Geopolitical Oil Price Risk and Economic Fluctuations*

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Abstract

This paper seeks to understand the general equilibrium effects of time-varying geopolitical risk in oil markets. Answering this question requires simultaneously modeling downside risk from disasters, oil storage, and the endogenous determination of oil price and macroeconomic uncertainty. We find that shocks to the probability of geopolitically driven oil production disasters can have sizable effects on the oil market and macroeconomy but are not a major driver of macroeconomic fluctuations. Shocks to the probability of macroeconomic disasters are an important driver of oil price uncertainty, which helps explain why higher oil price uncertainty has been associated with lower real activity.

Keywords: Geopolitical risk, macroeconomic risk, time-varying uncertainty, rare disasters, oil, endogeneity, shock propagation, economic fluctuations, precautionary savings, inventories
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1 Introduction

Time-variation in geopolitical risk is widely considered an important determinant of fluctuations in economic activity. The financial press, international organizations, rating agencies and the investment community all vie to assess these risks and their likely impact on the economy. Clearly, geopolitical events matter not only when they occur on rare occasions, but also when investors and consumers make decisions in anticipation of the possibility of such events. This fact is nowhere more apparent than when it comes to geopolitical risk in energy markets. For example, many market analysts list risks to energy security as one of the top geopolitical risks of 2024. This assessment is driven in no small part by concerns about OPEC quota decisions, global access to Russian oil amidst Ukrainian attacks on Russian oil infrastructure and efforts to tighten the G7 price cap, dwindling strategic oil reserves, disruptions of oil shipments in the Red Sea and possibly in the Persian Gulf, and concerns about a widening conflict between Israel and Iran. Geopolitical events such as these are low probability but have potentially high impact on the economy, creating geopolitical risk.

There is a deep-rooted belief in macroeconomics that higher oil price uncertainty driven by geopolitical risk lowers domestic investment and consumption and hence real GDP.[1] The focus of our paper is to develop a better understanding of how time-variation in geopolitical risk in oil markets affects oil price uncertainty and economic fluctuations. Our analysis recognizes that, while downside geopolitical risk raises oil price uncertainty, not all surges in oil price uncertainty are driven by geopolitical events.

We present results from a calibrated dynamic stochastic general equilibrium (DSGE) model of the global economy that is designed to address the question of how geopolitical oil price risk

[1] For example, Bernanke (1983), Lee et al. (1995), Ferderer (1996), Edelstein and Kilian (2009), Elder and Serletis (2010), Baumeister and Kilian (2016a), Ready (2018), and Gao et al. (2022) discuss the impact of oil price uncertainty on U.S. real activity, while Kilian (2009), Jo (2014), and Cross et al. (2022) discuss its impact on global real activity. The perception that oil price volatility matters for the transmission of oil price shocks to the economy also helped spawn a large literature on the asymmetric transmission of oil price shocks (see, e.g., Bernanke et al., 1997; Davis and Haltiwanger, 2001; Hooker, 1996, 2002; Kilian and Vigfusson, 2011; Leduc and Sill, 2004; Lee and Ni, 2002; Mork, 1989; Ramey and Vine, 2010).

is linked to economic fluctuations. The model includes risk averse economic agents, an oil production sector, oil storage, and limited substitutability between oil and capital. The price of oil is determined endogenously. Since the model is global, we abstract from oil imports and exports and international capital flows. One key difference from earlier studies is that our model allows for both macroeconomic uncertainty and oil price uncertainty and that uncertainty is determined endogenously. Building on Gourio (2012), downside risk emanates from macroeconomic disasters and oil production disasters of stochastic length that occur with time-varying probabilities. Macroeconomic disasters are modeled as sharp declines in growth and may be viewed as the result of an economic crisis such as the Great Recession of 2008 or the Covid-19 recession of 2020. Oil production disasters are modeled after events such as the Iranian Revolution in 1979 or the invasion of Kuwait in 1990.

We find that shocks to the probability of an oil production disaster have large and persistent effects on oil inventories, the price of oil, and oil price uncertainty, whether this disaster is realized or not. These shocks can also have sizable effects on investment and output, but they are not a major driver of fluctuations in macroeconomic aggregates because large probability shocks are rare. Nor do they have much of an effect on macroeconopmic uncertainty. Shocks to the probability of a growth disaster, which increase macroeconomic uncertainty, have even larger effects on the oil market and the macroeconomy. These shocks also play a major role in the determination of oil price uncertainty, which helps explain why higher oil price uncertainty has historically been associated with lower real activity. Our analysis highlights that this association should not be interpreted as evidence of a causal link.

Incorporating downside risk is crucial for our results. While increases in oil price uncertainty may also be explained by stochastic volatility shocks to oil production, the latter shocks do not have strong recessionary effects because they generate risk tilted to the downside. We also show that the ability to store oil plays a central role. Without storage the responses of both oil market variables and macroeconomic aggregates to higher oil production risk tend to be muted, suggesting that DSGE models without storage fail to capture the full effects of shifts in oil production risk.

Oil storage also matters for the responses of the global economy to growth disaster shocks, underscoring the importance of jointly modeling oil production disasters and macroeconomic disasters.

Our model shows that changes in oil price uncertainty need not be an indication of exogenous shifts in the uncertainty about future oil supplies. Uncertainty about the oil price may reflect exogenous macroeconomic uncertainty shocks, mirroring the standard result that the real price of oil responds to shifts in the demand for oil. It may also reflect level shocks in the oil market or the macroeconomy, such as realizations of disasters. Thus, not only are level and uncertainty shocks not the same, as implicitly assumed in VAR-GARCH models, but the effects of a level shock in the data generating process are not separable from those of an uncertainty shock, as assumed in VAR models with stochastic volatility. Nor do it make sense to employ recursive linear VAR models with oil price uncertainty either ordered first or last since oil price uncertainty is simultaneously determined with macroeconomic aggregates. These results cast doubt on the ability of these models to correctly identify exogenous oil price uncertainty shocks. They also call into question a large body of empirical work that has produced seemingly robust evidence of large recessionary effects of oil price uncertainty shocks and shaped the policy debate about geopolitical risk in recent years.

Our work relates to several strands of the literature. First, it contributes to the large literature on the effects of uncertainty shocks on the macroeconomy (e.g., Berger et al., 2020; Bernstein et al., 2024; Bloom, 2009; Fernández-Villaverde et al., 2015; Gourio, 2012; Jurado et al., 2015; Leduc and Liu, 2016; Ludvigson et al., 2021) by focusing on the interaction between macroeconomic and oil price uncertainty. We show that modeling geopolitical oil production risk and macroeconomic risk jointly is necessary for understanding the evolution of oil price uncertainty.

Second, our analysis contributes to the literature making the case that oil price uncertainty shocks driven by geopolitical events are recessionary (e.g., Başkaya et al., 2013; Bernanke, 1983; Drakos and Konstantinou, 2013; Gao et al., 2022; Ready, 2018) and affect oil production and storage (e.g., Cross et al., 2022; Kellogg, 2014). We examine this question within a general equilibrium model with endogenous oil prices and endogenous oil price uncertainty. Unlike earlier DSGE studies with stochastic volatility shocks to either oil production or oil prices, we account for the fact that geopolitical oil price risk is inherently one-sided and reflects the stochastic arrival of oil production disasters driven by geopolitical events. We find that shifts in the probability of an oil production disaster cause exogenous changes in oil price uncertainty and can have large negative effects on the economy. However, because large probability shocks are infrequent, these shocks do not generate much volatility in macroeconomic aggregates.

Third, we contribute to the literature emphasizing the endogeneity of fluctuations in the price of oil with respect to macroeconomic aggregates (e.g., Braun, 2023; Kilian, 2009; Kilian and Murphy, 2014; Zhou, 2020). Whereas this earlier literature focused on showing that the level of the real price of oil is endogenously determined by oil demand and oil supply, our analysis shows that oil price uncertainty responds to both level and uncertainty shocks to macroeconomic aggregates, complicating the identification of exogenous oil price uncertainty shocks. These findings have important implications for empirical work seeking to establish the macroeconomic effects of shocks to oil price uncertainty (e.g., Cross et al., 2022; Elder and Serletis, 2010; Ferderer, 1996; Gao et al., 2022; Jo, 2014).

The remainder of the paper is organized as follows. In Section 2, we highlight the importance of geopolitical risk for the economy. We propose an index of the uncertainty in the real price of oil building on Jurado et al. (2015), trace its evolution since the 1970s, and discuss the relationship between downside risk in oil production and oil price uncertainty. We also stress that our index differs conceptually from the geopolitical risk index in Caldara and Iacoviello (2022), and we compare our index to the OVX measure of implied oil price volatility. Section 3 reviews why many economists expect oil price uncertainty to slow economic activity. Section 4 introduces a calibrated DSGE model of the global economy that elucidates the determination of oil price uncertainty and macroeconomic uncertainty. In Section 5, we study the relationship between oil price uncertainty and macroeconomic uncertainty, the transmission of uncertainty shocks to the economy, and the ability of these shocks to explain fluctuations in economic growth and oil price fluctuations. Our analysis also sheds light on the key economic mechanisms in the model and the importance of modeling downside risk. In Section 6, we discuss the relationship between our work and earlier

DSGE models of the transmission of oil price uncertainty shocks. Section 7 discusses implications of our analysis for empirical models of the effects of oil price uncertainty shocks. The concluding remarks are in Section 8.

2 MEASURING OIL PRICE UNCERTAINTY

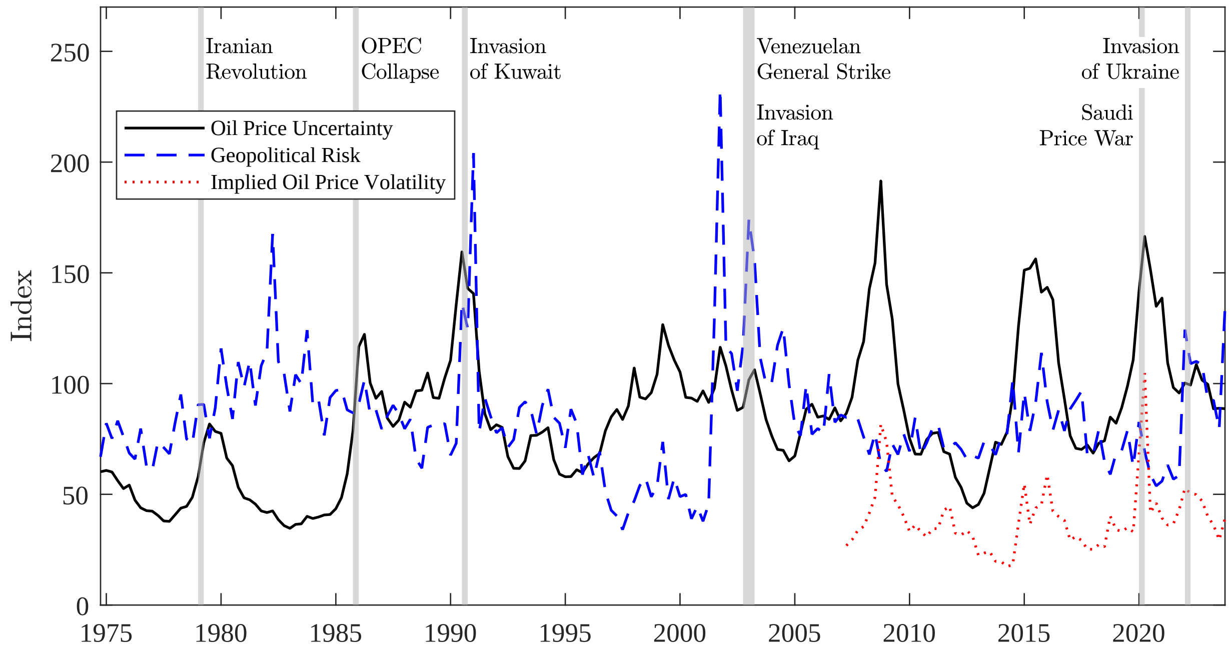
There has been growing interest in the impact of shifts in geopolitical risk in global commodity markets, in general, and in the oil market in particular in recent years. Historically, increases in oil price risk have been associated, for example, with uncertainty about the implications of the Iranian Revolution in 1979 and the outcome of the invasion of Kuwait in 1990. More recently, there was a surge in uncertainty about the possibility of Russia refusing to sell oil to Europe after the invasion of Ukraine in 2022 and then about the effectiveness of a price cap on Russian oil exports. Other recent sources of oil price uncertainty have included doubts about the ability of U.S. shale oil producers to maintain their production increases and changes in OPEC oil production quotas.

