}\sum_{j=1}^{h}\Delta y_{t+j} = a_h + b_h OilIV_t + b'_{x,h} x_t + error, \tag{2.1}$$

where $y$ is the macroeconomic variable of interest, $OilIV$ is the option-implied variance of oil prices, and $x$ is the vector of controls which in the benchmark approach includes the option-implied market variance as a measure of aggregate volatility, the oil price change, and the lag of the predicted variable itself. The horizon $h$ ranges from 1 to 4 quarters; for

[6] The correlations of oil and equity volatility with non-utilization-adjusted TFP growth are negative at -30% and therefore also weaker than those for the other measures of economic growth.

$h = 0$, we consider a contemporaneous relationship between the growth variable and the factors.[7]

As shown in the table, a rise in oil price variance is associated with a decline in current and future growth in macroeconomic consumption, GDP, investment, and employment, controlling for the market variance, oil return, and the lag of the predicted variable. The slope coefficients of oil variance are statistically significant contemporaneously and 1 quarter ahead for consumption growth, up to 2 quarters ahead for the growth rates in GDP and investment, and up to 3 quarters ahead for employment growth. The responses are magnified and the statistical significance improves in the period which excludes very volatile observations of the financial crisis. As shown in the Appendix Table A.1, outside of the financial crisis the negative effects of oil variance are significant at most of the considered horizons.

Similar to the oil variance, the market variance also has an adverse effect on economic growth. Indeed, Table 3 shows that the coefficients on the market variance are negative. However, across all horizons the estimates are never significantly different from zero (see Table A.1). In terms of the effect of oil prices, the signs of the coefficients are negative for consumption and GDP growth, positive for employment, and mixed for investment growth.

Interestingly, Table 3 shows that oil uncertainty does not have a strong identifiable effect on aggregate TFP. In fact, the loadings are insignificant and most of them are actually positive for utilization-adjusted TFP. Therefore the data provide no evidence for a strong link between oil price volatility and current or future aggregate productivity, indicating that the predictive relation between oil price volatility and macroeconomic variables is not driven by a negative TFP effect along the lines of Bloom et al. (2018).

To help assess the relative impact of variance shocks, we compute the cumulative impulse responses of macroeconomic fundamentals to a one-standard deviation shock in oil volatility or, respectively, equity volatility. As is well-known, identification crucially relies on the assumed order of the variables in the system. In our benchmark setting, the impulse responses are based on a lower-triangular Cholesky decomposition of a VAR(1) fitted to the corre-

[7] We extend the horizon to 5 years when we consider cumulative impulse response functions.

sponding macro series, change in oil prices, market volatility, oil volatility, and asset-price variables, namely the risk-free rate and the price-dividend ratio.[8] This corresponds to a conservative identification scheme in which shocks to the corresponding macro variable, oil prices, and equity volatility are assumed to be "exogenous" to oil volatility, and thus are being controlled for when identifying the response to a pure oil volatility shock.

Figure 2 shows that in our benchmark setting, oil and equity variances have a comparable negative impact on macroeconomic variables. One year after the impact of an 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 at all horizons for oil volatility; for equity volatility, only the effects on consumption and employment are significant throughout. Further, consistent with our earlier regression evidence, the volatility shocks do not lead to a decline in future TFP: the impulse response estimates are in fact positive, though often insignificant. Overall, our impulse response results are in line with our earlier evidence, and suggest a significant role of oil volatility shocks for the endogenous macroeconomic variables, above and beyond equity volatility.

In the benchmark setting, oil volatility is ordered last before the asset prices. The impact of oil uncertainty naturally increases when it is allowed to lead market volatility or to be exogenous to the macroeconomic variable itself. For example, as shown in Appendix Figure A.1, when oil volatility is ordered before equity volatility, the effects of equity volatility sizeably diminish, while the effects of oil volatility become much larger compared both to the benchmark and to the equity volatility under any ordering. Under this specification, following a one-standard deviation shock in oil (equity) volatility, consumption declines one year after impact by 0.30% (0.15%), output by 0.35% (0.10%), employment by 0.40% (0.20%), and investment by 2% (1%). The impact of volatility shocks is further magnified if the volatility shocks lead macro variables. As shown in Appendix Figure A.2, in that case the dynamic responses of oil volatility shocks are largest among all considered specifications.

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

## 2.3 Oil Price Volatility and the Oil Sector

Key to our economic story is a detailed understanding of how oil sector fundamentals, such as oil inventories, production, and consumption react to changes in oil-related uncertainty. Real options theory predicts that a rise in oil uncertainty makes real options in the oil sector more valuable, which gives firms incentives to stock up oil inventories.[9] As a result, the effective supply of oil for macroeconomic production is reduced, yielding a potential explanation for the negative effect on macroeconomic aggregates. To provide direct evidence for this mechanism, we extend the analysis of the last section and show the effects of oil price volatility on oil market fundamentals.

Table 2 shows the univariate correlations of oil uncertainty with growth rates in consumption, production, and inventories of oil, while Table 4 presents the regression evidence. The results show that oil price variance positively predicts oil inventory growth for the OECD countries up to 3 quarters ahead, with the largest and most significant loading for the first quarter. At the same time, we find that oil consumption growth is negatively predicted by oil price volatility contemporaneously and 1 quarter ahead. For oil production growth, we also find negative oil price variance loadings, however, the coefficients are not significant at any horizon, and generally, the effects are weaker than for oil consumption. The evidence suggests that at the considered horizons and at the macro level, the effects of oil volatility are not driven by the oil production (level) channel.[10] Rather, the empirical evidence is supportive of the real option mechanism for a reduction in *effective* supply and consumption of oil and a stocking up of oil inventories in response to a rise in oil uncertainty. Finally, note that the predictive power of market volatility for the oil sector fundamentals is quite weak, both in terms of the statistical significance and the signs of the effects.

[9]The real option character of oil and other commodity inventories is central to the *theory of storage* literature discussed in the introduction of this paper. Pirrong (2011) demonstrates the inventory-increasing effect of uncertainty in a dynamic, stochastic volatility setting. Increasing oil uncertainty should, in theory, also delay irreversible oil drilling investments (see Bernanke 1983) and reduce production from existing wells (see Litzenberger and Rabinowitz 1995). Understanding the empirical importance of these different channels on an aggregate level is part of the analysis in this section.

[10]While we focus on activities related to the actual production of oil, Kellogg (2014) shows evidence for potential delays in drilling based on micro-level data for Texas-based oil wells.

To gauge the quantitative impact of the respective variance shocks, we consider the cumulative impulse responses of oil consumption, oil inventory, and oil production to oil and equity volatility shocks. We fit a VAR(1) to oil production growth, oil return, market variance, oil price variance, 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 production, oil prices, and oil and equity volatilities. We present the results based on a conservative identification scheme in which market variance shocks lead oil variance; the results for the alternative ordering are similar. Figure 3 shows that a year after the impact of a positive oil volatility shock, oil inventories rise by about 0.20%, and oil consumption falls by about 0.30%. The impulse responses for equity volatility are smaller and by and large insignificant. The top panel of the figure also shows the cumulative impulse responses of oil production growth, which are computed in a similar way to the aggregate macroeconomic variables. Oil production does not respond to shocks in oil and equity volatility: the responses are effectively zero and insignificant for both volatilities, consistent with the regression evidence presented earlier.

## 2.4 Economic Identification of Oil Uncertainty Shocks

The empirical evidence suggests that, controlling for aggregate uncertainty and other economic variables, an increase in oil price volatility is associated with a drop in current and future economic activity and an increase in oil inventories. This is in line with the economic mechanism that higher underlying oil uncertainty increases the precautionary demand for oil and causes a stocking up of inventories. A potential concern is whether the included controls are indeed sufficient and appropriate to identify the effects of oil uncertainty relative to other factors, such as aggregate volatility or oil supply fluctuations. To provide further empirical support for our economic story, we consider an alternative, economically-motivated approach based on sign restrictions to identify the underlying oil uncertainty shocks. Identification by sign restrictions, as proposed by Faust (1998), Canova and De Nicoló (2002), and Uhlig (2005) in the context of monetary policy shocks, is attractive from an economic point of view as it does not impose a particular ordering on the different types of shocks. Instead, it uses restrictions on whether different variables respond positively or negatively to the shock of interest motivated by economic theory.[11]

In particular, we identify positive oil uncertainty shocks as such shocks that 1) lead to an increase of oil price volatility, 2) increase oil inventories, and 3) increase oil prices. As we show in our theoretical model in Section 3, this set of sign restrictions distinguishes oil uncertainty shocks from other relevant types of economic risks. For example, an exogenous negative oil supply *level* shock may endogenously increase oil price volatility and lead to rising oil prices, however, it has a negative effect on oil inventories. Macroeconomic uncertainty shocks may cause a simultaneous decline in aggregate output, investment, and consumption and an increase in oil price volatility and inventories, but they generally have a depressing effect on oil prices. Finally, shocks that increase oil prices and inventories but do not affect the volatility of oil prices may be due to shocks in sentiment or speculation, but not due to oil uncertainty. Technically, we implement the given sign restrictions by applying Uhlig's (2005) penalty function approach to a VAR(1) which includes, similar to the benchmark VAR in Section 2.2, the macroeconomic variable of interest, change in oil prices, oil and equity price volatility, asset price data, and oil inventories.

Figure 4 shows the cumulative impulse responses of the economic variables to the identified shock in oil uncertainty. The responses of oil volatility, oil prices, and oil inventories are, qualitatively, given by the sign restrictions imposed: the three variables increase on impact of a positive oil uncertainty shock. The responses of the other macroeconomic variables are, on the other hand, not restricted ex ante. The corresponding plots clearly confirm that oil uncertainty fluctuations have a considerable negative impact on macroeconomic variables. One year after the impact of an oil uncertainty shock, output declines by 0.50%, consumption by 0.40%, employment by 1.0%, and investment by 3.0%, as shown in the figure. At the same time, we do not find a significant impact of oil uncertainty on aggregate TFP.

An increase of oil price volatility due to oil uncertainty shocks is relatively transitory in nature, reverting almost completely back to normal in about a year. Nevertheless, the

[11] See Kilian and Lütkepohl (2017) for an in-depth textbook treatment of sign identification of structural VAR models.

cumulative effect on macroeconomic aggregates is persistent and remains statistically significant at the considered horizons. This result can be explained by the fact that a negative contemporaneous effect on macroeconomic output carries over to the future by depressing investment and the future capital stock, in line with our economic model in Section 3. Finally, we observe that the quantitative effect of the structurally identified oil uncertainty shocks on macroeconomic aggregates is larger compared to the response to oil price volatility shocks in the standard VAR (see Section 2.2). This finding is in line with the fact that the standard VAR with conservative ordering does not take into account part of the endogenous effect of oil uncertainty on macroeconomic quantities, oil prices, and equity volatility, while our structural identification approach does not shut down these effects.

## 2.5 Oil Uncertainty and Asset Prices

We next examine the relation between oil uncertainty and asset valuations for the aggregate market and its economic sectors. Table 2 shows that the market index falls at times of high oil volatility: the contemporaneous correlation between market returns and oil implied volatility is -30% for the whole sample, and -15% excluding the Financial Crisis. The impulse response evidence based on the sign-based identification approach, presented in Figure 4, confirms a significant and persistent decline in the market price-dividend ratio due to a positive oil uncertainty shock; the evidence based on traditional VAR identification is similar.

