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Oil price shocks and macroeconomic dynamics in resource-rich emerging economies under regime shifts ☆

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ABSTRACT

How do global oil price fluctuations affect macroeconomic activity and monetary policy in resource-rich emerging economies? This paper tackles this question by developing a unified emerging market/rest-of-the-world DSGE framework featuring Ricardian and Non-Ricardian households, an oil-producing sector, a fuel subsidy programme, and a regime-switching process. The model is estimated using Bayesian methods, allowing us to be agnostic regarding regime shifts in the monetary policy rule and oil price volatility. Using data for Nigeria, we find substantial empirical support for the regime-switching behaviour and discuss how macroeconomic implications of oil price shocks may vary depending on the nature of the shock, monetary policy responses, and the fuel subsidy policy in place. Apart from providing important insights into the monetary policy transmission mechanism, the paper offers a novel, flexible, and functional model for future policy analysis, especially in resource-rich emerging countries.

1. Introduction

Exogenous oil price shocks are capable of changing institutional frameworks or market conditions, and have been known to be associated with macroeconomic instabilities in many oil-exporting developing countries due to their heavy dependence on oil revenues. Thus, policymakers and researchers in these oil-dependent economies are often confronted with a number of recurring questions, including: what happens to the macroeconomy after an unexpected oil price change? Can increasing uncertainty about future prices or policy responses caused by oil price shocks generate significant macroeconomic implications? These questions are important not only for resource-rich developing economies, but also for the developed ones. This is because sharp and persistent movements in oil prices could have non-trivial implications for the stability of the global economy.

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On the empirical front, there is much evidence suggesting that the responses of macroeconomic aggregates to an oil price shock are nonlinear and/or time-varying in nature and that the policy responses can be subject to episodic movements in oil prices.[1] A common understanding regarding the possible source of nonlinearities is that institutional and political factors can also contribute to exacerbating shock's pro-cyclicality. For oil-rich emerging economies with weak fiscal institutions, monetary policy plays an important role in stabilizing the economy following an oil price shock.

However, monetary policy response to the macroeconomic fluctuations arising from oil price shocks may vary for a number of reasons. These include the state of the economy prior to the shock, the size and persistence of the shock, the prevailing dominant macroeconomic objectives of the government, and the effectiveness of monetary policy tools relative to prevailing fiscal policy regime. These factors may cause the central bank and indeed the domestic economy to respond to oil price shocks in a nonlinear way (Bodenstein et al., 2012). For instance, under a managed float exchange rate regime, the availability of robust external reserves enables the central bank to support the local currency more effectively in the face of a negative oil price shock. This sort of policy move by the central bank could moderate the transmission of an oil shock to the domestic economy.

The contrary holds when the economy is under a situation of low external reserves prior to the occurrence of an oil price shock. More so, changes in the behaviour of the fiscal authority may cause a switch in monetary policy response to episodic oil price changes. A fiscal regime that ensures resource earnings are properly managed helps the central bank to focus on its price stability objective, and be not pressured to pursue quasi-fiscal objectives, especially in times of economic crises (Kormilitsina, 2011; Benmelech and Tzur-Ilan, 2020). Thus, recent debates emphasize a range of views over the macroeconomic effects of an oil shock as well as the variations in those effects with respect to policy responses as well as economic conditions and states.

Macroeconomic policy in oil-producing emerging countries faces significant challenges arising from the unique characteristics of their economies. However, while the transmission mechanisms of oil shocks and policy responses are largely understood for oil-importing developed economies, less attention has been given to the subject for oil-exporting emerging economies. These economies tend to exhibit a situation where oil endowment is bad for growth, as resource abundance in those countries has been identified as one of the major causes of weak institutions and economic mismanagement. They also tend to operate within complex economic and policy environments with financial market inefficiencies, high dependence on fuel imports, low refining capacity, and inability to efficiently switch to alternative energy sources. The fiscal authorities, due to weak institutions and tax systems, often face political pressures to follow pro-cyclical fiscal policy. With the policy-induced price rigidities underlying these economies (e.g. through fuel subsidy regulations), fiscal volatility and imbalances are a major issue associated with oil shocks.