The focus of our paper is to develop a better understanding of how time-variation in geopolitical risk in oil markets affects oil price uncertainty and hence economic fluctuations. Our starting point is the downside risk to oil production caused by these events. These downside risks are inherently subjective because they relate to events that have not occurred. In contrast, oil price uncertainty can be quantified using econometric methods. This does not make oil price uncertainty a good indicator of geopolitically driven downside risk in oil production, however, because these two variables need not go hand-in-hand. While downside geopolitical risk to oil production raises oil price uncertainty, not all surges in oil price uncertainty are driven by geopolitical events, as illustrated next.

Figure 1 quantifies the uncertainty about the real price of oil in global oil markets since the modern oil market emerged in the early 1970s. We follow Jurado et al. (2015) in measuring oil price uncertainty ($\mathcal{U}_{p^o}$) as the one-quarter ahead conditional volatility of the unpredictable component from a predictive model of the real price of oil.[2] This definition highlights the fact that

[2]Details of the construction of the uncertainty measure can be found in Appendix A.

Figure 1: Oil price uncertainty, 1974Q4-2023Q4



Notes: The solid line shows the uncertainty about the percent change in the real price of oil obtained by deflating the U.S. refiners' acquisition cost for oil imports by the U.S. CPI for all urban consumers. The method used to quantify this uncertainty is based on Jurado et al. (2015). The dashed line is the quarterly average of the historical GPR series in Caldara and Iacoviello (2022). The dotted line is the option-implied crude oil price volatility index (OVX) published by the Chicago Board Options Exchange.

what matters for economic decision making is not whether the price of oil has become more or less variable, but whether it has become more or less predictable.[3] The real price of oil is defined as the U.S. refiners' acquisition cost for oil imports, as is standard in the literature, deflated by the implicit GDP deflator. The predictable component of the growth rate of the real price of oil is approximated using a diffusion index based on largely the same set of variables used by Jurado et al. (2015), augmented by the real price of oil, updated, and aggregated to quarterly frequency.

We estimate the uncertainty about the price of oil from 1974Q4 to 2023Q4. There are large spikes in 1979, 1986, and 1990 at the time of the Iranian Revolution, the collapse of OPEC, and the invasion of Kuwait. Not all geopolitical events are associated with surges in oil price uncertainty,

[3]The definition of uncertainty in Jurado et al. (2015) is closely related to the formal measure of predictability in Diebold and Kilian (2001), since lack of predictability implies uncertainty.

however. For example, neither the outbreak of the Iran-Iraq War in late 1980 nor the outbreak of the Israel-Hamas War in the last quarter of 2023 had a discernible impact on the index.

The largest spike in oil price uncertainty in 2008 was not driven by geopolitical risk, but by macroeconomic risk created by the Great Recession. Similarly, the surge in oil price uncertainty in 2015 appears to be driven by market forces rather than geopolitics (see Baumeister and Kilian, 2016b), as was a smaller spike in uncertainty during the Asian Financial Crisis of the late 1990s. Sometimes, geopolitical events coincide with surges in macroeconomic risk, as was the case in early 2020 when the Covid-19 recession occurred at the same time as the Saudi price war in the oil market.

Figure 1 also shows that our oil price uncertainty index differs systematically from the geopolitical risk (GPR) index of Caldara and Iacoviello (2022), which quantifies the newspaper coverage of geopolitical events not limited to oil markets. The GPR index does not capture oil price uncertainty associated with macroeconomic risk, nor does it capture variation in oil price uncertainty clearly driven by geopolitical risk in oil markets. For example, the direction of these indices differs in the early 1980s. In addition, the relative magnitude of changes in these indices is quite different. Their correlation is essentially zero.

Our oil price uncertainty index also differs conceptually from the implied volatility index (OVX) published by the Chicago Board Options Exchange, which is only available starting in 2007. However, the correlation of 0.71 between our index and the OVX is much higher than its correlation with the GPR index. There is no indication that the implied volatility measure has an informational advantage, allowing it to respond to shifts in geopolitical uncertainty more quickly.[4]

3 WHY ECONOMISTS THINK OIL PRICE UNCERTAINTY MATTERS

Interest in fluctuations in oil price uncertainty dates to the mid-1980s. Economists at the time observed that the economy entered a steep recession after the 1979/80 oil price surge, but a simi-

[4]In related work, Gao et al. (2022) derive an index similar to the OVX series using oil options back to 1990Q1. The relationship between these indices is similar over the extended sample.

larly large drop in the price of oil in 1986 did not cause a large economic expansion. This fact is consistent with two mutually exclusive narratives. One is that the relationship between oil prices and the U.S. economy is linear, which implies that the effect of oil price shocks on the economy is modest at best and that the recession in the early 1980s is explained in substantial part by other shocks (e.g., Barsky and Kilian, 2002). This explanation is consistent with DSGE models of the transmission of oil price shocks that predict that rising oil prices will modestly slow growth in oil-importing economies, as consumers' income is reduced and firms face higher production costs, and, conversely, falling oil prices will modestly stimulate growth in oil-importing economies (e.g., Backus and Crucini, 2000).[5]

The other narrative is that this relationship is nonlinear with positive oil price shocks having disproportionately larger effects on the economy. Macroeconomists for many years have been partial to this interpretation. A leading explanation of the nonlinearity required to explain the disproportionately large effect of positive oil price shocks and the negligible effects of negative oil price shocks, is that the rise in oil price uncertainty associated with the 1979/80 oil price surge caused consumer spending and business fixed investment to drop, amplifying the effects of rising oil prices, whereas in 1986 an increase in oil price uncertainty associated with the fall in oil prices largely offset the stimulus from lower oil prices.

The theoretical justification for this explanation relies on the real options theory of investment in Bernanke (1983) as well as the effect of rising uncertainty on precautionary savings and consumer spending (e.g., Başkaya et al., 2013; Edelstein and Kilian, 2009; Plante and Traum, 2012). A closely related third argument is that firms build oil inventories when oil price uncertainty rises, which raises the real price of oil, lowers oil consumption, and hence depresses economic activity (e.g., Cross et al., 2022; Gao et al., 2022; Kilian, 2009; Kilian and Murphy, 2014).

[5]There have been many attempts to design macroeconomic models that amplify the transmission of oil price shocks (e.g., Aguiar-Conraria and Wen, 2007; Atkeson and Kehoe, 1999; Finn, 2000; Rotemberg and Woodford, 1996). These theoretical models are not necessarily supported by the data, however. More importantly, being able to generate a larger recession after 1979/80 makes it even more difficult to explain the absence of an economic expansion in 1986.

3.1 Real options theory

The most commonly cited reason why oil price uncertainty shocks matter for economic activity was articulated by Bernanke (1983) in a partial equilibrium setting.[6] Bernanke's point is that—to the extent that the cash flow from an irreversible investment project depends on the price of oil or its derivatives—all else equal, increased uncertainty about the price of oil prompts firms to delay investments. As a result, investment expenditures drop and real output declines. Uncertainty for this purpose may be measured by the expected conditional volatility of the real price of oil over the relevant investment horizon. Exactly the same reasoning applies to purchases of energy-intensive consumer durables such as cars (see Edelstein and Kilian, 2009).

There are several caveats to this application of real options theory. First, the quantitative importance of this channel depends on how important the real price of oil is for investment and durable consumption decisions and on the share of such expenditures in aggregate spending. For example, it seems intuitive that uncertainty about the price of oil would be important for decisions about oil drilling in Texas (see Kellogg, 2014). It is less obvious that it would be as important for investment in other sectors of the economy such as textile production or information technology, the expected profitability of which does not depend as much on oil prices.

Second, there is reason to believe that for longer-term investment projects, the variation over time in the uncertainty about the real price of oil is small. Consider an airline purchasing new planes that are expected to fly for 20 years. The cash flow from this investment clearly depends on fuel prices and an increase in expected fuel price uncertainty, all else equal, should cause the airline to delay the investment. However, the predictable component of the variance of the real price of oil quickly reverts to the unconditional variance at longer horizons, so one would not expect variation in the conditional variance at monthly or quarterly frequency to have a large effect on the investment decision. This casts doubt on the view that the value of the real option is large.

Third, Bernanke (1983) takes the real oil price as exogenously given. This simplifying assumption does not hold in practice, complicating the analysis. The concern is that we may attribute to oil price uncertainty the effects of macroeconomic uncertainty that are much more likely to affect

[6] For related discussion of the effects of uncertainty shocks more generally see Pindyck (1991) and Bloom (2014).

the cash flow from the investment.

Finally, as discussed in Section 4.4, it is unclear whether the importance of the real options channel survives in general equilibrium. Thus, the overall importance of this channel for the aggregate economy is open to question.

3.2 PRECAUTIONARY SAVINGS

A complementary reason first articulated in Edelstein and Kilian (2009) is that households' increased uncertainty about their future income in the wake of unexpected changes in the real price of oil will cause an increase in precautionary savings. In this interpretation, oil price uncertainty may affect a wide range of consumer expenditures. This argument has subsequently been formalized in Plante and Traum (2012) and Başkaya et al. (2013). Precautionary savings are driven by risk aversion embodied in the utility function. Thus, precautionary savings may also be caused by other uncertainty shocks, as discussed in Carroll and Kimball (2008).

While a response of precautionary savings to oil price uncertainty shocks may seem persuasive in a partial equilibrium setting, its quantitative importance becomes less obvious when moving to general equilibrium models. For example, higher uncertainty may cause households to work more in general equilibrium, allowing them to spend more, all else equal, and offsetting the precautionary savings motive for reducing consumption, as shown in Plante and Traum (2012).