We further find that oil uncertainty has a differential impact across economic sectors. Specifically, we consider the portfolios of *Durable*- versus *Nondurable*-goods producing firms among the 12 industry portfolios in the Fama-French database, as well as the *Oil* portfolio among the 30 industries.[12] We regress current and future excess returns of these portfolios on the shocks to oil and equity uncertainty, as well as oil and market returns, and report the results in Table 5. The top panel of the table relies on standard VAR innovations to oil and equity volatility to measure the two variance shocks. In the bottom panel, we use the oil

[12] We also constructed portfolios of durable and nondurable goods producers using the BEA input-output tables as in Gomes, Kogan, and Yogo (2009) and Eraker, Shaliastovich, and Wang (2015), and the oil producers using the industrial segment information from the Compustat Historical Segments database. The results are very similar.

uncertainty shocks identified under the sign restrictions approach described in Section 2.4; for market uncertainty, we impose a single sign restriction that a market volatility shock increases equity volatility. Under both identification schemes, the oil uncertainty shock has a large negative effect on contemporaneous returns in the durables-producing sector. Controlling for the market uncertainty and other factors, the durables portfolio exposure to oil uncertainty is -0.95 (-0.40) under the standard (sign-based) identification approach. The exposure of the nondurable sector is also negative but much weaker, with loadings of -0.23 (-0.08). Interestingly, the exposure of the oil sector is actually positive: it is 0.42 (0.51) under the standard (sign-based) approach. This finding is in line with our economic model in Section 3, which predicts positive oil industry returns due to the increased oil price after oil uncertainty shocks.

The patterns in the exposures of portfolio returns mimic those of sectoral production growth, suggesting that a large part of the equity exposures can be explained by the cash flow effect of oil uncertainty shocks. Figure 5 shows that future industrial production in the durable goods sector has a pronounced negative response to oil uncertainty. The response of the nondurable sector is also negative, but considerably weaker. For the oil mining sector, industrial production responds positively with modest statistical significance. The differential effect on durables and nondurables is broadly consistent with the hypothesis in Bernanke (1983) and the empirical evidence in Elder and Serletis (2010) that durable goods industries are more strongly exposed to oil-related uncertainty. Our model in Section 3 provides an economic intuition for these results based on a differential sensitivity of durables and nondurables industries to oil as an input factor.

Table 5 further documents results on the predictability of future portfolio returns by uncertainty shocks. Across all portfolios and identification approaches, an increase in oil variance predicts a rise in future returns. However, the slope coefficients and the statistical significance are quite weak. This evidence is consistent with Christoffersen and Pan (2014) who find predictive power of implied oil volatility for equity returns only in the period from 2005 to 2012. Overall, the findings indicate that oil volatility affects asset prices primarily through the cash flow, rather than the discount rate channel. High oil volatility predicts a reduction in future cash flows, which causes equity prices to fall.

### 2.6 Robustness

We consider multiple alternative specifications to check the robustness of our results. Our main findings do not change if we control for aggregate uncertainty using the Baker, Bloom, and Davis (2016) economic policy uncertainty index (see Table 6) or the conditional variance of consumption growth (see Table 7) instead of the market variance. While the slope coefficients for all three macroeconomic uncertainty measures are also negative, the estimates are insignificantly different from zero for almost all predicted variables and horizons, showing that oil price volatility actually drives out macroeconomic volatility as a predictor of economic growth. In terms of the sample selection, we confirm that our main results hold in a longer sample from 1984 in which we 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.1). In terms of alternative controls, we add additional asset-price variables to our regressions, such as the market price-dividend ratio, the real rate, and the term spread (Table A.4), or other measures of uncertainty in other economic sectors, such as in corn, sugar, copper, and gold markets.[13] All results are quantitatively very similar to the benchmark findings, and suggest that oil variance significantly predicts current and future economic activity and oil sector variables, above and beyond standard aggregate volatility measures.

[13] These additional results are available on request.

# 3 Model

We explain our empirical findings within a macro asset pricing model in the style of Hitzemann (2016) and Ready (2018), featuring an oil sector and a general macro sector. As the main novel ingredient, we introduce stochastic uncertainty regarding the oil supply into the model. Shocks to oil supply uncertainty endogenously translate to changes in oil price volatility, motivating the use of price-based oil uncertainty measures 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, investment, and employment, as well as aggregate equity prices.

## 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 $\iota = \tilde{\iota}^o$ 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 land $\bar{Z}$ that is converted into productive oil wells $U_t$ according to the total factor productivity $A_t$ of the overall economy. From existing oil wells, oil is extracted at a stochastic extraction rate $\kappa_t$,

$$E_t = \kappa_t U_t, \tag{3.6}$$

and the overall amount of oil contained in productive oil wells evolves as

$$U_{t+1} = (1-\kappa_t)U_t + A_t\bar{Z}. \tag{3.7}$$

Keeping the model as simple as possible, we do not explicitly consider the oil drilling decision in here and take the rate at which new oil wells are opened as exogenous.

The extracted amount of oil, $E_t$, is added to the producer's above-ground inventories. 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 framework, we identify the impact of these shocks with the effects of fluctuating oil price uncertainty 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 intertemporal elasticity of substitution $\psi$. The utility maximization is subject to the standard wealth constraint

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

and the labor supply constraint

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

## 3.2 Equilibrium

To calculate the model equilibrium, we derive the firms' and the household's first order conditions.[14] 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

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

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

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

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

$$R_{t+1}^I = \frac{\alpha(1-\tilde{\iota}) \frac{Y_{t+1}}{K_{t+1}^{\frac{1}{o}} Z_{t+1}^{1-\frac{1}{o}}} + ((1-\delta) + G_{t+1}{}' \frac{I_{t+1}}{K_{t+1}} - G_{t+1}) Q_{t+1}^I}{Q_t^I}, \tag{3.24}$$

with $Q_t^I = \frac{1}{1-G_t'}$, and the return on oil inventories

$$R_{t+1}^S = \frac{(1-\omega-\Pi_t') Q_{t+1}^S}{Q_t^S}, \tag{3.25}$$

with $Q_t^S = P_t$. Based on these expressions, we can define the equity market return $R_{t+1}^M$ as the weighted average of the returns in the general macro and the oil sector.

[14]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.

Given the risk-free rate

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

we calculate the unlevered equity risk premium as

$$R_{ex,t}^{LEV} = (1 + \overline{DE})(R_t^M - R_{t-1}^f) \tag{3.27}$$

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. In particular, we apply the pruning scheme proposed by Andreasen, Fernández-Villaverde, and Rubio-Ramírez (2018). This approach especially allows us to reliably compute impulse response functions to oil volatility shocks at the model's ergodic mean, as it provides closed-form expressions for them.

## 3.3 Calibration

We calibrate the model to inspect the economic mechanism and to demonstrate its broader consistency with macroeconomic aggregates and asset prices. We begin with a straightforward calibration of the presented baseline model, which successfully generates the negative effect of increased oil uncertainty on the macroeconomy through precautionary inventory stock-ups, in direct accordance to our empirical results. Our model also reproduces the quantitative magnitude of the effects when standard amplification mechanisms are incorporated, as we show in Section 3.5.

Table 8 shows the parameters of the baseline calibration. 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. The subjective discount factor $\beta$ is set to 0.96. In a similar vein, we choose the parameters $\alpha$, $\delta$, $\mu$, $\xi$, $\tau$, $\xi_L$, $\sigma_A$, $\phi$, $\sigma_x$, $\rho_w$, and $\sigma_w$ describing the general macroeconomy in line with recent production-based asset pricing papers (e.g., Ai, Croce, and Li 2013, Croce 2014, Kung and Schmid 2015).

For the oil sector, we ensure that the economy's oil consumption (in monetary units) amounts to 4% of its general consumption, as in the data, by calibrating the oil share $\iota$ to match this ratio (see Table 9). The economy's sensitivity to oil input is further driven by the elasticity of substitution $o$ between oil and physical capital, for which values in the literature vary widely. We start with a modest value of 0.4 in our baseline calibration and demonstrate subsequently that a lower $o$ amplifies the effect of oil uncertainty shocks. Oil inventory costs $\omega$ as well as the mean $\eta$ and the mean-reversion $\chi$ of the oil production rate are chosen according to the benchmark calibration of Hitzemann (2016). The oil inventory stock-out cost parameter $\pi$ is calibrated such that the model matches the level of oil inventories relative to yearly oil production.

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.

Table 9 shows the matched moments in the first panel, and the second panel 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 general equilibrium asset pricing models without an oil sector. The model especially inherits the well-known tension in production-based models between investment and consumption volatilities and the equity premium. Matching the volatilities of investment and consumption more closely through lower capital adjustment costs would thus come at the price of a lower equity premium, which is already reduced in our model due to the aggregation effect of quarterly time frequency, as pointed out by Bansal, Kiku, and Yaron (2010).

## 3.4 Effect of Oil Uncertainty Shocks

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 6. 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 effective oil supply negatively affects the output of the final goods producer. Therefore, the precautionary savings effect in the oil sector spills over to the general macroeconomy. In consequence of the declining output, the consumption and investment of the general good also decreases, and employment declines as well. 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 evident when we vary the value of $o$, as shown by Figure 7. In the case of a lower $o$, the impact on the macro sector is clearly more pronounced than in the baseline calibration, while it is the other way round for a higher $o$.

The model also explains the behavior of oil prices and equity in response to oil uncertainty shocks. Figure 6 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. The last two impulse responses in Figure 6 illustrate 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 7), 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 nondurables producing firms. The differential behavior of durables and nondurables 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 goods producers is that their production is more sensitive to oil as an input factor. By changing the elasticity of substitution between oil and capital from low to high, we show in Figure 7 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 nondurable ones (high $o$).

## 3.5 Quantitative Results and Amplification

While the presented model results perfectly explain our empirical findings qualitatively, the quantitative magnitude of the effect is significantly larger in the data than in the calibrated baseline model. Figure 7 suggests that assuming a lower elasticity of substitution $o$ strengthens the effect of oil uncertainty shocks, but we find that even very low values still leave part of the effect unexplained. This observation is reminiscent of the literature on oil supply *level* shocks, which finds that amplification mechanisms have to be accounted for in order to explain the observed effects quantitatively. To this end, Finn (2000) suggests an amplification mechanism based on energy-dependent capacity utilization. Rotemberg and Woodford (1996) show that the effect of oil shocks is amplified by imperfect competition and time-varying markups, and Baqaee and Farhi (2018) demonstrate the amplification through input-output relations of intermediate goods sectors.

We incorporate the latter two mechanisms in a simplified way by introducing exogenously time-varying markups into our model together with an intermediate goods multiplier as in Jones (2011).[15] These ingredients formally result from an extension of our model that features an interlinked and imperfectly competitive intermediate goods sector (see also Hitzemann and Yaron 2018). The impact of oil uncertainty shocks is amplified then as a result of increasing markups in times of low effective oil supply, which reduce macroeconomic output further. Linkages of intermediate goods sectors serve as an additional multiplier for the quantitative magnitude of this effect. Technically, these amplifiers enter the aggregate production function (3.1) and the first order conditions (3.20), (3.21), and (3.24), and we provide the modified equations and calibration details in Appendix A.3.

Impulse response functions for the amplified model are shown in Figure 6. As we see, the impact of oil uncertainty shocks on the macroeconomy is much larger than in the baseline model, in line with intuition. In particular, we obtain a decrease in output by 0.2% and a fall in consumption by more than 0.1% on a one standard deviation increase of oil supply uncertainty. Investment declines by more than 0.6%, and employment is reduced by almost 0.1%. These results lie, for all variables, within the outer (90%) error bands of our empirical results in Figure 2, and in most cases even within the inner (68%) error band.

Note that in both the amplified and the baseline model, the effect of oil uncertainty shocks is still less persistent than in the data. There are several possible explanations for this result. First, there are potential lags for the adjustment of inventories in the real world due to physical frictions, which lead to a slower increase (and subsequent decrease) of inventories compared to the model. Second, similar lags as well as rigidities that exist in the macro sector are not incorporated into our model. Finally, it is possible that the agents' estimate

[15] We do not incorporate the mechanism proposed by Finn (2000) due to the doubts on its robustness highlighted by Kormilitsina (2016).

of the oil production volatility's mean-reversion rate $\rho_v$ deviates from our calibrated value, which is implicitly inferred from the persistence of oil price volatilities. Changing the value of $\rho_v$ from 0.25 to 0.5 indeed yields a higher persistence of both oil price volatilities and the response of macroeconomic variables, as illustrated by Figure 6.