Under these circumstances, policy for maintaining stability and the responsibility to keep domestic demand stable in the face of fluctuating oil revenues may largely lie with the monetary authorities; implying that the real effects of oil price shocks can be caused by the subsequent monetary policy responses.[2] Observing the recent episodes of heightened volatility in the international oil prices (Fig. 1) gives us an impetus to examine not only the responsiveness of monetary policy, but also the relationship between the endogenous policy response of the central bank and exogenous oil price variations (i.e. the structural sources of monetary policy). Furthermore, explaining the stagnant growth of many developing oil-exporting countries such as Angola and Nigeria, especially in comparison to the high-performers of South Asia, during periods of volatile oil prices, is of significant relevance to policy.

The broad aim of this paper is to contribute to the literature on emerging markets business-cycle theory by studying the macroeconomic implications of possible policy interactions in response to major energy price fluctuations. Quantitative results are generated based on data for Nigeria. We chose Nigeria because it is a large net oil exporter, and it characterizes the typical resource-rich emerging markets.[3]

To examine possible changes in policy stance in response to episodic oil price fluctuations, we pursue a specific objective that explains a plausible hypothesis that tracks the mechanism through which oil price shocks can indirectly affect the demand side of the real economy. In view of the political expediencies faced by the fiscal authority in Nigeria with fuel subsidy regulations and frequent adjustments of budgetary expenditure, we focus on the role of monetary policy in managing aggregate demand. Given its objective to rein in inflationary pressures, how does monetary policy respond to oil price shocks and can such responses be time-varying depending on the nature of the shock? In this regard, our core research objective is to study how the macroeconomic implications of oil price shocks may differ depending on the volatility of oil price shocks and the monetary policy responses given the time variation in the amount of uncertainty faced by policymakers.

To this end, we first formally investigate the responses of output to an identified oil price shock by estimating an empirical model, and then consider a small open-economy (SOE) DSGE model that captures the oil price propagation mechanism and the subsequent monetary policy adjustment that occurs, with the hope of disentangling the effects of policy on business cycles. We achieve the specific objectives of the paper by carrying out a systematic examination of the model-implied dynamics computed based

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[1] See Bernanke et al. (1997), Hamilton (2003), Kilian (2008), Hamilton (2009), Kilian (2009), Kilian and Vigfusson (2011) and Herrera et al. (2015), among others.

[2] As oil price shocks in emerging economies can cause severe macroeconomic imbalances, the impact of the shock on monetary policy has non-trivial implications for maintaining macroeconomic stability. For example, Blanchard and Gali (2007) and Bjornland et al. (2018) are two of the few studies that explicitly assess the role of oil in the macroeconomy and in analyzing the so-called good policy versus good luck hypothesis. The former, based on a split sample estimation, finds that less volatile oil shocks (i.e. good luck) can explain a significant part of the reduction in macroeconomic volatility in the US. In contrast to Blanchard and Gali (2007), the latter, using a regime-switching framework, suggests that the effectiveness of monetary policy (i.e. good policy) has played an important part in the stabilization outcomes prior to the Great Moderation period.

[3] Nigeria continues to depend on oil revenue with less diversification towards non-oil exports and industrialization. The CBN database suggests that, between 2000-2018, oil and gas in Nigeria accounted for about 40% of GDP, 72% of government revenue, and 95% of exports earnings. Thus, shocks to oil prices generate volatility in both real spending and oil revenue, especially when oil prices are increasing and even in periods of declining oil prices.