3.3 PRECAUTIONARY INVENTORY DEMAND

A third channel by which increased oil price uncertainty can reduce economic activity operates through precautionary demand for oil inventories. This channel was introduced in Kilian (2009) and expanded on in Kilian and Murphy (2014) and Cross et al. (2022). These studies emphasized that higher precautionary demand driven by increases in oil price uncertainty, all else equal, will raise the real price of oil and reduce global economic activity by discouraging oil consumption.[7] DSGE models incorporating oil storage have been presented in Olovsson (2019) and Gao et al. (2022) who stress that firms hold precautionary oil inventories in response to oil price uncertainty.

[7] This analysis in turn builds on the theoretical insights in Alquist and Kilian (2010) of how mean-preserving shifts in the uncertainty about future oil supply shortfalls affect the real price of oil through inventory accumulation.

4 A MODEL OF THE PROPAGATION OF UNCERTAINTY SHOCKS

In this section, we introduce a DSGE model of the global economy designed to elucidate the determinants of oil price uncertainty. Focusing on the global economy allows us to sidestep the complications involved in modeling oil importing and exporting economies and to concentrate on the essence of the endogeneity problem.

4.1 MODEL The model is a nonlinear stochastic growth model augmented to include oil production. Oil is used as an intermediate input by a representative firm that produces a final good. The model allows for precautionary savings as well as oil storage, which has been shown to play an important role in driving fluctuations in oil prices (see Kilian and Murphy, 2014). The distinguishing feature of the model is that it includes downside risk to both oil production and output growth. While downside risk to oil production can be thought of as arising from geopolitical events, downside risk to the macroeconomy involves rare, sharp economic downturns, such as the Great Recession or the COVID-19 Recession that are not otherwise captured by the model.

We follow Gourio (2012) in modeling such events as disasters that arrive with a small, but time-varying probability.[8] Time-variation in the probability of oil production and output growth disasters induces exogenous variation in oil price uncertainty and macroeconomic uncertainty. While the idea of modeling downside risk in the economy as growth disasters with time-varying probability is not new, we are the first to apply this approach to modelling geopolitical risk in the oil market.[9] One advantage of this approach compared to the more traditional approach of subjecting oil production growth to a stochastic volatility shock is that it accounts for the fact that the risk agents are typically concerned with in practice is not two-sided. Rather these risks involve a sharp reduction in oil production. Such rare disasters matter not only because of their impact when they occur, but, more importantly, because agents' behavior reflects the anticipation of these disasters even when they are not realized in the data.

[8] Related applications of disaster risk include Barro and Ursúa (2012), Gourio (2013), Gourio et al. (2013), Wachter (2013), Shen (2015), Farhi and Gabaix (2016), Olovsson (2019), Kim (2022), Kilian et al. (2024), among others.

[9] Olovsson (2019) uses a related approach, except that his model treats the probability of an oil disaster as constant.

Productivity and Growth Disasters The growth rate of productivity, $g_t = a_t/a_{t-1}$, follows

$$\ln g_t = \ln \bar{g} + \sigma_g \varepsilon_{g,t} - \zeta_g(v_t^g - \bar{\pi}_1^g), \quad \varepsilon_{g,t} \sim \mathbb{N}(0,1),$$

where $\bar{g}$ is the steady state-growth rate. The indicator variable v_t^g equals 1 if a growth disaster occurs and 0 otherwise. The transition matrix for v_t^g is summarized by

$$\Pr(v_{t+1}^g = 1 | v_t^g = 1) = \bar{q}^g, \quad \Pr(v_{t+1}^g = 1 | v_t^g = 0) = p_t^g,$$

where the probability of a growth disaster follows

$$\ln p_t^g = (1 - \rho_p^g)\ln \bar{p}^g + \rho_p^g \ln p_{t-1}^g + \sigma_p^g \varepsilon_{p,t}^g, \quad \varepsilon_{p,t}^g \sim \mathbb{N}(0,1).$$

The size of the disaster is determined by ζ_g, and $\bar{\pi}_1^g = \frac{\bar{p}^g}{1+\bar{p}^g-\bar{q}^g}$ is the unconditional probability of the disaster. Following Gourio (2012), capital is destroyed when the disaster occurs. Let k_t denote the inherited stock of capital and i_t denote investment. The capital stock evolves according to

$$k_{t+1} = e^{-\zeta_g v_{g,t+1}}((1-\delta)k_t + i_t - \phi(i_t/k_t)k_t).$$

The functional form of the adjustment cost follows Jermann (1998) and is given by

$$\phi(i_t/k_t) = i_t/k_t - (\mu_1 + \tfrac{\mu_2}{1-1/\nu}(i_t/k_t)^{1-1/\nu}),$$

where $\mu_1 = (\bar{g} - 1 + \delta)/(1-\nu)$ and $\mu_2 = (\bar{g} - 1 + \delta)^{1/\nu}$.

Final Goods Firm A representative firm maximizes profits by choosing investment (i_t), capital (k_t), labor (n_t), and oil (o_t) inputs. The firm produces a final good y_t using a Cobb-Douglas technology that aggregates labor and capital services, which are produced using a normalized CES production function that aggregates capital and oil with elasticity of substitution σ.

The firm's profit maximization problem is given by

$$V_t = \max_{n_t, k_{t+1}, o_t, i_t} y_t - i_t - p_t^o o_t - w_t n_t + E_t[x_{t+1} V_{t+1}]$$

subject to

$$k_{t+1} = e^{-\zeta_g v_{g,t+1}}((1-\delta)k_t + i_t - \phi(i_t/k_t)k_t),$$
$$y_t = y_0(a_t n_t)^{1-\xi}\left((1-\alpha)(k_t/k_0)^{1-1/\sigma} + \alpha(o_t/o_0)^{1-1/\sigma}\right)^{\xi/(1-1/\sigma)},$$

where δ is the depreciation rate of capital, $1-\xi$ is the share of labor in gross output, and α controls the share of oil in the capital services aggregate. The terms y_0, k_0, and o_0 are scale factors that are set so that α is equal to the cost share of oil in the capital services aggregator. These normalizations do not affect the results but dramatically simplify the model calibration.[10]

The first-order conditions for the firm's problem are given by

$$w_t = (1-\xi)y_t/n_t,$$
$$p_t^o = \xi\alpha\frac{(o_t/o_0)^{1-1/\sigma}}{(1-\alpha)(k_t/k_0)^{1-1/\sigma}+\alpha(o_t/o_0)^{1-1/\sigma}}\frac{y_t}{o_t},$$
$$E_t[x_{t+1}r_{t+1}^i] = 1,$$

where

$$r_{t+1}^i \equiv e^{-\zeta_g v_{g,t+1}}(r_{t+1}^k + (1-\delta+\mu_1+\tfrac{\mu_2}{\nu-1}(i_{t+1}/k_{t+1})^{1-1/\nu})p_{t+1}^k)/p_t^k,$$
$$r_t^k \equiv \xi(1-\alpha)\frac{(k_t/k_0)^{1-1/\sigma}}{(1-\alpha)(k_t/k_0)^{1-1/\sigma}+\alpha(o_t/o_0)^{1-1/\sigma}}\frac{y_t}{k_t},$$
$$p_t^k \equiv \frac{1}{1-\phi'(i_t/k_t)} = \frac{1}{\mu_2}(\tfrac{i_t}{k_t})^{1/\nu}.$$

Oil Production and Oil Disasters The production of oil is exogenous and given by

$$o_t^s = a_t^o e_t.$$

This assumption is commonly used in DSGE models of the oil market, given the paucity of data for the oil sector. The permanent component, a_t^o, reflects factors that influence the productive potential of the oil sector, including the evolution of oil reserves and technological progress that increases the ability of the sector to extract oil from current reserves. The transitory component reflects temporary changes in the production of oil not directly connected with those factors, such as weather-driven or geopolitical supply disruptions. The effect of oil production disasters on

[10] A more detailed discussion of normalized CES production functions can be found in Klump et al. (2012).

global oil production is modeled as transitory, given evidence that geopolitical supply disruptions have not had long-lasting effects on global oil production.

The permanent component is cointegrated with productivity in the rest of the economy,

$$a_t^o = \kappa_0 g_t^{\kappa_1} \epsilon_{t-1}^{\kappa_2} a_{t-1}^o,$$

where $\epsilon_t = a_t/a_t^o$, κ_1 determines the impact response of a growth shock on a_t^o, and κ_2 affects the speed at which a_t^o converges to a_t. This setup allows for a slow response of oil production to productivity growth shocks in the rest of the economy, which is a key feature of the data.[11]

We allow for geopolitically driven oil production shortfalls in the transitory component,

$$\ln e_t = (1-\rho_e)\ln \bar{e} + \rho_e \ln e_{t-1} + \sigma_e \varepsilon_{e,t} - \zeta_e(v_t^e - \bar{\pi}_1^e), \quad \varepsilon_{e,t} \sim \mathbb{N}(0,1).$$

The indicator variable v_t^e equals 1 if an oil production disaster occurs and 0 otherwise. The transition matrix for v_t^e is summarized by

$$\Pr(v_{t+1}^e = 1 | v_t^e = 1) = \bar{q}^e, \quad \Pr(v_{t+1}^e = 1 | v_t^e = 0) = p_t^e,$$

where the probability of an oil disaster follows

$$\ln p_t^e = (1-\rho_p^e)\ln \bar{p}^e + \rho_p^e \ln p_{t-1}^e + \sigma_p^e \varepsilon_{p,t}^e, \quad \varepsilon_{p,t}^e \sim \mathbb{N}(0,1).$$

The size of the disaster is determined by ζ_e, and $\bar{\pi}_1^e = \frac{\bar{p}^e}{1+\bar{p}^e-\bar{q}^e}$ is the unconditional probability of the disaster. This process ensures that oil disasters have large but temporary effects on oil production.

Oil Storage A representative oil storage firm maximizes profits by choosing inventories, s_{t+1}, and how much oil to supply to the final goods firm, o_t. The firm's maximization problem is given by

$$V_t^o = \max_{o_t, s_{t+1}} \; p_t^o o_t + E_t[x_{t+1} V_{t+1}^o]$$

[11]When $\kappa_1 = 1$ and $\kappa_2 = 0$, $a_t^o = a_t$, so the production of oil responds immediately to changes in productivity elsewhere in the economy. This special case corresponds to the assumption made in Gao et al. (2022). We are the first to account for cointegration in a DSGE model with oil, but cointegrated TFP processes have been used in two-country international real business cycle models (e.g., Rabanal et al., 2011).

subject to

$$s_{t+1} = (1-\omega)s_t + o_t^s - o_t - \tfrac{\pi}{2}(s_t/a_t)^{-2}a_t,$$

where ω is the cost of storage. Following Gao et al. (2022), there is an adjustment cost, π, that prevents stockouts ($s = 0$) from occurring, as they are not observed in the global oil market.

The first-order condition for the storage firm is given by

$$1 = E_t[x_{t+1} r_{t+1}^s],$$

where

$$r_{t+1}^s \equiv ((1-\omega+\pi(s_{t+1}/a_{t+1})^{-3})p_{t+1}^o)/p_t^o.$$

Household A representative household maximizes the present discounted value of utility by choosing consumption, c_t, hours worked, n_t, bond holdings, b_{t+1}, and equity shares, s_{t+1}^e, which have unit net supply. The household has Epstein-Zin recursive preferences to distinguish between risk aversion, γ, and the intertemporal elasticity of substitution, ψ (see Epstein and Zin, 1989).