## 3.6 Distinction from Oil Supply Shocks and Macroeconomic Uncertainty Shocks

In the empirical analysis of this paper, we argue that oil-specific volatility shocks can clearly be distinguished from oil supply (level) shocks on the one hand, and from macroeconomic volatility shocks on the other hand. We show in the following that the difference to these other types of shocks particularly manifests itself in the response of oil inventories and oil prices, providing a model-based foundation for our sign-based identification approach in Section 2.4.

Figure 8 depicts the economy's response to a negative oil supply shock $\varepsilon_t^{\kappa}$, which leads to an increase in oil prices and has a considerable negative effect on the main macroeconomic aggregates. In stark contrast to oil uncertainty shocks, however, the oil price increase coincides with a *fall* in oil inventories due to the lower actual oil supply. This overall behavior is in line with the findings of a long-standing literature on the effect of oil shocks on the macroeconomy, for example Hamilton (1983), Barsky and Kilian (2004), Hamilton (2008), and Hitzemann and Yaron (2018). Therefore, the response of oil inventories provides a clear distinction of oil supply (level) and oil uncertainty shocks, as inventories rise due to increased precautionary demand for the latter ones, lowering the *effective* oil supply to the economy without affecting the actual supply.

Furthermore, we argue that oil uncertainty shocks are distinct from general macroeconomic uncertainty shocks, $\varepsilon_t^{w}$. As widely documented in the recent literature, macro uncertainty shocks affect economic growth through at least two different channels: First, high macro uncertainty can have a negative effect on total factor productivity by slowing down the reallocation of misallocated capital and labor, as highlighted by David, Hopenhayn, and

Venkateswaran (2016) and Bloom et al. (2018). Second, increased uncertainty can negatively or positively affect macroeconomic investment, depending on whether the "option to delay" or a precautionary savings motive is more pronounced in a particular context.

To account for the negative effect on TFP in a reduced-form way, we consider a model variant in which macro uncertainty shocks are negatively correlated with TFP shocks $\varepsilon_t^A$. In addition, we also analyze our baseline model in which there is no correlation between both types of shocks and only the second effect operates. As Figure 9 shows, an increase in macro uncertainty expectedly materializes predominantly as a negative growth shock in the first case, leading to lower output, investment, consumption, employment, and equity returns. While these effects are similar to the depressing effect of an oil uncertainty shock, the main difference is that the increase in macro uncertainty and the resulting decline in TFP lead to a decreasing oil demand in the long run, yielding a lower oil price. This is, again, in direct contrast to oil uncertainty shocks, which yield higher oil prices together with with higher inventories. Our empirical evidence furthermore shows that there is no significant effect of oil uncertainty shocks on the economy's TFP, which additionally distinguishes them from the considered macro uncertainty shocks.

In the case without a negative effect of macroeconomic uncertainty on TFP, it is clear ex ante that a decline in investment due to increased uncertainty will mechanically lead to a rise in consumption due to the resource constraint, and vice versa, unless output is significantly affected. Figure 9 reveals that in our setting, agents increase current investment at the expense of current consumption, which is in line with the results of Croce (2014). The economic reason behind this effect is a precautionary savings motive in the macro sector: by raising the capital stock, agents have an additional cushion against potentially large negative productivity shocks in the future. This mechanism additionally results in a positive market return on impact due to the higher investment demand, confirming that the economy's overall response to a macro uncertainty shock is very different to oil uncertainty shocks also in this second case. Finally, note that the effect of macro uncertainty shocks on investment and consumption can turn around in the case of non-convex capital adjustment costs, leading to delayed investments and a rise of consumption on impact (see Bloom et al. 2018). This behavior stands nevertheless in contrast to oil uncertainty shocks, which lead to both lower investment and consumption.

### 3.7 Further Robustness

Finally, we analyze whether the demonstrated effect of oil uncertainty shocks in our model hinges on particular model assumptions. To this end, we consider an additional model variant in which the intertemporal elasticity of substitution is lower than in our benchmark model. We are especially interested in the case of an IES smaller than 1, and choose a value of 0.9 for this robustness check. Secondly, we consider a model variant with fixed labor supply. Considering this variant sheds light on the question whether the flexibility of labor supply is a critical ingredient for our results, as one could imagine a mechanism in which output decreases in response to oil uncertainty shocks not only due to increasing oil inventories, but also due to a decrease of labor. Figure 10 presents the effect of oil uncertainty shocks for these two alternative model specifications. As one can directly observe, the economy's response is in both cases very similar to our baseline model, suggesting that both the particular value of the IES and the flexibility of labor supply are not critical for our results.

## 4 Conclusion

We present empirical evidence that the volatility of oil prices 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, controlling for the 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 investment 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.

# Tables and Figures

Table 1: **Summary Statistics**

| | Mean | Std. Dev. | AR(1) |
|---|---|---|---|
| Consumption growth | 1.63 | 0.79 | 0.54 |
| GDP growth | 1.65 | 1.21 | 0.40 |
| Investment growth | 1.78 | 6.14 | 0.33 |
| Employment growth | 1.36 | 1.08 | 0.90 |
| Util.-adj. TFP growth | 1.00 | 1.40 | 0.00 |
| | | | |
| Excess equity return | 6.62 | 17.30 | 0.02 |
| Excess oil return | 3.97 | 39.29 | -0.08 |
| | | | |
| Equity volatility | 20.08 | 7.61 | 0.58 |
| Oil volatility | 34.38 | 13.58 | 0.59 |
| | | | |
| Oil production growth | 1.14 | 2.63 | -0.07 |
| Oil inventory growth | 0.71 | 2.71 | 0.07 |
| Oil consumption growth | 0.63 | 2.65 | -0.22 |

The table reports summary statistics for the macroeconomic, asset-price, and volatility variables. Oil and equity volatilities are implied volatilities, constructed from oil and equity option data, and are expressed in volatility (standard deviation) units. Volatilities are quarterly from 1990Q1 to 2014Q1, and all other data are quarterly from 1984Q2 to 2014Q1. Means and standard deviations are annualized.

Table 2: **Correlation Evidence**

| | Oil Var | Equity Var | 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 |
| Util.-adj. TFP growth | 0.09 | 0.15 | 0.11 |
| | | | |
| Excess equity return | -0.30 | -0.57 | 0.04 |
| Excess oil return | -0.21 | -0.15 | 1.00 |
| Equity variance | 0.57 | 1.00 | -0.15 |
| | | | |
| Oil production growth | -0.14 | -0.15 | -0.17 |
| Oil inventory growth | 0.03 | -0.04 | -0.38 |
| Oil consumption growth | -0.36 | -0.12 | 0.20 |
| | | | |
| | *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 |
| Util.-adj. TFP growth | 0.10 | 0.16 | 0.13 |
| | | | |
| Excess equity return | -0.15 | -0.50 | -0.17 |
| Excess oil return | 0.03 | 0.03 | 1.00 |
| Equity variance | 0.49 | 1.00 | 0.03 |
| | | | |
| Oil production growth | -0.09 | -0.12 | -0.30 |
| Oil inventory growth | -0.10 | -0.14 | -0.30 |
| Oil consumption growth | -0.37 | 0.00 | 0.14 |

The table reports correlations between variance measures, oil returns, and aggregate economic and asset-price variables. Variance measures correspond to the implied variances computed from oil and equity option prices. The top panel uses quarterly data from 1990Q1 to 2014Q1, and the bottom panel excludes the 2006Q3-2008Q4 Financial Crisis 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 |
| *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 results for macroeconomic variables by their own lag, oil variance, equity variance, and oil return. Variance measures correspond to the implied variances computed from oil and equity option prices. Newey-West standard errors are in parentheses. Data are quarterly from 1990Q1 to 2014Q1.

Table 4: **Oil Sector Predictability Evidence**

| | Lag Growth | | Oil Var | | Equity Var | | Oil Return | | Adj. $R^2$ |
|---|---|---|---|---|---|---|---|---|---|
| *Oil Production Growth:* | | | | | | | | | |
| 0q ahead | -0.21 | (0.08) | -4.64 | (3.86) | -12.09 | (16.95) | -0.66 | (0.82) | 0.02 |
| 1q ahead | -0.14 | (0.09) | 0.46 | (3.73) | 5.23 | (12.20) | 0.85 | (0.54) | -0.00 |
| 2q ahead | -0.10 | (0.05) | -2.16 | (1.94) | 9.49 | (9.23) | 0.72 | (0.34) | 0.02 |
| 3q ahead | 0.00 | (0.04) | 0.82 | (1.24) | -0.93 | (7.13) | 0.32 | (0.27) | -0.03 |
| 4q ahead | -0.08 | (0.03) | 0.05 | (1.10) | 1.57 | (6.53) | 0.39 | (0.25) | 0.01 |
| *Oil Inventory Growth:* | | | | | | | | | |
| 0q ahead | 0.14 | (0.08) | 1.67 | (3.08) | -10.49 | (15.21) | -2.32 | (0.43) | 0.16 |
| 1q ahead | 0.17 | (0.07) | 4.11 | (2.12) | 3.11 | (10.39) | 0.25 | (0.65) | 0.01 |
| 2q ahead | 0.05 | (0.07) | 0.80 | (2.41) | 6.34 | (9.19) | -0.02 | (0.42) | -0.03 |
| 3q ahead | 0.01 | (0.04) | 0.41 | (1.57) | 0.79 | (7.59) | -0.37 | (0.35) | -0.03 |
| 4q ahead | -0.03 | (0.04) | -0.47 | (1.42) | 3.29 | (7.29) | 0.02 | (0.28) | -0.04 |
| *Oil Consumption Growth:* | | | | | | | | | |
| 0q ahead | -0.20 | (0.09) | -14.17 | (4.08) | 7.17 | (13.39) | -0.26 | (0.51) | 0.06 |
| 1q ahead | -0.16 | (0.09) | -6.13 | (2.89) | -11.40 | (14.39) | -2.21 | (0.79) | 0.08 |
| 2q ahead | -0.11 | (0.07) | 0.49 | (4.90) | -9.96 | (16.99) | -0.92 | (0.50) | 0.02 |
| 3q ahead | 0.02 | (0.05) | 3.95 | (3.09) | -11.91 | (8.30) | -0.05 | (0.38) | -0.02 |
| 4q ahead | -0.00 | (0.04) | 2.98 | (2.59) | -11.39 | (9.08) | -0.51 | (0.36) | 0.01 |