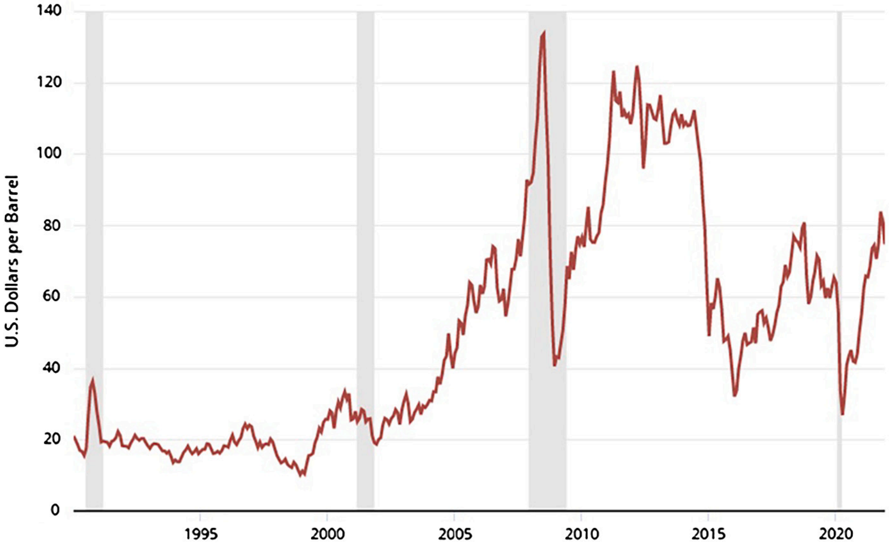

Fig. 1. Oil price fluctuations.
Source: International Monetary Fund, retrieved from FRED, Federal Reserve Bank of St. Louis. The shaded areas indicate the NBER recessions.

on a unified emerging market/rest-of-the-world DSGE framework that incorporates a discrete-state Markov chain and a structural oil-producing sector.

In particular, we estimate and compare the following models with specific regime-switching features: (i) A baseline with constant (time-invariant) parameters, incorporating non-Ricardian households and an oil sector that permits incomplete pass-through of international oil price into the retail price of fuel – Model 0; (ii) Regime shifts in both the monetary policy rule and oil price volatility measures (with a synchronized Markov chain) – Model 1; (iii) A variant of Model 1 that assumes complete pass-through of international oil price into the retail price of fuel – Model 2.[4] We examine the relative importance of each scenario in explaining the macroeconomic implications of episodic movements in oil prices and the response of monetary policy.

The baseline model is set out for the Nigerian economy that is fit for purpose and to capture the dynamic interactions between economic variables and policy interventions. The model features an oil producer and a fiscal authority that governs the level of fuel subsidies. The fuel subsidy programme determines the pass-through effect of international oil price into domestic prices. The monetary authority follows a simple Taylor rule responding gradually to aggregate inflation, domestic output and the exchange rate. The modelling of monetary policy is consistent with the operations of the Central Bank of Nigeria (CBN), which currently adopts a monetary targeting framework, uses the Monetary Policy Rate as a key instrument for signalling monetary policy stance, and has very recently moved to a regime of market-based exchange rate determination.

Our contributions, by incorporating switching with probabilistic transitions between regimes of major oil price fluctuations (i.e. assuming non-Gaussianity of the shock that characterizes the domestic economy), include (1) accounting for nonlinearities in the response of oil-exporting emerging economies to an identified oil price shock with a fully-specified dynamic structural model; (2) allowing for time variation in the effect of shocks in the case where variances are subject to stochastic switches between volatility states; (3) giving an explicit role to the monetary policy stance in propagating the real effect of the shock for an economy with a rather inflexible exchange rate system[5]; (4) accounting for the pass-through effect of oil prices to domestic prices.

The novelty of our paper lies in the application to emerging open economies, the emphasis on the time-varying structural parameters,[6] and the study of policymakers' behaviour in models characterized by a fuel subsidy regime, a well-articulated fiscal transmission mechanism, and financial market frictions. While much of the existing research studies the US data and data from other developed economies, our focus is on Nigeria as the few existing studies on resource-rich emerging economies fail to reach a consensus regarding the economic implications of oil shocks and the endogenous response of monetary policy. In addition, our paper is empirically based to enable quantitative analysis supplemented by careful modelling of a structural model that allows for the propagation of oil sector shocks to examine the mechanism through which oil shocks impact on business cycles and stabilization outcomes, while gauging the empirical relevance of the impact of shocks. Similar studies are, to our knowledge, non-existent.