The household's maximization problem is given by

$$J_t = \max_{c_t, n_t, s_{t+1}^e, b_{t+1}} \left((1-\beta)u_t^{1-1/\psi} + \beta(E_t[J_{t+1}^{1-\gamma}])^{\frac{1-1/\psi}{1-\gamma}}\right)^{\frac{1}{1-1/\psi}}$$

subject to

$$u_t = c_t^{\chi}(a_t(1-n_t))^{1-\chi},$$

$$c_t + p_t^e s_{t+1}^e + b_{t+1}/r_t = w_t n_t + (p_t^e + d_t^e)s_t^e + b_t,$$

where β is the discount factor, χ is a preference parameter, p_t^e is the equity price, r_t is the risk-free rate, w_t is the wage rate, and d_t^e are dividends from firm ownership.

The first-order conditions for the household are given by

$$\chi w_t(1-n_t) = (1-\chi)c_t,$$

$$1 = E_t[x_{t+1} r_t],$$

$$1 = E_t[x_{t+1} r_{t+1}^e],$$

where

$$r^e_{t+1} \equiv (p^e_{t+1} + d^e_{t+1})/p^e_t,$$
$$x_{t+1} \equiv \beta(u_{t+1}/u_t)^{1-1/\psi}(c_t/c_{t+1})(J_{t+1}/z_t)^{1/\psi-\gamma},$$
$$z_t \equiv (E_t[J^{1-\gamma}_{t+1}])^{1/(1-\gamma)}.$$

The equity risk premium is defined as

$$r^{ex}_t \equiv r^e_t - r_{t-1}.$$

Market Clearing Following Jermann (1998) and Gourio (2012), both the final goods and storage firms issue bonds to finance their assets, where ϑ determines leverage. Aggregate firm dividends are given by

$$d^e_t = d^f_t + d^s_t - \vartheta(E_{t-1}k_t - \tfrac{1}{r_t}E_t k_{t+1}) - \vartheta(E_{t-1}s_t - \tfrac{1}{r_t}E_t s_{t+1}),$$

where $d^f_t = y_t - i_t - p^o_t o_t - w_t n_t$ and $d^s_t = p^o_t o_t$.

Asset market clearing implies that $s^e_t = 1$ and total bond issuance is given by

$$b_t \equiv b^f_t + b^s_t = \vartheta(E_{t-1}k_t + E_{t-1}s_t).$$

Market clearing in the goods market implies

$$c_t + i_t = y_t.$$

Due to the stochastic trend in productivity, we detrend the model by defining $\tilde{x}_t = x_t/a_t$. The detrending process introduces the growth terms $g_t = a_t/a_{t-1}$ and $g_{o,t} = a^o_t/a^o_{t-1}$. Appendix D provides the detrended equilibrium system of equations.

Uncertainty We follow Plante et al. (2018) and Bernstein et al. (2024) and define output uncertainty as the conditional volatility of log output growth, which is given by

$$\mathcal{U}^y_t = \sqrt{E_t[(\ln(y_{t+1}/y_t) - E_t[\ln(y_{t+1}/y_t)])^2]}.$$

This definition is equivalent to the uncertainty surrounding the level of log output because y_t is known at time t and cancels from the definition of $\mathcal{U}_t^y$. We define oil price uncertainty, $\mathcal{U}_t^{p_o}$, analogously as the uncertainty surrounding $\ln(p_{t+1}^o/p_t^o)$ at time t.

4.2 SOLUTION METHOD Modeling the oil sector considerably increases the computational cost of solving the model compared to a model that only includes macroeconomic risk. Our model has 8 state variables $(\ln e_t, k_t, s_t, v_t^g, v_t^e, \ln p_t^g, \ln p_t^e, \epsilon_{t-1})$, 5 of which are related to the oil market. There are 4 continuous and 2 discrete shocks. The existence of time-varying disaster risk prevents the use of perturbation methods, which are common in the stochastic volatility literature. We therefore employ a nonlinear solution method. Specifically, the model is solved using the policy function iteration algorithm described in Richter et al. (2014), which is based on the theoretical work in Coleman (1991). The algorithm minimizes the Euler equation errors on each node in the state space and computes the maximum change in the policy functions. It then iterates until the maximum change is below a specified tolerance. Appendix C describes the solution method in more detail.

4.3 CALIBRATION Given the paucity of global macroeconomic data, we calibrate the model under the assumption that the world economy resembles the U.S. economy. While this model abstracts from many features of the actual global economy, it provides a useful benchmark and a natural starting point for studying the role of downside risk in the global economy. The parameters shown in Table 1 are informed by moments in the data and the related literature.[12] The moments are computed using data from 1975Q1 to 2019Q4. Appendix B documents our data sources.

The discount factor β is set to 0.9945 to match the mean real interest rate. The relative risk aversion coefficient, γ, and intertemporal elasticity of substitution are set to 10 and 2, respectively, consistent with Gourio (2013), Croce (2014), Gao et al. (2022), and several other recent studies.[13]

The elasticity of substitution between capital and oil, σ, is set to 0.13 to match the volatility

[12]Estimation using Bayesian methods or the simulated method of moments is not possible due to the high dimensionality of the model. Even when using a supercomputer with $10{,}000$ cores, it takes multiple days to solve our model.

[13]Swanson (2018) shows how to compute risk aversion under recursive preferences with an endogenous labor supply. Under our utility kernel, γ corresponds to risk aversion over consumption and leisure.

Table 1: Model calibration

Parameter	Value	Target
Discount Factor (β)	0.9945	$E(r)$
Risk Aversion (γ)	10	Gao et al. (2022), Croce (2014)
Intertemporal Elasticity (ψ)	2	Gao et al. (2022), Croce (2014)
Capital-Oil Elasticity of Substitution (σ)	0.13	$SD(\Delta p^o)$
Capital Depreciation Rate (δ)	0.025	Depreciation on fixed assets and durables
Capital-Oil Share of Production (ξ)	0.4043	Total economy labor share
Investment Adjustment Cost (ν)	1.7	$SD(\Delta i)$
Oil Inventory Depreciation Rate (ω)	0.025	Casassus et al. (2018), Gao et al. (2022)
Mean Growth Rate ($\bar{g}$)	1.0039	$E(\Delta y)$
Leverage (ϑ)	0.9	$SD(r^{ex})$
Utility Weight on Leisure (χ)	0.47	Frisch labor supply elasticity of 2
Elasticity of Oil Supply to TFP (κ_1)	0	Newell and Prest (2019)
Oil Supply Adjustment Speed to TFP (κ_2)	0.05	Half life of 3.5 years
Growth Shock SD (σ_g)	0.01	$SD(\Delta y)$
Oil Production Shock Persistence (ρ_e)	0.6	$AC(\Delta o^s)$
Oil Production Shock SD (σ_e)	0.012	$SD(\Delta o^s)$
Growth Disaster Size (ζ_g)	0.025	$E(r^{ex})$
Probability of Entering Growth Disaster ($\bar{p}_g$)	0.0025	Occurs in expectation every 100 years
Probability of Exiting Growth Disaster ($\bar{q}_g$)	0.9	Gourio (2012)
Growth Disaster Probability Persistence (ρ_{pg})	0.8	$SD(\mathcal{U}_y)$
Growth Disaster Probability SD (σ_{pg})	1.2	$AC(\mathcal{U}_y)$
Oil Production Disaster Size (ζ_e)	0.05	Kilian (2008)
Probability of Entering Oil Disaster ($\bar{p}_e$)	0.015	Occurs in expectation every 15 Years
Probability of Exiting Oil Disaster ($\bar{q}_e$)	0.67	Expected duration of 3 quarters
Oil Disaster Probability Persistence (ρ_{pe})	0.8	$SD(\mathcal{U}_{p^o})$
Oil Disaster Probability SD (σ_{pe})	1.2	$AC(\mathcal{U}_{p^o})$

of the growth rate of oil prices. Backus and Crucini (2000) adopt the same functional form of the production function and use a similar value (0.09). The Cobb-Douglas weight on capital services (ξ) is set to match the average labor share for the total economy. The investment adjustment cost parameter, ν, is set to match the volatility of per capita investment growth. The capital depreciation rate, δ, matches the annual average rate of depreciation on private fixed assets and durable goods. The oil inventory depreciation rate, ω, is set to 0.025 following Casassus et al. (2018) and Gao et al. (2022). As in other studies including Basu and Bundick (2017), the leverage parameter, ϑ, is set to 0.9 to help match the volatility of the equity premium.

The mean growth rate of productivity, $\bar{g}$, is set to 1.0039 to match the average growth rate of per capita real GDP. The standard deviation for the growth shock, σ_g, is set to 0.01 to help match the volatility of GDP growth. The calibration of the growth disaster parameters is guided by several moments in the data as well as the parameter choices in Gourio (2012). We set the size of the disaster, ζ_g, to 0.025 to match the mean equity premium. The mean probability of entering the disaster state, $\bar{p}_g$, is set to 0.0025, which implies that these disasters happen once every 100 years in expectation. The persistence, ρ_{pg}, and standard deviation, σ_{pg}, of this probability are set to 0.8 and 1.2, respectively, to help match the autocorrelation and volatility of output uncertainty. The fixed probability of exiting a growth disaster, $\bar{q}_g$, is set to 0.9, in line with Gourio (2012). This value implies that growth disasters, on average, last 2.5 years. As shown in Appendix E, the responses to an average growth disaster are very similar to those reported in Gourio (2012), who documents that his responses resemble the empirical estimates in Barro et al. (2013).

The value of κ_1 is set to 0, implying that productivity in the oil sector is unresponsive to changes in productivity in the rest of the economy within the first quarter. This is consistent with the view that oil production in the short run is determined entirely by geological constraints (see Newell and Prest, 2019). We set κ_2 to 0.05, so the half-life of the deviation between a_t^o and a_t is 3.5 years. The persistence and standard deviation of the oil production process, ρ_e and σ_e, are set to 0.6 and 0.012, respectively, to match the autocorrelation and volatility of global oil production. We set the size of the oil production disaster, ζ_e, to 0.05, in line with evidence in Kilian (2008). The mean probability of entering the oil disaster state, $\bar{p}_e$, is set to 0.015 so that disasters occur every 15 years in expectation, motivated by historical data on major OPEC supply disruptions. The persistence, ρ_{pg}, and standard deviation, σ_{pg}, of this probability are set to 0.8 and 1.2, respectively, to help match the autocorrelation and volatility of oil price uncertainty. The fixed probability of exiting an oil production disaster, $\bar{q}_g$, is set to 0.67 so that it lasts, on average, for 3 quarters, which implies a reduction in global oil production for about 3 years with the shortfall diminishing over time.[14]

[14] It may seem that options data could be used to help with the calibration. This is not the case. One challenge is that tail probabilities estimated from equity options as in Barro and Liao (2021) do not help quantify macroeconomic tail risk, but only equity risk. The distinction between financial risk and macroeconomic risk has been emphasized in Gao et al. (2022) and Ludvigson et al. (2021). Likewise, oil disaster probabilities are not be recoverable from oil options because these prices reflect both oil and macroeconomic disaster risk in unknown combinations.