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

Table 5: **Asset Pricing Evidence**

| | Oil Unc | | Market Unc | | Oil Return | | Market Return | | Adj. $R^2$ |
|---|---|---|---|---|---|---|---|---|---|
| | | | | *Uncertainty shocks from standard VAR* | | | | | |
| *Durable Goods Industry:* | | | | | | | | | |
| 0q ahead | -0.95 | (0.33) | -2.03 | (1.51) | -0.00 | (0.04) | 1.02 | (0.17) | 0.69 |
| 1q ahead | 0.41 | (0.46) | 2.84 | (3.67) | 0.08 | (0.07) | 0.42 | (0.20) | 0.00 |
| 2q ahead | 0.57 | (0.40) | 2.40 | (2.63) | -0.05 | (0.05) | 0.28 | (0.15) | 0.02 |
| 3q ahead | 0.37 | (0.37) | 2.17 | (1.38) | -0.04 | (0.04) | 0.22 | (0.12) | 0.02 |
| 4q ahead | 0.22 | (0.36) | 1.74 | (1.12) | -0.05 | (0.03) | 0.15 | (0.11) | 0.02 |
| *Nondurable Goods Industry:* | | | | | | | | | |
| 0q ahead | -0.23 | (0.29) | -0.85 | (1.08) | -0.09 | (0.03) | 0.56 | (0.11) | 0.58 |
| 1q ahead | 0.55 | (0.32) | 2.00 | (1.66) | 0.11 | (0.04) | 0.19 | (0.11) | 0.09 |
| 2q ahead | 0.39 | (0.22) | 0.44 | (1.05) | 0.04 | (0.03) | 0.08 | (0.07) | 0.01 |
| 3q ahead | 0.26 | (0.17) | 0.66 | (0.60) | 0.01 | (0.02) | 0.06 | (0.06) | -0.00 |
| 4q ahead | 0.32 | (0.15) | 0.57 | (0.52) | -0.00 | (0.01) | 0.08 | (0.06) | 0.03 |
| *Oil Industry:* | | | | | | | | | |
| 0q ahead | 0.42 | (0.29) | -4.44 | (1.07) | 0.21 | (0.03) | 0.41 | (0.08) | 0.70 |
| 1q ahead | 0.05 | (0.31) | 1.25 | (1.98) | 0.01 | (0.05) | 0.23 | (0.13) | -0.02 |
| 2q ahead | 0.11 | (0.21) | 0.65 | (1.54) | -0.01 | (0.03) | 0.14 | (0.08) | -0.02 |
| 3q ahead | 0.15 | (0.23) | 0.64 | (1.03) | -0.01 | (0.02) | 0.13 | (0.07) | -0.01 |
| 4q ahead | 0.24 | (0.22) | 0.24 | (0.83) | -0.00 | (0.02) | 0.10 | (0.07) | -0.02 |
| | | | | *Uncertainty shocks under sign restrictions* | | | | | |
| *Durable Goods Industry:* | | | | | | | | | |
| 0q ahead | -0.40 | (0.34) | -2.91 | (1.65) | 0.02 | (0.05) | 1.06 | (0.19) | 0.67 |
| 1q ahead | 0.39 | (0.37) | 3.24 | (3.45) | 0.06 | (0.07) | 0.43 | (0.21) | 0.00 |
| 2q ahead | 0.84 | (0.26) | 2.89 | (2.39) | -0.08 | (0.05) | 0.33 | (0.15) | 0.04 |
| 3q ahead | 0.55 | (0.26) | 2.48 | (1.15) | -0.06 | (0.05) | 0.25 | (0.11) | 0.03 |
| 4q ahead | 0.41 | (0.32) | 1.92 | (0.97) | -0.07 | (0.04) | 0.18 | (0.10) | 0.04 |
| *Nondurable Goods Industry:* | | | | | | | | | |
| 0q ahead | -0.08 | (0.21) | -1.08 | (1.01) | -0.09 | (0.04) | 0.57 | (0.11) | 0.58 |
| 1q ahead | 0.80 | (0.26) | 2.49 | (1.56) | 0.08 | (0.04) | 0.24 | (0.10) | 0.12 |
| 2q ahead | 0.44 | (0.19) | 0.78 | (1.02) | 0.02 | (0.03) | 0.09 | (0.08) | 0.03 |
| 3q ahead | 0.24 | (0.14) | 0.90 | (0.56) | -0.00 | (0.02) | 0.07 | (0.06) | -0.00 |
| 4q ahead | 0.23 | (0.14) | 0.86 | (0.54) | -0.01 | (0.02) | 0.07 | (0.06) | 0.01 |
| *Oil Industry:* | | | | | | | | | |
| 0q ahead | 0.51 | (0.23) | -4.07 | (0.96) | 0.18 | (0.03) | 0.43 | (0.08) | 0.70 |
| 1q ahead | 0.02 | (0.28) | 1.33 | (1.98) | 0.01 | (0.05) | 0.22 | (0.14) | -0.02 |
| 2q ahead | 0.14 | (0.19) | 0.77 | (1.45) | -0.02 | (0.03) | 0.15 | (0.09) | -0.02 |
| 3q ahead | 0.07 | (0.18) | 0.80 | (0.90) | -0.02 | (0.02) | 0.13 | (0.08) | -0.02 |
| 4q ahead | 0.15 | (0.17) | 0.49 | (0.75) | -0.01 | (0.03) | 0.09 | (0.07) | -0.02 |

The table reports the exposures of portfolio equity returns in durable, nondurable, and oil producing sectors to shocks in oil and equity market uncertainties, and oil and market returns. Oil and market uncertainty shocks are identified from the benchmark VAR (first panel), or the VAR with sign restrictions (second panel). Results are based on quarterly data from 1990Q1 to 2014Q1. Newey-West standard errors are in parentheses.

Table 6: **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 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 |
| *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 |

The table reports predictability results for macroeconomic and oil sector variables by their own lag, oil variance, policy uncertainty, and oil return. Oil variance is measured as the implied variance computed from oil option prices, and we use the Baker, Bloom, and Davis (2016) policy uncertainty measure. Newey-West standard errors are in parentheses. Data are quarterly from 1990Q1 to 2014Q1.

Table 7: **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 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 |
| *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 |

The table reports predictability results for macroeconomic and oil sector variables by their own lag, oil variance, macroeconomic variance, and oil return. Variance measures correspond to the implied variance computed from 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 8: **Model Parameters**

| Parameter | | Value | |
|---|---|---|---|
| | | Baseline | Amplified |
| *Preferences* | | | |
| Subjective discount factor | $\beta$ | 0.96 | |
| Risk aversion | $\gamma$ | 10 | |
| Intertemporal elasticity of substitution | $\psi$ | 2 | |
| *General macroeconomy* | | | |
| Capital share | $\alpha$ | 0.34 | |
| Depreciation rate of capital | $\delta$ | 0.06 | |
| Average growth rate | $\mu$ | 1.8% | |
| Capital adjustment costs | $\xi$ | 3.0 | 7.0 |
| Share of final goods in consumption | $\tau$ | 0.205 | |
| Elasticity of substitution between leisure and consumption goods | $\xi_L$ | 1.2 | |
| Volatility of productivity risk | $\sigma_A$ | 3.35% | |
| Autocorrelation of expected growth | $\phi$ | 0.925 | |
| Volatility of long-run risk | $\sigma_x$ | $0.1\sigma_A$ | |
| Mean-reversion of volatility of macro productivity | $\rho_w$ | 0.855 | |
| Volatility of volatility of macro productivity | $\sigma_w$ | 3.46% | |
| Price markup elasticity | $\varepsilon_\theta$ | — | 0.05 |
| Share of intermediate goods sector | $\nu$ | — | 0.5 |
| *Oil sector* | | | |
| Oil share of production | $\iota$ | 0.011 | 0.290 |
| Elasticity of substitution between oil and capital | $o$ | 0.400 | 0.225 |
| Oil inventory costs | $\omega$ | 0.1 | |
| Oil stock-out costs | $\pi$ | 0.0000005 | 0.0000005 |
| Average oil production rate | $\eta$ | 0.08 | |
| Mean-reversion of oil productivity | $\chi$ | 0.87 | |
| Volatility of oil productivity | $\sigma_\kappa$ | 6.6% | 4.8% |
| Mean-reversion of oil production volatility | $\rho_v$ | 0.28 | 0.25 |
| Volatility of oil production volatility | $\sigma_v$ | 56% | 54% |

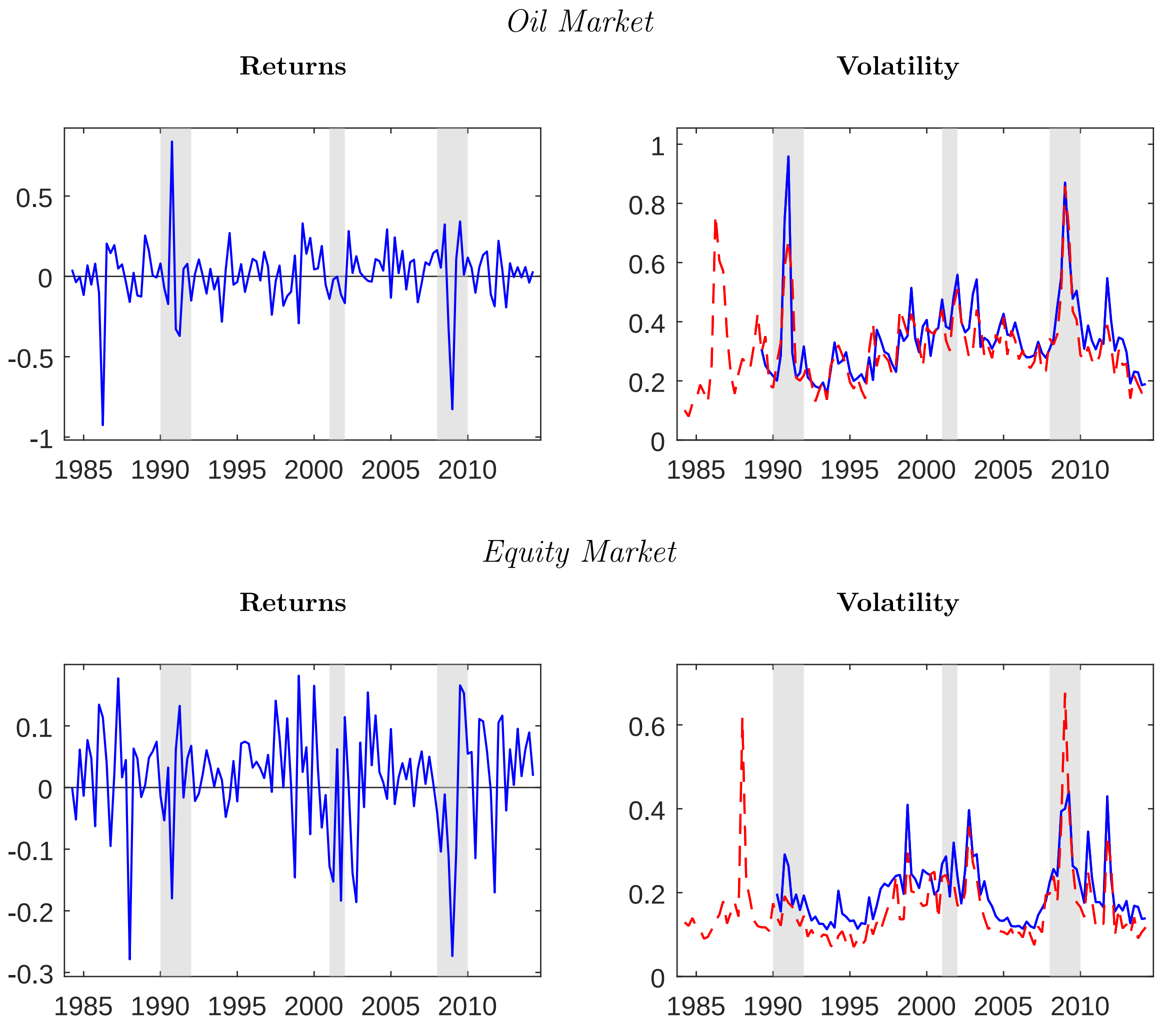
The table reports the parameters of the calibrated model, both for the baseline and the amplified version. Parameters describing the household's preferences as well as the general structure of the macroeconomy and the oil sector are set according to the literature. The oil share parameter, the oil stock-out cost parameter, and the parameters describing the volatility of oil supply are calibrated to match the moments in the first panel of Table 9. All parameters are annualized.