Table 2: Data and simulated moments

Moment	Data	Model	Moment	Data	Model
$E(\Delta y)$	0.39	0.31	$SD(\Delta p^o)$	14.39	14.73
$E(s/o)$	0.97	0.95	$SD(r^{ex})$	8.29	4.85
$E(p^o o/y)$	0.045	0.049	$SD(\mathcal{U}_y)$	14.51	17.86
$E(r^{ex})$	2.18	2.21	$SD(\mathcal{U}_{p^o})$	29.95	34.87
$E(r)$	0.22	0.18	$AC(\Delta y)$	0.32	0.40
$SD(\Delta y)$	0.74	1.00	$AC(\Delta o^s)$	-0.11	0.08
$SD(\Delta i)$	1.95	2.03	$AC(\mathcal{U}_y)$	0.87	0.79
$SD(\Delta o^s)$	2.01	2.03	$AC(\mathcal{U}_{p^o})$	0.93	0.80

Notes: The model is calibrated to data from 1975Q1-2019Q4. $SD(\mathcal{U}_y)$ and $SD(\mathcal{U}_{p^o})$ have been normalized by $SD(\Delta y)$ and $SD(\Delta p^o)$, respectively, to be consistent with the normalization in Jurado et al. (2015).

To compute the model-implied moments, we simulate the model $10{,}000$ times, each with 180 periods to match the length of the quarterly data used to calibrate the model. We calculate moments of interest in each simulated data set and then compute the average moments across all simulations. Table 2 compares the data and model-implied moments. The model closely matches most of the targeted moments. This includes moments related to oil market dynamics (e.g., the standard deviation oil price growth, the standard deviation and autocorrelation of oil production growth, and the oil expenditure share), real activity (e.g., the standard deviation and autocorrelation of output growth and the standard deviation of investment), asset prices (e.g., the mean risk-free rate and equity risk premium), and uncertainty (e.g., the standard deviations of output and oil price uncertainty). Jointly matching all four of these key aspects of the economy gives us confidence that the model provides a good description of oil market, real activity, and uncertainty dynamics.

4.4 DISCUSSION Our model incorporates precautionary savings by households in response to higher oil price uncertainty as well as storage, the two main economic mechanisms that are thought to propagate oil price uncertainty shocks. While we do not model real options arising from irreversible investment as in Bernanke (1983), our model features limited substitutability between capital and oil. This feature causes the expected return on investment to decline when the probability of an oil production disaster increases, generating recessionary effects in the model.

Although Bernanke's theoretical analysis is often cited in support of models of oil price volatility shocks, it is not well appreciated that Bernanke was not modeling a monthly or quarterly oil price volatility shock. Rather, he envisioned agents being uncertain about whether the price of oil would permanently move to a higher level or not, which is a different thought experiment. In his model there are two types of capital that differ by their oil efficiency. The irreversibility of the investment decision causes risk averse agents to postpone the acquisition of either type of capital. The difficulty in generalizing this model to general equilibrium is that it requires aggregating different types of capital across many firms.

A closely related model that deals with the aggregation of different types of capital in general equilibrium was proposed by Atkeson and Kehoe (1999). In their putty-clay model there is a continuum of capital goods index by their oil efficiency. Existing capital goods use oil in fixed proportions, so, in the short run, there is no substitutability between capital and oil. However, firms may invest in new capital with different oil efficiency in response to changes in the price of oil. Although this point is not the focus of Atkeson and Kehoe (1999), their model implies that higher oil price uncertainty would reduce investment, as discussed in Plante and Traum (2012).

The reason we do not incorporate the putty-clay framework within our model is that two key assumptions made by Atkeson and Kehoe (1999) do not hold in our model. One is that the price of oil is exogenous; the other is that under their assumptions oil consumption does not respond to the price of oil on impact. These assumptions not only allow Atkeson and Kehoe to abstract from storage, but they allow them to aggregate across different types of capital without the need to track the distribution of capital types. The fact that the infinite-dimensional state space of capital stocks in the model can be reduced to a one-dimensional space facilitates the solution of their model.

In contrast, in our model the price of oil is endogenously determined. Suppose, for example, that there is an oil supply shock. In that case, we must add storage to the model because otherwise equilibrium in the oil market is unattainable. If oil consumption is predetermined and hence unresponsive to the oil price fluctuations caused by the oil supply shock, oil inventories must absorb any imbalances in the oil market each period. It can be shown that, as a result, the oil inventory moments of the simulated model data differ substantially from the oil inventory moments in the actual data. It may seem that this problem could be addressed by dropping the assumption that oil consumption is unresponsive to the price of oil, but this would render the capital stock intractable, which is why we do not consider the putty-clay framework in our model. However, our model with disaster risk generates investment and output responses that are qualitatively consistent with those in models of irreversible investment. The reason is that in our model risk averse agents are reluctant to invest given the limited substitutability between capital and oil.

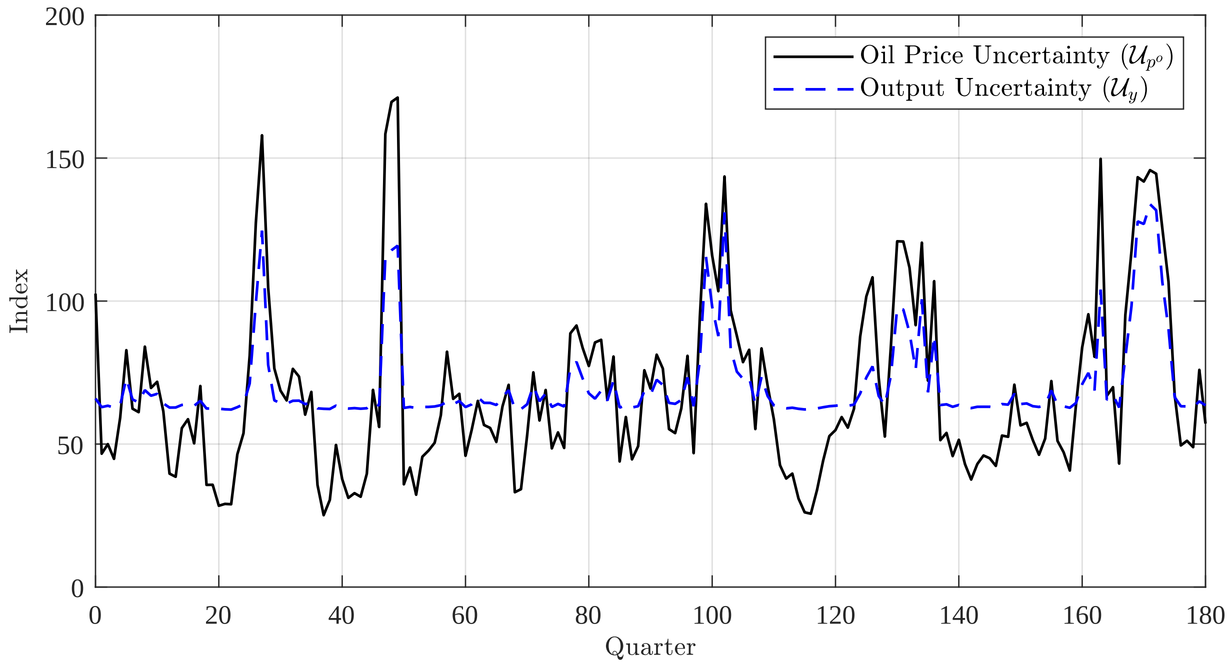
5 WHAT IS THE ROLE OF UNCERTAINTY SHOCKS?

As discussed in Section 3, economists' intuition about the impact of oil price uncertainty shocks continues to be based on insights from partial equilibrium models or from general equilibrium models with exogenous oil price volatility shocks and no fluctuations in macroeconomic uncertainty. This section examines the role of uncertainty shocks within the context of a general equilibrium model with endogenous time-varying uncertainty about the price of oil and output.

5.1 RELATIONSHIP BETWEEN OIL PRICE UNCERTAINTY AND OUTPUT UNCERTAINTY The DSGE model provides a useful benchmark for what we would expect the relationship between oil price uncertainty and output uncertainty to be in the data. The simulated data in Figure 2 serve three purposes. First, it shows that the DSGE model is capable of generating fluctuations in oil price uncertainty that are qualitatively similar to those shown in Figure 1. Second, it illustrates that output uncertainty and oil price uncertainty are not independent. In particular, major increases in oil price uncertainty tend to be associated with major increases in output uncertainty. The model helps us understand to what extent this relationship is driven by exogenous shifts in macroeconomic risk, exogenous shifts in geopolitical risk in oil markets, or by other shocks. Third, it shows that oil price uncertainty tends to be more volatile than output uncertainty.

5.2 TRANSMISSION OF UNCERTAINTY SHOCKS In practice, economic agents will rarely witness disasters. Typically, disasters matter only because there is a probability that they may be

Figure 2: Simulation draw of uncertainty series



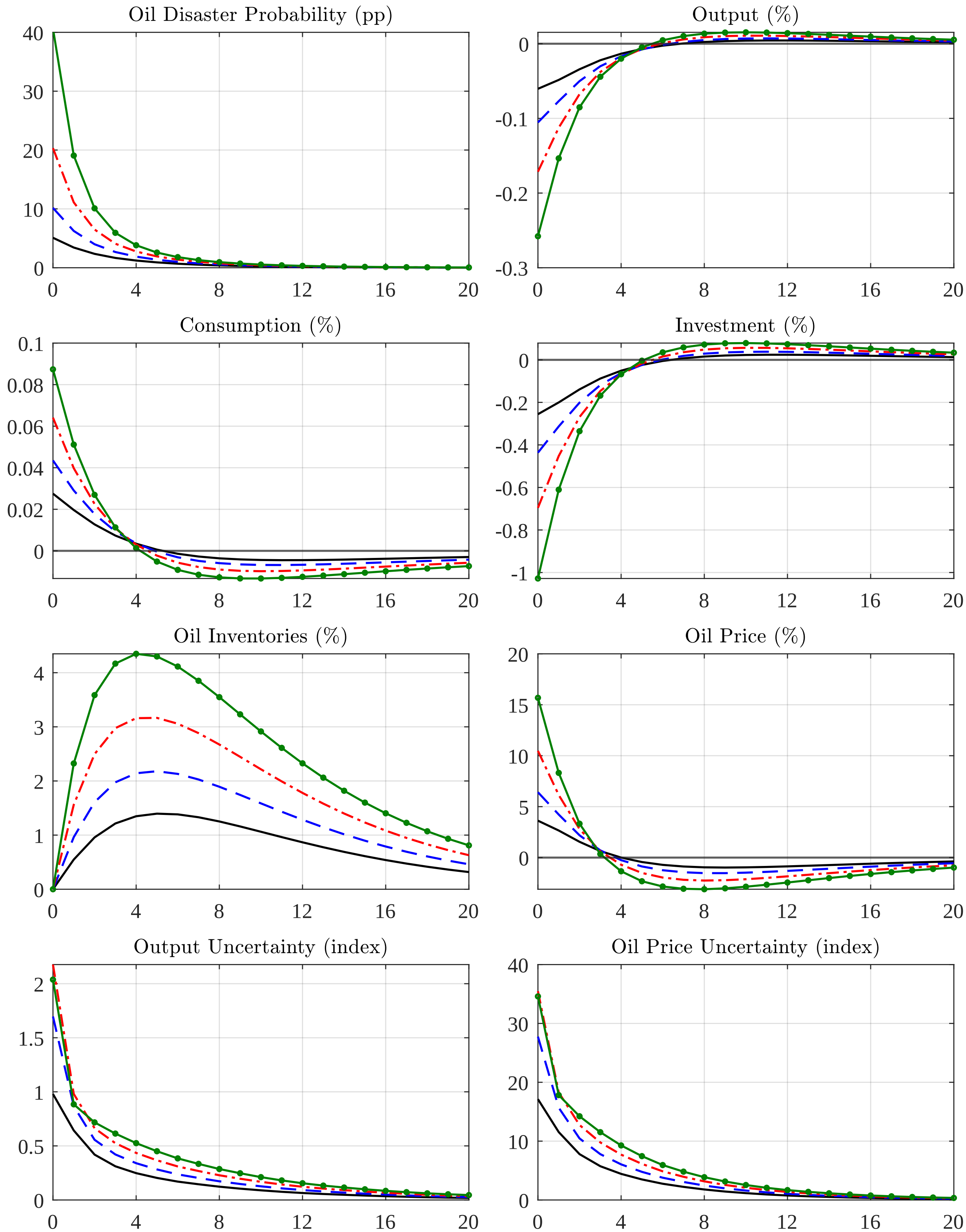
Notes: $\mathcal{U}_y$ and $\mathcal{U}_{p^o}$ have been normalized by $SD(\Delta y)$ and $SD(\Delta p^o)$, respectively, to be consistent with Jurado et al. (2015).