Table 9: **Moments**

| Calibrated Moments | | | |
|---|---|---|---|
| Statistic | Data | Model | |
| | | Baseline | Amplified |
| Oil input relative to general consumption | | | |
| $\mathbb{E}[P * J/C]$ | 0.04 | 0.04 | 0.04 |
| Oil inventory-production ratio | | | |
| $\mathbb{E}[S/E]$ | 0.29 | 0.29 | 0.29 |
| Oil price volatility | | | |
| $\sigma(p_t)$ [%] | 34.38 | 34.35 | 33.96 |
| Oil price vol of vol | | | |
| $\sigma(\sigma_t(p))$ [%] | 13.58 | 13.68 | 13.60 |
| Oil price vol autocorrelation | | | |
| $\rho(\sigma_{t-1}(p), \sigma_t(p))$ [%] | 0.59 | 0.60 | 0.61 |
| **Price and Quantity Moments** | | | |
| Statistic | Data | Model | |
| | | Baseline | Amplified |
| Investment-output ratio | | | |
| $\mathbb{E}[I/Y]$ [%] | 15.88 | 26.11 | 23.09 |
| Relative volatility of general consumption and output | | | |
| $\sigma(\Delta c)/\sigma(\Delta y)$ | 0.65 | 0.90 | 0.73 |
| Relative volatility of general investment and output | | | |
| $\sigma(\Delta i)/\sigma(\Delta y)$ | 5.07 | 1.86 | 2.62 |
| Relative volatility of oil inventories and oil production | | | |
| $\sigma(\Delta s)/\sigma(\Delta e)$ | 1.03 | 0.62 | 1.05 |
| Risk-free rate | | | |
| $\mathbb{E}[r_t^f]$ [%] | 1.23 | 1.28 | 1.90 |
| Volatility of risk-free rate | | | |
| $\sigma(r_t^f)$ [%] | 1.04 | 1.53 | 1.61 |
| Equity risk premium | | | |
| $\mathbb{E}[r_{ex,t+1}^{LEV}]$ [%] | 6.62 | 3.69 | 1.97 |

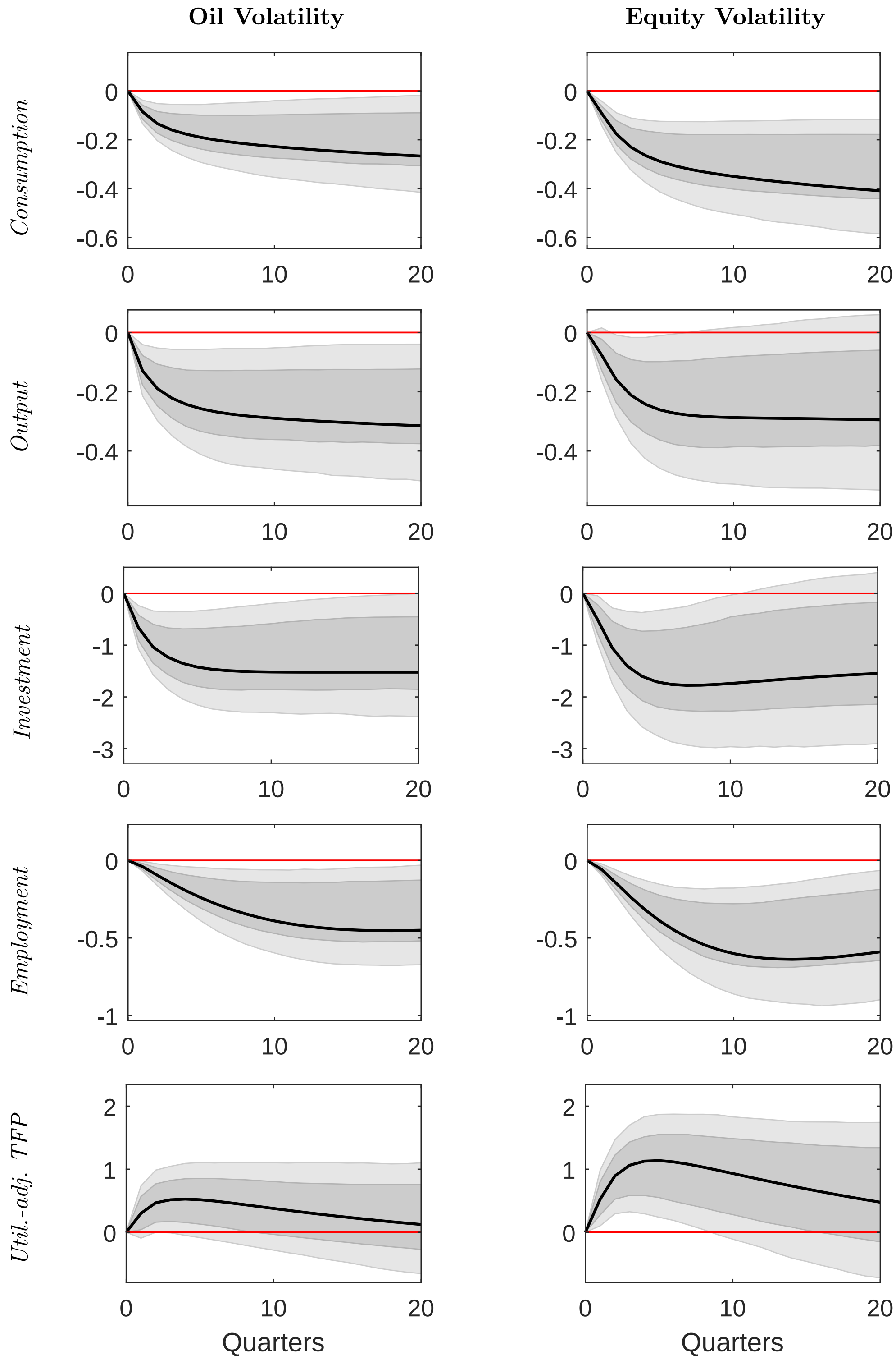
The table reports the moments that the model is explicitly calibrated to, as well as other price and quantity moments. We simulate the model on a quarterly basis and aggregate moments to an annual frequency.

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



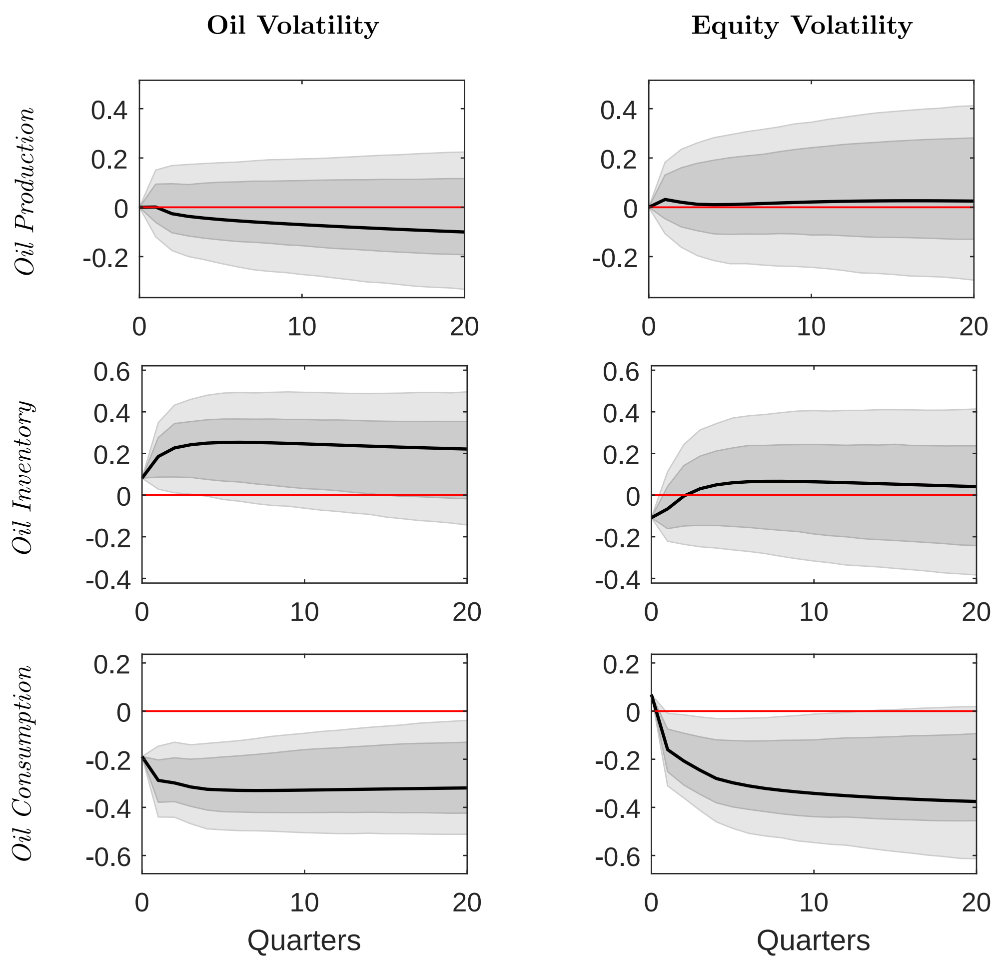

The figure shows the excess returns (left panels) and volatilities (right panels) in oil and equity markets. Implied volatilities (solid line) are constructed from equity and oil option data, and realized volatilities (dashed line) are based on daily return data. The volatilities are expressed in annualized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

Figure 2: **Impulse Responses of Macroeconomic Variables to Volatility Shocks**



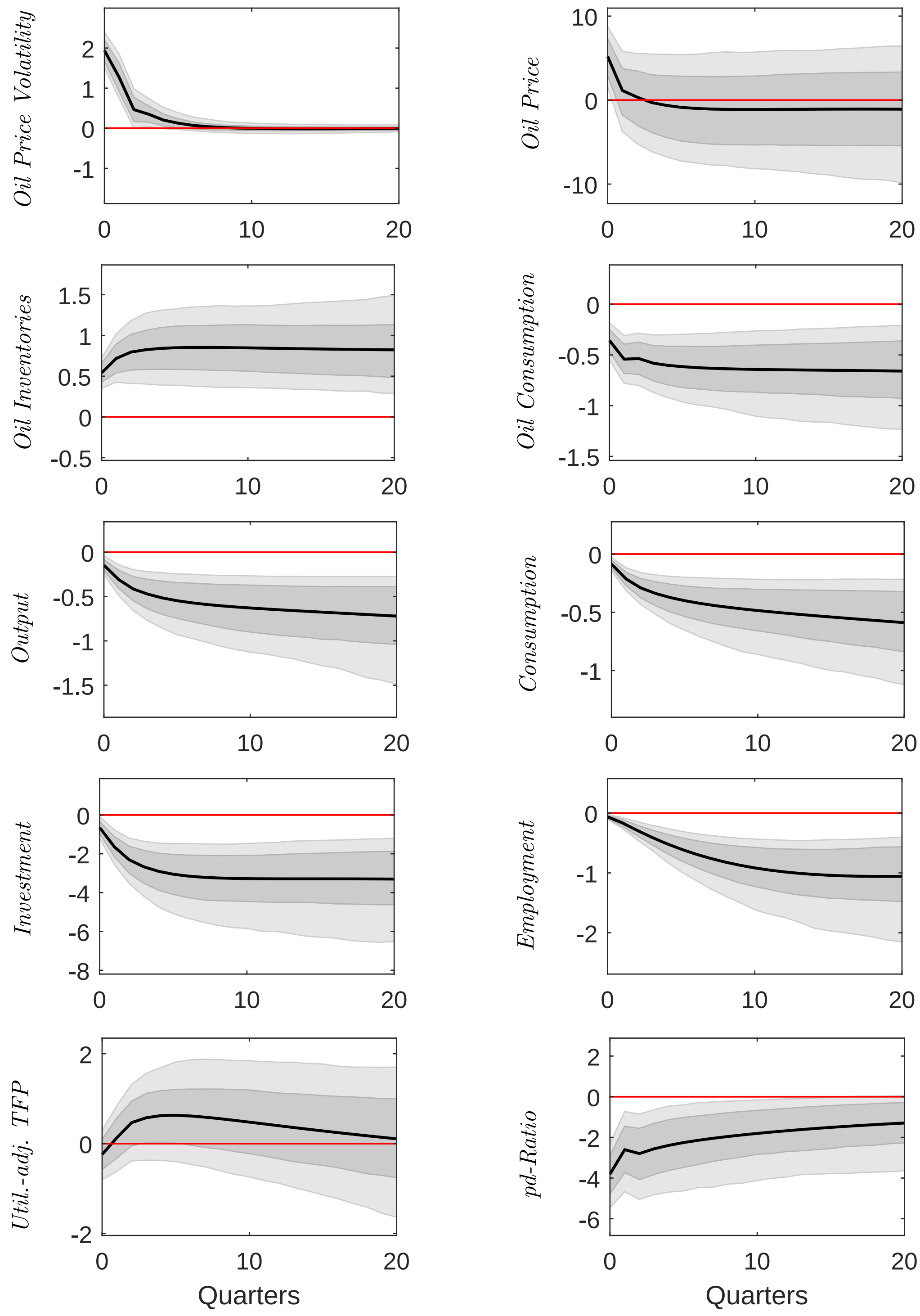

The figure shows the impulse responses of macroeconomic variables to positive shocks to implied oil volatility (left panels) and equity volatility (right panels). The impulse responses are based on a lower-triangular Cholesky decomposition of a VAR(1) fitted to the corresponding macroeconomic series, 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. Changes are in percent.

Figure 3: **Impulse Responses of Oil Sector Variables to Volatility Shocks**



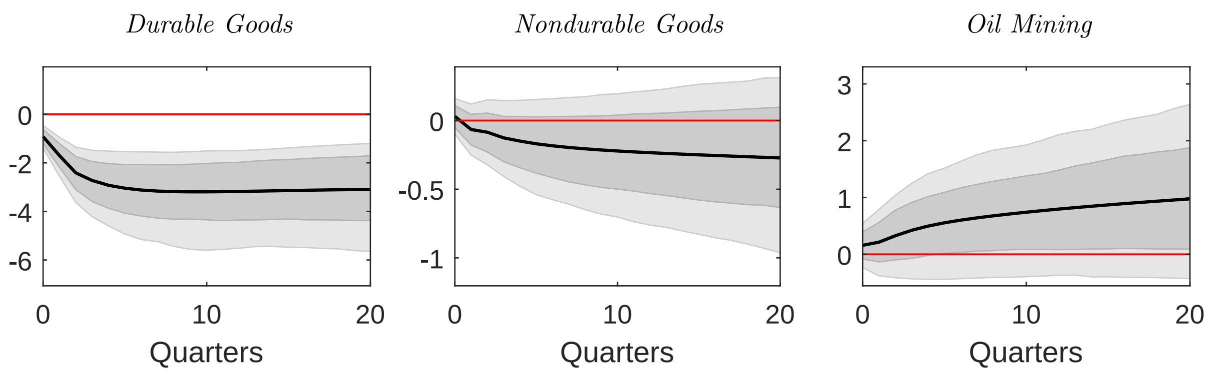

The figure shows the impulse responses of oil sector variables to positive shocks to implied oil volatility (left panels) and equity volatility (right panels). The impulse responses are based on a lower-triangular Cholesky decomposition of a VAR(1) fitted to: 1) oil production growth, oil return, market variance, oil variance, risk-free rate, and the market-price-dividend ratio (top panel); 2) oil production growth, oil return, market variance, oil variance, oil inventory or oil consumption growth, risk-free rate, and 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. Changes are in percent.

Figure 4: **Impulse Responses to Oil Uncertainty Shocks**



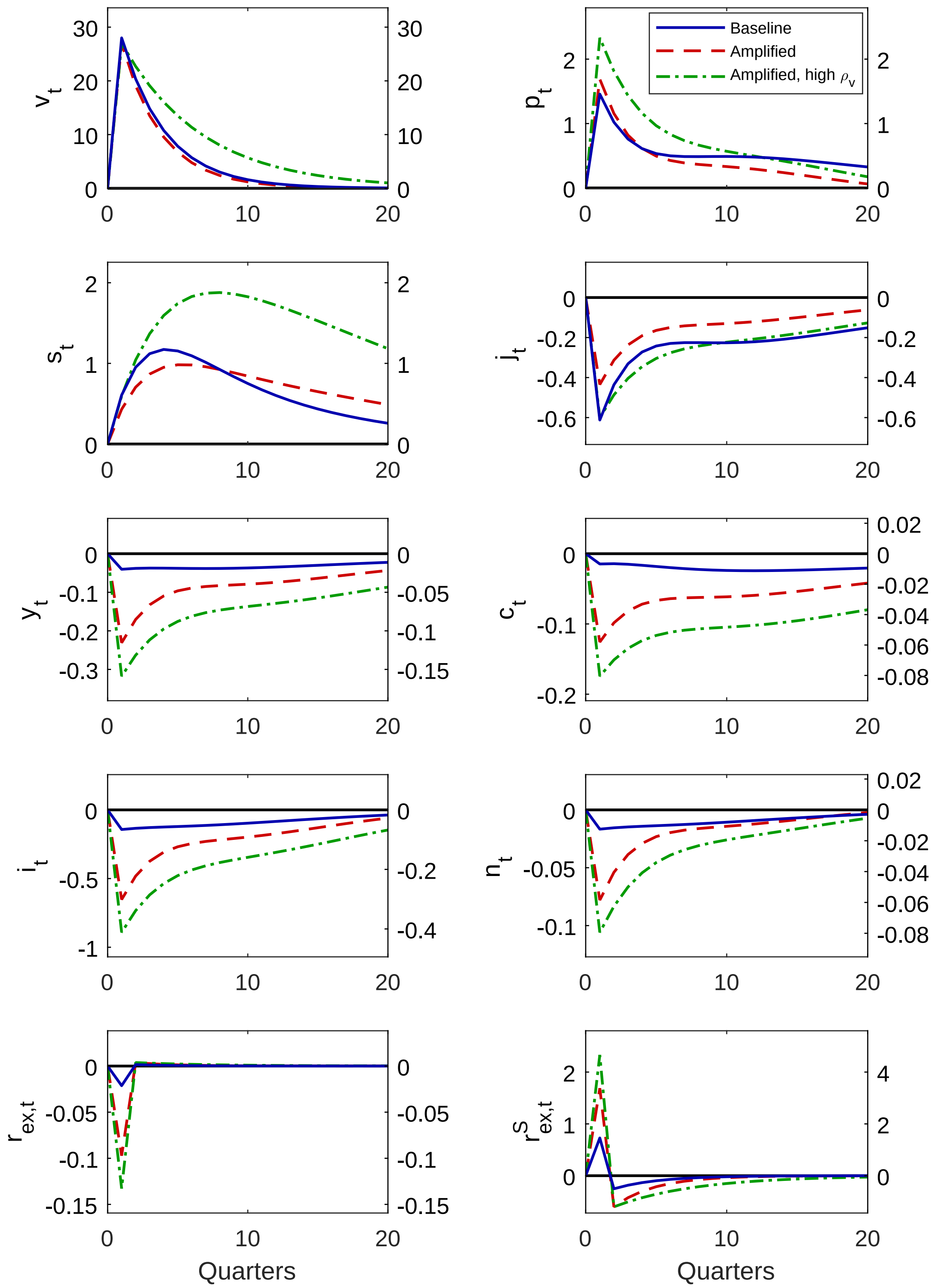

The figure shows the impulse responses of economic variables to positive oil uncertainty shocks. The oil uncertainty shock is identified from the VAR under the sign restrictions that it contemporaneously increases oil price volatility, oil inventory, and oil prices. The VAR(1) is fitted to the corresponding macroeconomic series, oil return, market variance, oil variance, risk-free rate, market price-dividend ratio, and oil inventories. Light and dark gray regions indicate 90% and 68% confidence intervals computed by block bootstrap. Data are quarterly from 1990Q1 to 2014Q1. Changes are in percent.

Figure 5: **Impulse Responses of Sectoral Production to Oil Uncertainty Shocks**



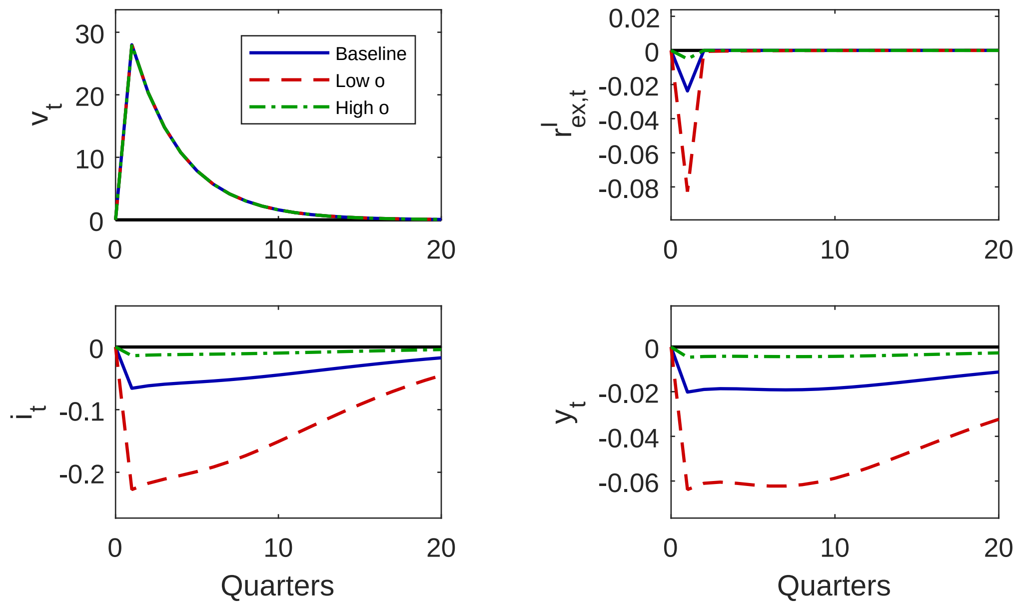

The figure shows the impulse responses of sectoral industrial production to positive oil uncertainty shocks. The oil uncertainty shock is identified from the VAR under the sign restrictions that it contemporaneously increases oil price volatility, oil inventory, and oil prices. The VAR(1) is fitted to the corresponding macroeconomic series, oil return, market variance, oil variance, risk-free rate, market price-dividend ratio, and oil inventories. Light and dark gray regions indicate 90% and 68% confidence intervals computed by block bootstrap. Data are quarterly from 1990Q1 to 2014Q1. Changes are in percent.