realized in the future. As we highlight in this section, changes in the probability of a disaster, which generate fluctuations in uncertainty, are sufficient to create large responses in the oil market and the macroeconomy even when no disasters actually occur.

Oil Disaster Probability Figure 3 shows the responses of key model variables when the exogenous oil disaster probability is increased by 5, 10, 20, and 40 percentage points (pp), respectively. Higher odds of an oil production disaster generate stronger precautionary storage demand, reflected in a persistent build-up of oil inventories. This raises the price of oil, with the initial increase ranging from about 4% for a 5pp shock to the disaster probability to 16% for a 40pp shock.

The probability shock reduces investment, with the effect ranging from a 0.26% drop for a 5pp shock to just over 1% for a 40 pp shock. The negative effect on investment arises for two distinct reasons. First, an oil production disaster, if it were to occur, would reduce the return to capital, since oil and capital are complements in production of the final good. Thus, the higher probability of such a disaster lowers the expected return from investing in capital. Second, the

Figure 3: Responses to an oil production disaster probability shock



Notes: Responses in deviations from the baseline. Simulations assume no disasters are realized.

return to capital today declines because higher precautionary demand for oil inventories raises the price of oil. Together, these two effects push down output, but the overall magnitude is modest since the investment share in output is small and there is a slight increase in consumption.

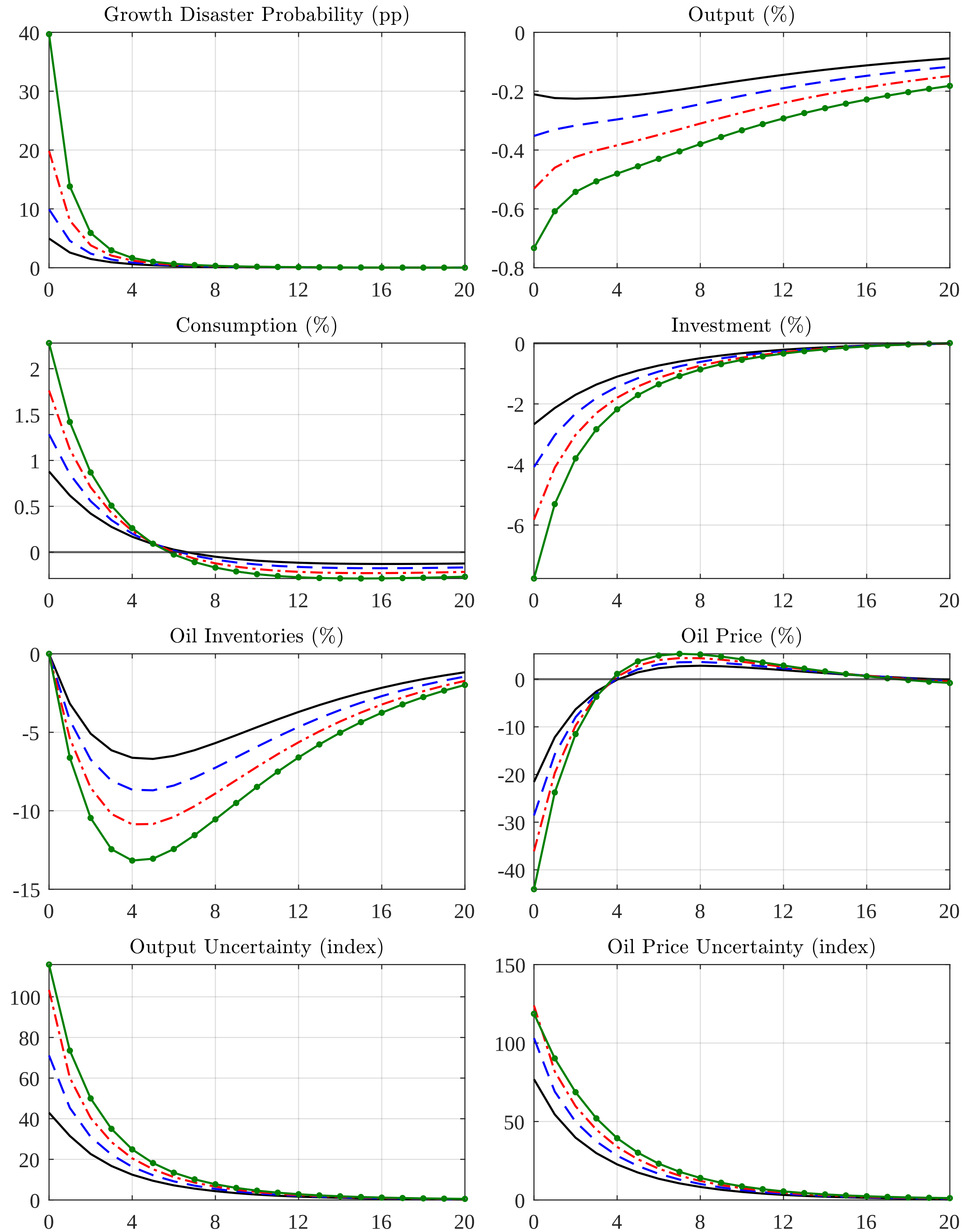
The consumption response is marginally positive just like the response to macroeconomic disaster risk in Gourio (2012), indicating that the precautionary savings motive is not the primary driver of the consumption response. Mechanically, this occurs because households in the model lack alternative investment opportunities. With a temporarily lower incentive to invest, households have no choice but to consume more today and less in the future.[15]

Higher odds of an oil production disaster raise both output uncertainty and oil price uncertainty, but the effects on oil price uncertainty are an order of magnitude larger. For example, a 5pp increase in the probability of an oil disaster raises the output uncertainty index only by 1, but the oil price uncertainty index by 17. Thus, the oil disaster probability shock looks in some ways like an exogenous oil price uncertainty shock. However, as discussed later, the downside risk inherent in the oil production disaster leads to very different responses compared to a stochastic volatility shock to oil production.

The model shows that the recessionary effects of the probability shock are reflected in output immediately, but are short-lived. The responses do not change proportionately with the shock size. For example, the responses of output and the price of oil to a 20pp increase in the oil disaster probability are only 2.8 times larger than when the probability rises by 5pp. This result highlights that exogenous variation in uncertainty transmits to the macroeconomy nonlinearly. Raising the disaster probability beyond a certain point lowers oil price uncertainty because the agents in the model perceive the disaster as increasingly likely. At the same time, the recessionary effect of the disaster probability shock strengthens.

[15]The sign of the consumption response could change in a model with additional frictions. We are unable to explore this possibility because modeling these frictions would increase the number of state variables in the model to the point of making the already unusually large DSGE model intractable. This is not a first-order concern for our analysis since the overall effect on real GDP is clearly negative, reflecting the response of investment. Thus, as long as the consumption response is modest, its sign is largely immaterial for assessing the recessionary effect of oil disaster probability shocks.

Figure 4: Responses to a growth disaster probability shock



Notes: Responses in deviations from the baseline. Simulations assume no disasters are realized.

Growth Disaster Probability A growth disaster acts like a negative demand shock in the oil market by reducing real activity and lowering oil demand. This plays a key role in understanding how the oil market responds to an increased probability of an output growth disaster.

Figure 4 shows the responses when the exogenous disaster probability increases by 5, 10, 20, and 40pp, respectively. An increase in the probability of a growth disaster has substantial, albeit short-lived, effects on the price of oil. For example, a 5pp increase in the probability causes the price of oil to decline by 22% on impact. There are two related but somewhat distinct mechanisms at play. First, as in Gourio (2012), the higher probability directly reduces the expected return to capital, which lowers oil demand today since capital and oil are complements. Second, lower current and expected oil demand also reduces the expected return from holding oil inventories. As a result, oil currently held in storage is sold off, pushing down the oil price even further.

Although the reduction in the price of oil is beneficial for the economy, the net effect of this probability shock on output is negative. In fact, the decline in output is much larger than from the oil disaster probability shock of the same magnitude. This is because the growth probability shock transmits directly to output rather than through the share of oil in output, which is small. In addition, the response is much more persistent than the response to the oil disaster probability shock.

In related work, Gourio (2012) showed that an increase in the probability of a growth disaster causes the uncertainty about equity prices to rise. Our results show that the same shock also has a major effect on output uncertainty and oil price uncertainty. Thus, the growth disaster probability shock acts in some ways like an exogenous uncertainty shock. As with the oil disaster probability shock, however, the downside risk inherent in the growth disaster has very different quantitative implications than a stochastic volatility shock.