Figure 6: **Model-Based Impulse Responses to Oil Uncertainty Shocks**



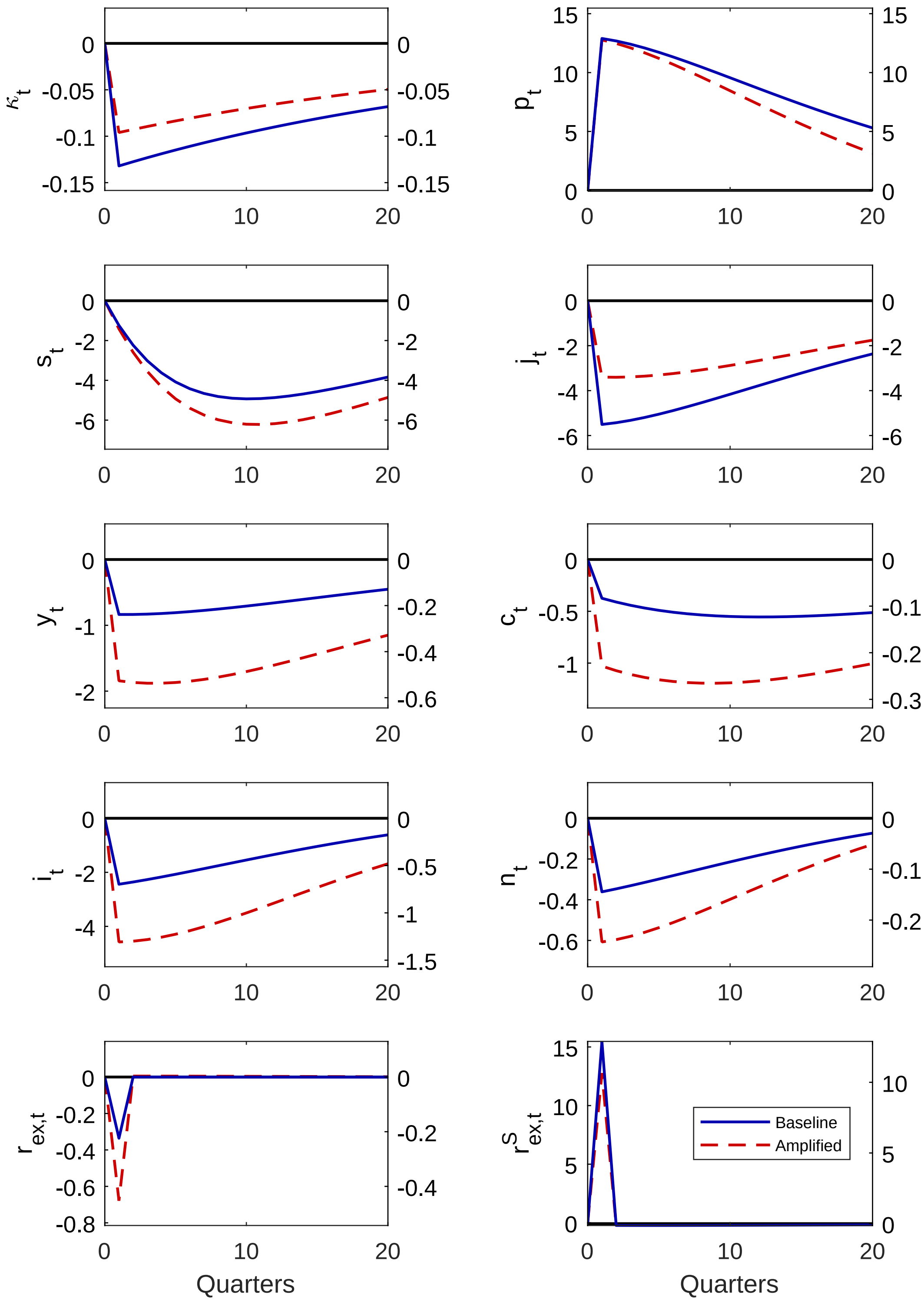

The figure shows model-based impulse response functions for a positive one-standard-deviation shock to oil production volatility $v_t$. The blue solid lines and the right axis stand for the baseline model, the left axis and red dashed lines for the amplified model, and green dot-dashed lines for the amplified model with increased persistence $\rho_v$ of oil production volatility. Changes are in percent.

Figure 7: **Model-Based Impulse Responses to Oil Uncertainty Shocks: Different Oil Input Sensitivities**



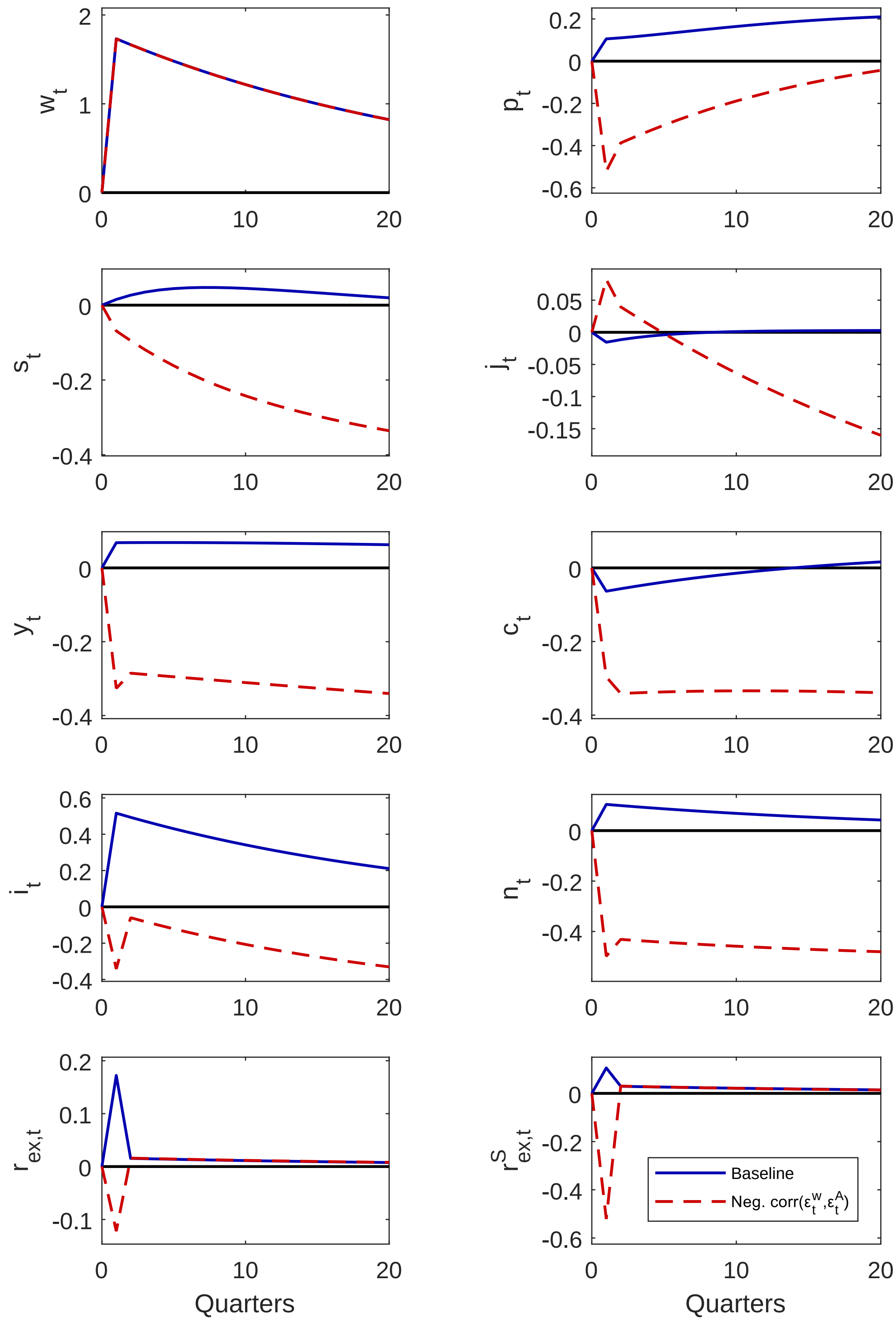

The figure shows model-based impulse response functions for a positive one-standard-deviation shock to oil production volatility $v_t$. The impulse responses are calculated for the baseline model calibration parameters, but for different levels of the oil elasticity $o$. The blue solid lines stand for the baseline calibration with $o = 0.4$, the red dashed lines for $o = 0.35$, and the green dot-dashed lines for $o = 0.45$. Changes are in percent.

Figure 8: **Model-Based Impulse Responses to Oil Supply Shocks**



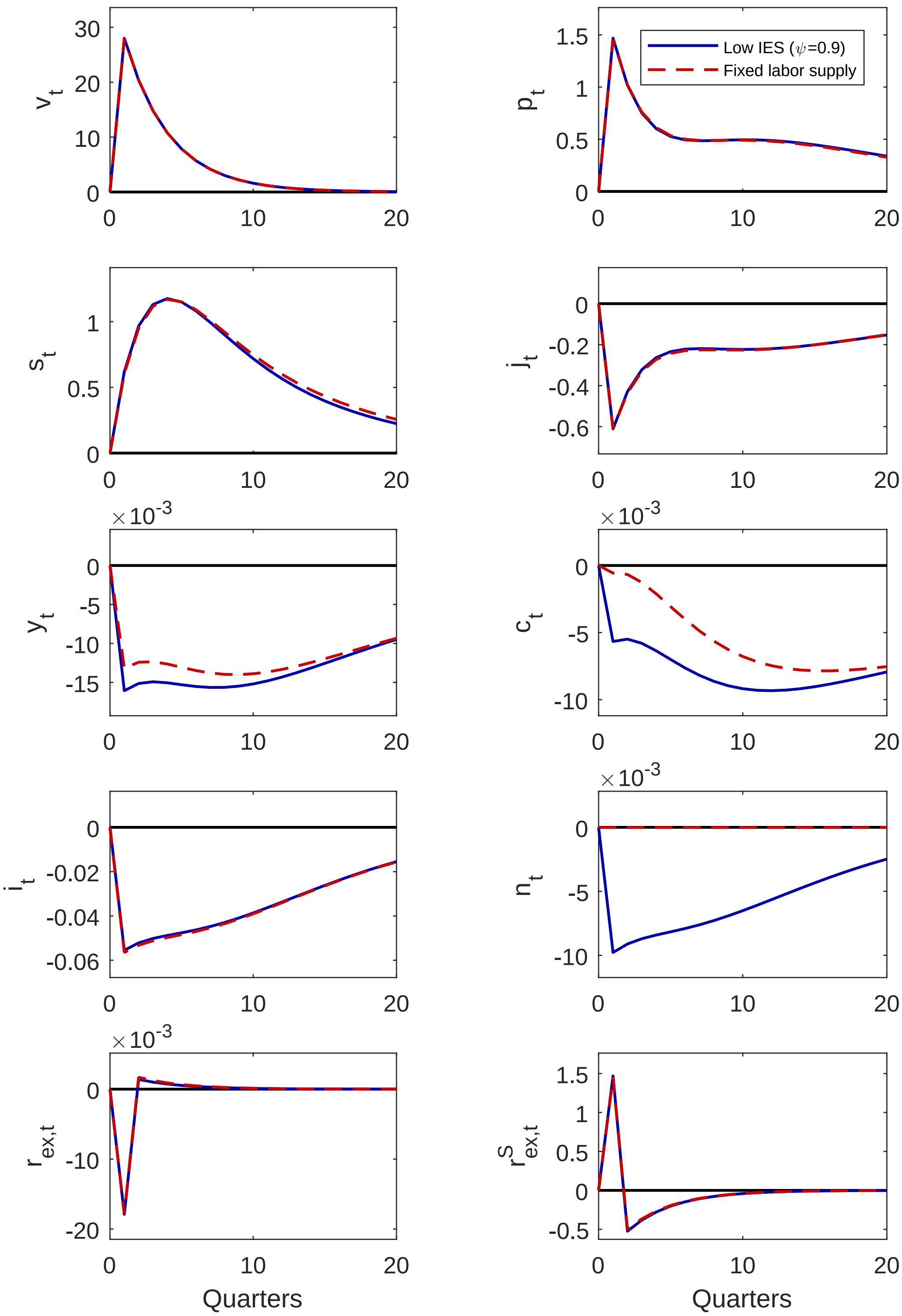

The figure shows model-based impulse response functions for a negative one-standard-deviation shock to the oil production rate $\kappa_t$. The blue solid lines and the right axis stand for the baseline model, the red dashed lines and the left axis for the amplified version. Changes are in percent.

Figure 9: **Model-Based Impulse Responses to Macro Uncertainty Shocks**




The figure shows model-based impulse response functions for a positive one-standard-deviation shock to macroeconomic volatility $w_t$ in the baseline model. The red dashed lines stand for the case of a negative correlation between macro uncertainty shocks and TFP shocks, $\text{corr}(\varepsilon_t^w, \varepsilon_t^A) = -0.3$, the blue solid lines for the case of zero correlation. Changes are in percent.

Figure 10: **Model-Based Impulse Responses to Oil Uncertainty Shocks: Robustness**




The figure shows model-based impulse response functions for a positive one-standard-deviation shock to oil production volatility $v_t$ for two alternative calibrations. The blue solid lines stand for a calibration with an IES $\psi$ of 0.9, the red dashed lines stand for a model variant with fixed labor supply, $n_t = \bar{n}$. Changes are in percent.

# A Appendix

## A.1 Oil Volatility Measure

For computing implied oil volatilities in a model-free way, we obtain daily data on futures and option prices on West Texas Intermediate (WTI) light sweet crude oil from the Commodity Research Bureau (CRB). 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).[16] 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 compute the 30-day model-free option implied volatility following Bakshi, Kapadia, and Madan (2003), truncating upper and lower strike prices at $K_t = F_{t,T} \cdot \exp\{\pm 6\sigma(T-t)\}$.[17]

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%.