As in Figure 3, the responses do not scale proportionately with the increase in the growth disaster probability. For example, a 5pp increase leads to a 22% decline in the price of oil, whereas the oil price declines by 36% when the probability rises by 20pp. This is true for the other variables, as well, once again highlighting the nonlinearity in the transmission of uncertainty. As the growth disaster probability increases further, the recessionary effect strengthens but the response of oil

Table 3: Decomposition of key volatilities

Moment	Data	Model		
		Baseline	No Output Disaster Risk	No Output Disaster Risk or Oil Production Disaster Risk
$SD(\Delta y)$	0.74	1.00	0.64	0.63
$SD(\Delta i)$	1.95	2.03	1.02	0.92
$SD(\Delta o^s)$	2.01	2.03	2.00	1.35
$SD(\Delta p^o)$	14.39	14.73	5.70	2.08
$SD(r^{ex})$	8.29	4.85	0.29	0.29
$SD(\mathcal{U}_y)$	14.51	17.86	0.70	0.13
$SD(\mathcal{U}_{p^o})$	29.95	34.87	15.13	1.02

Notes: The models without disaster risk remove both the probability shock and the disaster state. $SD(\mathcal{U}_y)$ and $SD(\mathcal{U}_{p^o})$ have been normalized by $SD(\Delta y)$ and $SD(\Delta p^o)$ in the baseline model, respectively, to be consistent with Jurado et al. (2015).

price uncertainty declines, reflecting greater certainty about a reduction in output.

The key difference between the two disaster probability shocks is that the growth disaster probability shock has substantial effects on both uncertainty variables, whereas the oil disaster probability shock does not. Thus, comovement between oil price uncertainty and output uncertainty, as documented in Figure 2, tends to reflect shifts in macroeconomic risk rather than geopolitical risk.

5.3 How much volatility is due to output risk and geopolitical risk?

Table 3 shows that the model generally does an excellent job at capturing the volatility in the data. Dropping the output disaster risk from the DSGE model substantially lowers the ability of the model to explain the volatility in the data. The resulting model not only substantially understates the standard deviation of the two uncertainty series, but it also understates most other data moments.

Dropping both output disaster risk and the geopolitical risk underlying oil production disasters from the model further lowers the volatilities. In particular, it removes virtually all variability in the two uncertainty measures and much of the variability in the real price of oil. However, it has little effect on the volatility of macroeconomic aggregates, highlighting the limited role geopolitical risk plays in generating macroeconomic volatility.

There are two key takeaways from these results. First, output disaster risk is a major driver of fluctuations in oil price uncertainty, highlighting that oil price uncertainty is not exogenous as is often assumed in the literature. Second, oil production disaster risk is not a major driver of fluctuations in macro aggregates or output uncertainty, suggesting that oil price uncertainty does not play a major role in driving business cycles.[16]

5.4 ALTERNATIVE MODEL SPECIFICATIONS

In this section, we highlight key features of our model by considering alternative specifications. We first illustrate the central role of oil storage. We then contrast our model with earlier models incorporating stochastic volatility shocks.

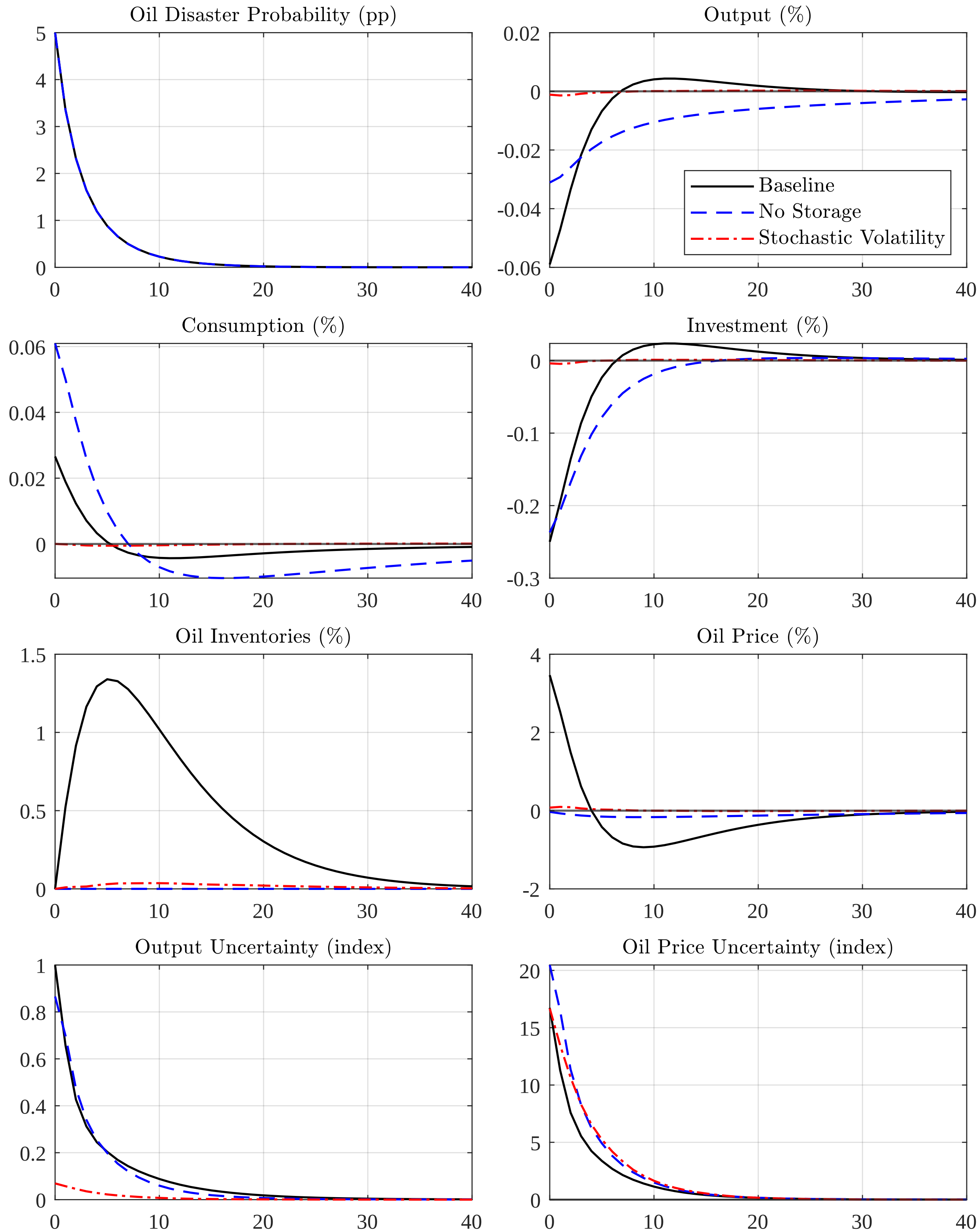
Role of storage There are important movements in oil inventories whenever the probability of a disaster increases. These movements affect the price of oil and, therefore, the evolution of macroeconomic aggregates and uncertainty. In this section, we investigate how important storage is for those responses by comparing the baseline results to those from a model without storage.

Figure 5 shows the responses for the oil disaster probability shock. The key difference is that the price of oil declines slightly in the model without storage, whereas it increases substantially in the baseline model. In the absence of storage, the response of the oil price is driven entirely by the expectation of lower output, which reduces the demand for oil and modestly lowers its price. Given the muted response of the price of oil, the impact effect on output is also reduced. However, even in the absence of storage, the effect on oil price uncertainty remains substantial.

Figure 6 shows that storage also plays a key role in the propagation of a growth disaster probability shock. In the model with storage, a higher probability of a disaster leads to a reduction in oil inventories due to the greater likelihood of a recession. This causes a substantial decline in the price of oil, which does not occur in the no-storage model. Since a lower oil price offsets some of the negative effects of this shock on the macroeconomy, the impact effect on output is larger when the model does not contain storage. Oil price uncertainty is much less responsive to a change in the growth disaster probability. Overall, our results demonstrate that storage is a key ingredient for

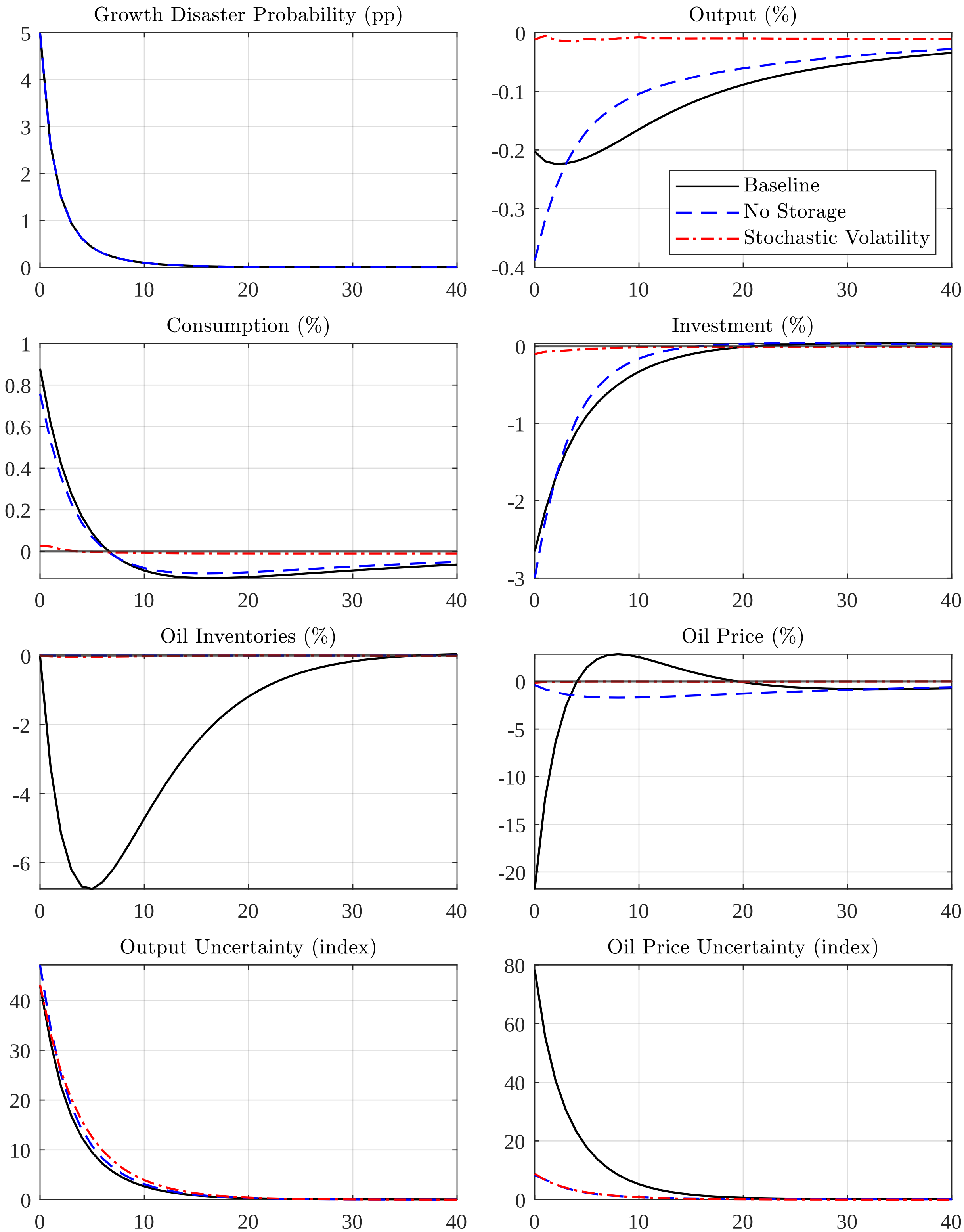
[16]The analysis in Table 3 conditions on the same calibration as the baseline model. Recalibrating the model in the last column results in a systematic mismatch with the data moments. While raising the volatility of the shocks to oil production and productivity growth allows the model to match $SD(\Delta o^s)$ and $SD(\Delta y)$, the recalibrated model is unable to match $SD(\Delta p^o)$ and $SD(\Delta i)$ or, for that matter, the volatilities of uncertainty.