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

[17] 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 capital law of motion (3.3):

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

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

$$Q_t^I = \frac{1}{1 - G_t'}. \quad \text{(A.2)}$$

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

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

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

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

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

$$P_t = \frac{\partial Y_t}{\partial J_t} = \alpha \tilde{\iota} \frac{Y_t}{J_t^{\frac{1}{o}} Z_t^{1-\frac{1}{o}}}. \quad \text{(A.5)}$$

**Oil producer** In a similar way, consider (3.10) at time 0 and add the Lagrange multiplier $Q_t^S$ for the resource constraint (3.8)

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

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 Amplified Model

As described in Section 3.5, we consider a version of our model in which the effect of oil uncertainty shocks on the macroeconomy is amplified through time-varying markups and an intermediate goods multiplier. Technically, we specify markups $\theta_t = \mu_\theta J_t^{\varepsilon_\theta}$ to be driven by the oil input $J_t$ to the productive sector. For positive elasticity $\varepsilon_\theta$, we thus obtain countercyclical markups in line with Rotemberg and Woodford (1996) due to the negative relation of effective oil supply and macroeconomic output. The interlinked intermediate goods sector with share $\nu$ amplifies markups to a factor of $\Theta_t = \theta^{\frac{1}{1-\nu}}$ in line with Jones (2011).

Altogether, these amplifiers alter equations (3.1), (3.20), (3.21), and (3.24) of our model as follows:

$$Y_t = \Theta_t \cdot \lambda J_t^\zeta \cdot (A_t N_t)^{1-\alpha} Z_t^\alpha \tag{3.1'}$$

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

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

$$R_{t+1}^I = \frac{\frac{\alpha(1-\tilde{\iota})}{\Theta_t}\frac{Y_{t+1}}{K_{t+1}^{\frac{1}{o}} Z_{t+1}^{1-\frac{1}{o}}} + ((1-\delta) + G_{t+1}{}'\frac{I_{t+1}}{K_{t+1}} - G_{t+1})Q_{t+1}^I}{Q_t^I} \tag{3.24'}$$

with a scaling factor $\lambda J_t^\zeta$ resulting from the Jones (2011) multiplier.

We calibrate the model as reported by Table 8. Most values are the same as in the baseline calibration, except the parameters $\iota$, $\pi$, $\sigma_\kappa$, $\rho_v$, and $\sigma_v$, which are chosen to match the moments in the first panel of Table 9, as well as the adjustment costs $\xi$ and the oil elasticity $o$, which we set to 0.225 in line with Ready (2018). For the introduced amplifiers, we set the elasticity $\varepsilon_\theta$ of markups to 0.05, and the share $\nu$ of the intermediate goods sector is set to 0.5 in line with Jones (2011). The scaling parameters $\mu_\theta$, $\lambda$, and $\zeta$ are fixed at 1.3, 0.2, and 0.3, respectively.

## A.4 Appendix Tables and Figures

Table A.1: **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 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 |
| *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 |

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

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 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 |
| *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 |

The table reports predictability results for macroeconomic and oil sector variables by their own lag, oil variance, equity variance, and oil return. Variance measures correspond to realized variances computed from daily oil and equity 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 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 |
| *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 |

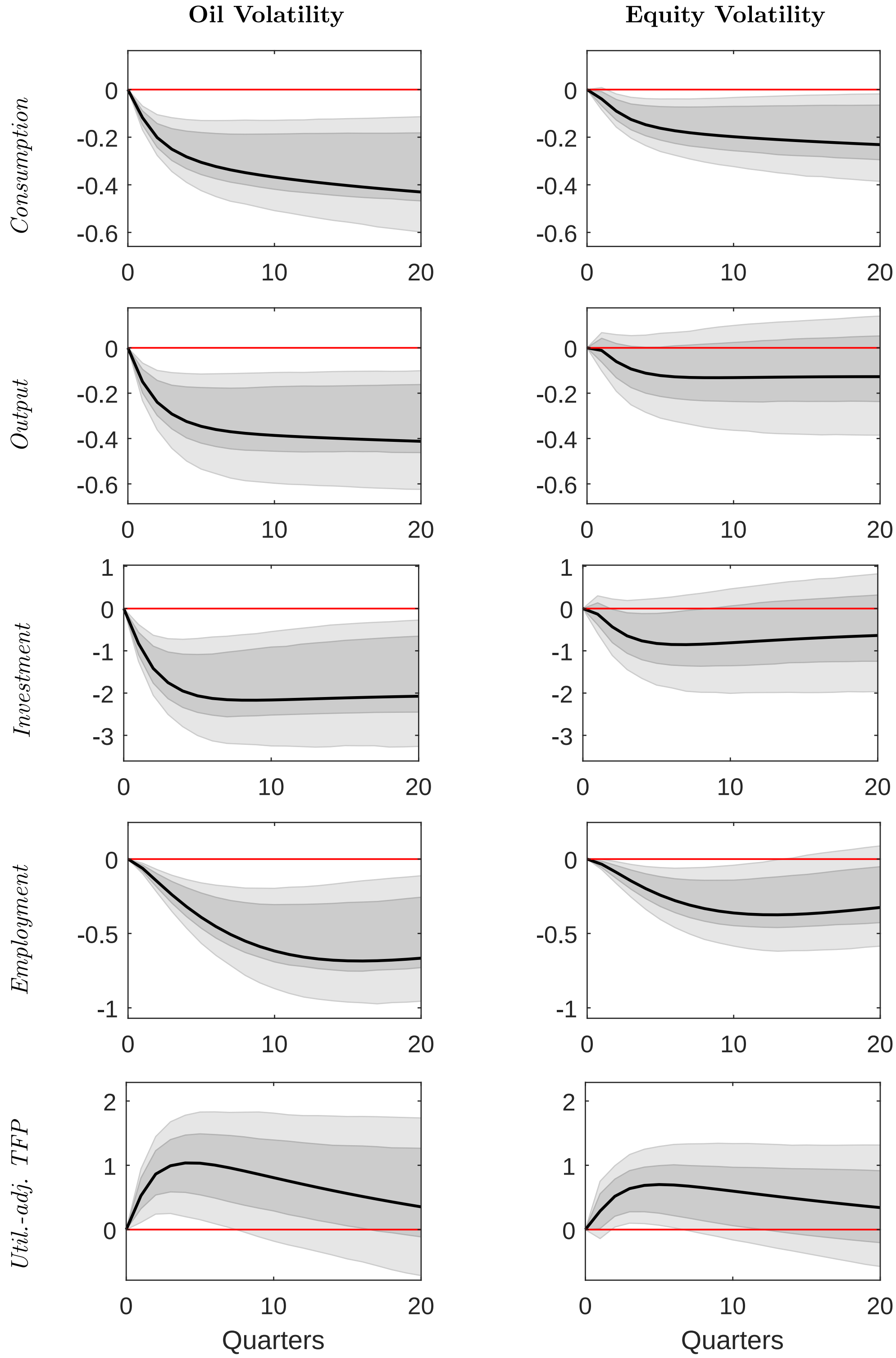
The table reports predictability results for macroeconomic and oil sector variables by their own lag, oil variance, equity variance, and oil return. Variance measures correspond to the continuous variation computed from oil prices, and realized variance computed from equity prices. Newey-West standard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

Table A.4: **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 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 |
| *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 |

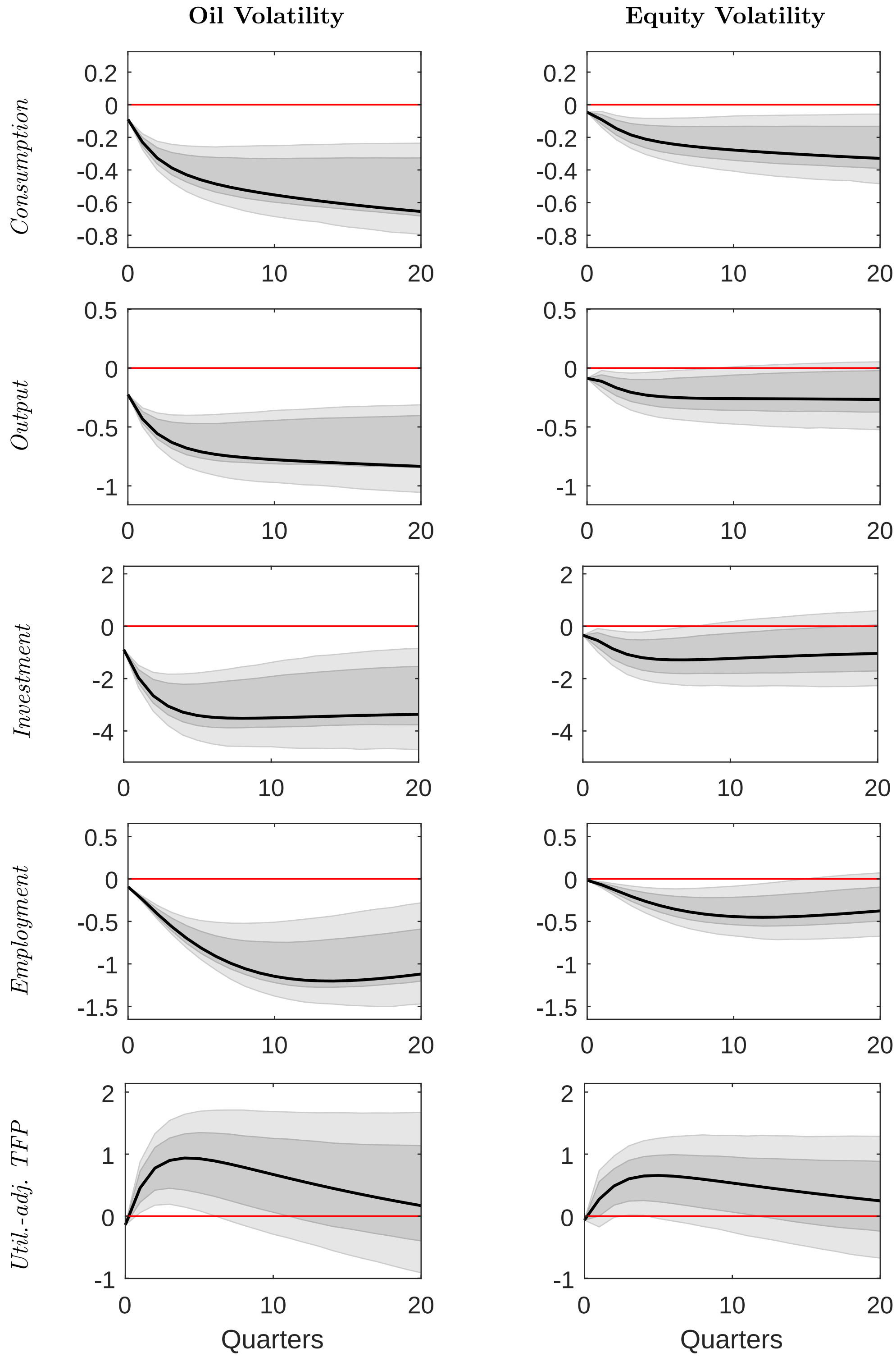
The table reports predictability results for macroeconomic and oil sector variables by their own lag, oil variance, equity variance, oil return, the market price-dividend ratio, the real risk-free rate, and the term spread. Variance measures correspond to the implied variances computed from oil and equity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

Figure A.1: **Impulse Responses of Macro Series to Volatility: Alternative Ordering**




The figure shows the impulse responses of macroeconomic variables to positive shocks 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. Changes are in percent.

Figure A.2: **Impulse Responses of Macro Series to Volatility: Exogenous Volatility**




The figure shows the impulse responses of macroeconomic variables to positive shocks 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. Changes are in percent.

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