Figure 5: Responses to an oil production disaster probability shock



Notes: Responses in deviations from the baseline. Simulations assume no disasters are realized.

Figure 6: Responses to a growth disaster probability shock



Notes: Responses in deviations from the baseline. Simulations assume no disasters are realized.

understanding the effects of uncertainty in both the oil market and the macroeconomy.

Role of downside risk Stochastic volatility (SV) is an alternative way of generating time-varying oil price uncertainty that has been used in previous studies (e.g., Başkaya et al., 2013; Gao et al., 2022; Plante and Traum, 2012).[17] In this section, we compare the results from the baseline model to those from a model where uncertainty is generated by SV rather than time-varying downside risk.

Specifically, we introduce an exogenous volatility shock into productivity and oil production,

$$\ln g_t = \ln \bar{g} + \sigma_{g,t-1}\varepsilon_{g,t},$$

$$\ln e_t = (1-\rho_e)\ln \bar{e} + \rho_e \ln e_{t-1} + \sigma_{e,t-1}\varepsilon_{e,t},$$

$$\ln \sigma_{g,t} = (1-\rho_{sv}^g)\ln \bar{\sigma}_g + \rho_{sv}^g \ln \sigma_{g,t-1} + \sigma_{sv}^g \varepsilon_{sv,t}^g,$$

$$\ln \sigma_{e,t} = (1-\rho_{sv}^e)\ln \bar{\sigma}_e + \rho_{sv}^e \ln \sigma_{e,t-1} + \sigma_{sv}^e \varepsilon_{sv,t}^e,$$

where all shocks are standard normally distributed. The parameters of the level processes are unchanged. The persistence of both SV processes, ρ_{sv}^g and ρ_{sv}^e, is set to 0.8 to match the persistence of the disaster probability processes. The standard deviation of the growth SV shock, $\varepsilon_{sv,t}^g$ is set to 0.09 to match the volatility of output growth uncertainty. Analogously, the standard deviation of the oil production SV shock, $\varepsilon_{sv,t}^e$ is set to 0.22 to match the volatility of oil price uncertainty.

Figure 5 compares the responses to an SV shock in oil production, $\varepsilon_{sv,t}^e$, to the responses to our baseline oil disaster probability shock, $\varepsilon_{p,t}^e$. The $\varepsilon_{sv,t}^e$ shock is set so the SV specification generates the same impact effect on oil price uncertainty as the oil disaster probability shock. Qualitatively, these shocks move the model variables in the same direction, but there are quantitatively significant differences. While the SV shock generates sizable fluctuations in both output uncertainty and oil price uncertainty, it otherwise has little effect on the macroeconomy and the oil market.

The key difference between the two modeling choices is that an oil disaster introduces a source of downside risk into the economy because it makes a sharp drop in oil production more likely. As a result, when the probability of a disaster increases, it not only increases uncertainty but

[17] Stochastic volatility has also been used to model exogenous uncertainty shocks in a number of other settings including fiscal policy (Fernández-Villaverde et al., 2015), monetary policy (Mumtaz and Zanetti, 2013), household preferences (Basu and Bundick, 2017), and the global interest rate (Fernández-Villaverde et al., 2011).

also shifts the conditional mean of economic outcomes. This generates a stronger precautionary demand motive, which pushes up the price of oil. The SV shock, on the other hand, is akin to a mean-preserving spread. It generates a sizable increase in uncertainty but has little effect on the conditional mean. Hence, the responses of the price of oil and output are muted. A similar result holds when replacing the growth probability shock with a SV shock on productivity growth, as shown in Figure 6. We conclude that SV shocks are unable to capture the effects of increase in uncertainty associated with major geopolitical events that affect the oil market.[18]

6 Relationship to the Existing Literature

We are not the first to study the transmission of oil price uncertainty shocks within a DSGE model. For example, Başkaya et al. (2013) analyze the business cycle implications of oil price uncertainty based on a stylized oil-importing small open economy. One important difference is that oil price uncertainty is exogenous in their model. In contrast, our analysis is specifically designed to make explicit that oil price uncertainty in general depends on level shocks as well as macroeconomic uncertainty shocks. Allowing for both macroeconomic and oil price uncertainty is important when assessing their respective roles in explaining economic fluctuations, as illustrated in Section 5.3. Another important difference is their use of SV shocks. Our results in Section 5.4 show that models with SV are unable to match important features of geopolitically driven oil production events.

Our DSGE model shares some features with the theoretical model in Gao et al. (2022) in that both models allow the price of oil to be endogenously determined and are concerned with uncertainty shocks. One key difference is that their model features SV shocks to the production of oil and to productivity growth rather than downside risk. Another difference is that Gao et al. do not examine the response of oil price uncertainty to other shocks in their model, nor does their

[18] Similar to our responses for the SV specification, Gao et al. (2022) find small impacts of oil production volatility shocks in their baseline model. They show that the responses are amplified when markups are assumed to be time-varying such that the markup falls with oil consumption. The responses are even larger when level and volatility shocks to oil production are also assumed to be negatively correlated. The empirical support for these assumptions is not clear. For example, time-varying markups are a standard feature of micro-founded New Keynesian models. Plante and Traum (2014) examine such a model where oil is an intermediate input and find that SV shocks to the price of oil have a negligible effect on the macroeconomy, casting doubt on the reduced-form setup used in Gao et al. (2022).

work address the implications of the endogeneity of oil price uncertainty for empirical work.

The study related most closely to ours is perhaps Olovsson (2019) with the important difference that while Olovsson allows for oil storage and oil production disasters, his model does not allow the disaster probability to vary over time, nor does it include macroeconomic disasters. In addition, the focus of his paper is not on uncertainty. Our DSGE model also differs from the theoretical model in Ready (2018) who does not study responses to oil price uncertainty shocks, but reports comparative statics with respect to a regime shift in the slope of the oil production process.

Finally, what sets our work apart from all these earlier studies is that we address the implications of the endogeneity of oil price uncertainty for the identification of oil price uncertainty shocks in empirical work. This question, which we turn to next, has not been addressed in prior work.

7 Implications for Empirical Work

The model in Section 4 highlights that oil price uncertainty endogenously responds not only to exogenous uncertainty about future oil production driven by geopolitical events, but also to exogenous uncertainty about the future path of the economy. Thus, geopolitically driven oil price uncertainty shocks differ in general from shocks to observed oil price uncertainty, as measured by the method of Jurado et al. (2015) or the OVX oil volatility index. This result is consistent with practitioners' understanding that uncertainty about the oil price reflects not only uncertainty about future oil production, but also uncertainty about future oil consumption driven by macroeconomic uncertainty, financial uncertainty, and policy uncertainty. For example, market commentators in recent years have routinely highlighted the role of uncertainty about the prospects of the Chinese economy, the resolution of the Covid-19 pandemic, and whether the U.S. economy is about to enter a recession in assessing the uncertainty about the price of oil. Perhaps less obviously, the model also shows that oil price uncertainty responds to level shocks in the macroeconomy, as shown in the responses to a growth disaster in Appendix E. This result invalidates the premise of exogenous oil price uncertainty shocks even when there are no exogenous shocks to macroeconomic uncertainty.

Our results cast doubt on the ability of standard empirical models to correctly identify exogenous oil price uncertainty shocks. For example, VAR models with GARCH errors, as in Elder and Serletis (2010), have two potential shortcomings. First, they postulate that every level shock to the price of oil is also an oil price uncertainty shock. In our model, level and uncertainty shocks affect oil price uncertainty differently. Second, they assume that positive and negative oil price shocks both increase oil price uncertainty. This is again inconsistent with our model. For example, as shown in Appendix F, a decrease in the probability of an oil production disaster decreases both the price of oil and oil price uncertainty.

Models that break the link between level and uncertainty shocks such as the VAR model with SV in Jo (2014) have their own limitations. Our analysis implies that empirical measures of oil price uncertainty shocks and shocks to the level of the price of oil are not independent, as assumed in VAR models with SV. The reason is that oil price uncertainty is endogenous and may be driven by the same shocks as the price of oil. For example, an increase in the probability of a growth disaster not only raises oil price uncertainty, but also causes storage demand to increase, raising the real price of oil.[19] In addition, the assumption that the effects of a rise and decline in oil price volatility on output are symmetric is violated in our model.

The insight that oil price uncertainty is simultaneously determined with macroeconomic aggregates applies not only to GARCH and SV models but also to recursively identified linear VAR models that order oil price uncertainty first in the spirit of Bloom (2009), such as Gao et al. (2022).[20] Thus, the seemingly robust empirical evidence from linear and nonlinear VAR models that oil price uncertainty shocks substantially lower real activity must be viewed with caution.

8 CONCLUDING REMARKS

There has been growing interest in the impact of shifts in geopolitical risk in global commodity markets, in particular in the market for crude oil. In this paper, we introduced a theoretical

[19] Moreover, as shown in Section 5, while an increase in oil price uncertainty may be alternatively generated by an SV shock to oil production, only a disaster probability shock generates large recessionary effects. Thus, one would not expect large recessionary effects of shocks to oil price uncertainty when estimating VAR models with SV.

[20] Exploring alternative recursive orderings does not address this concern, as shown in Kilian et al. (2024).

model of the global economy that is designed to address the question of how this risk affects oil price uncertainty and the macroeconomy. Unlike previous studies, we modeled geopolitical risk as downside risk to oil production and allowed oil price and macroeconomic uncertainty to be determined endogenously. Our results show that shocks to the probability of a major decline in global oil production driven by geopolitical events have major effects on the oil market, whether the disaster is actually realized or not. These shocks cause declines in output and investment that dwarf those found with more traditional stochastic volatility shocks, but they are not a major driver of fluctuations in macroeconomic aggregates or of macroeconomic uncertainty because large probability shocks are rare.

Our analysis highlighted the importance of jointly modeling macroeconomic and geopolitical risk. We showed that oil price uncertainty responds to level shocks in the macroeconomy and to macroeconomic uncertainty shocks, in addition to geopolitically driven oil price uncertainty shocks. Shocks to the probability of growth disasters are not only recessionary, but they also play a major role in the determination of oil price uncertainty, which helps explain why oil price uncertainty has historically been associated with reductions in real activity. This fact, along with other implications of our model discussed in the paper, calls into question standard empirical models of the transmission of oil price uncertainty shocks that provide seemingly robust evidence supporting the conventional wisdom that oil price uncertainty plays a major role in driving the business cycle.

Our analysis suggests that economists and policymakers need to rethink the role of geopolitical oil price risk in the global economy and be cognizant of the interplay between oil price uncertainty, macroeconomic uncertainty, and the state of the economy. In recent years, there has been growing awareness of geopolitical risks in other commodity markets including critical minerals, natural gas, and agricultural commodities. While we focus on the market for crude oil, our modeling approach is also relevant for these other commodity markets.

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