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[4] Our modelling strategy also includes several other regime-switching variants accommodating independent regime shifts in time-varying oil price volatility and independent chains in both the monetary policy rule and volatility measures.

[5] There have been different regimes of exchange rate policy in Nigeria ranging from a regime of fixed exchange rate in the early 1980s to a managed float in the 1990s up to the end of our baseline sample period.

[6] In order to illustrate the impact of oil price changes on the aggregate economy which may be nonlinear and state-dependent, researchers have primarily relied on time series estimators using parametric nonlinear VARs and nonparametric procedures.

In our empirical analysis, we use not only the same data set in both approaches, i.e., a flexible recursive system and a structural DSGE model, but also obtain qualitatively similar results. We find substantial evidence in support of the time-varying nature of oil price shocks in Nigeria, which allows us to capture the significant increase in oil price volatility over time. In addition, we find some evidence in favour of stochastic switches in the monetary policy parameters, which is important in understanding the behaviour of policymakers during high-variance episodes. The data fit of the baseline model improves significantly with the addition of several regime-changing assumptions. Monetary policy also contributes to the nonlinear macroeconomic responses to oil price shocks.

By carefully examining our sample and model simulations, our results and analysis can be used to motivate further investigation into the roles of oil in understanding the growth process specific to oil-rich developing countries. Also, by introducing episodic nonlinearities in a SOE, the model provides a novel and flexible framework, and the reliable conditional moments, to be employed for future policy analysis. Our findings and analysis withstand a number of robustness checks and provide important insights into the monetary policy transmission mechanism in the post-financial crisis world.

The rest of the paper is organized as follows. Section 2 discusses the key literature related to our paper. Section 3 examines the relationship between output and oil prices based on an estimated nonlinear dynamic structural model, while Section 4 sets out the baseline DSGE model. Section 5 explains the various regime-switching specifications which are estimated and compared with the baseline framework. Section 6 describes the data as well as solution and estimation methodologies. Section 7 discusses the results, model comparison and empirical properties. Section 7 also focuses on the interactions among oil price volatility, subsidies, and monetary policy, while Section 8 considers the implications of alternative assumptions regarding certain model features and robustness of the main results when we extend the sample period to cover the more recent data. Section 9 concludes. Online Appendices provide details of the model and solutions that are standard in the DSGE literature as well as the priors, calibration and robustness exercises.

2. Related literature

There are three strands of literature related to our paper. The first strand is a largely econometrics literature studying oil price shocks. The large empirical literature focuses separately on the shocks' (i) asymmetric output effects and (ii) state dependence, and offers different explanations on the existence of nonlinearities. For example, Barsky and Kilian (2004), Kilian (2009) and Ramey and Vine (2011) study the sources of the underlying oil price shocks while Rahman and Serletis (2010) and Holm-Hadulla and Hubrich (2017) evaluate how central banks respond to oil shocks, accounting for time variation in the impact of shocks. The major discussion under this strand of literature is around the changing estimated effects of oil price shocks, and the use of alternative methods for studying such changing effects. This motivates us to take account of time-dependent nonlinearities in modelling the impact of oil shocks.

Studying episodic changes of macroeconomic shocks is difficult and requires nonlinear techniques. SVAR-based studies that explicitly allow for nonlinearities, such as in Holm-Hadulla and Hubrich (2017), find mixed evidence but the existence of a VAR representation can be compromised due to non-invertibility/-fundamentalness.[7] Using the method of Local Projections (LP) of Jorda (2005), one can side-step the intervening step of a VAR. The LP approach or nonlinear autoregressive distributed lags models are indeed more flexible than traditional VARs in terms of estimating nonlinear relationships and do not require structural shocks that are independently identified.[8] For example, Garzon and Hierro (2021) extend the linear model by applying the LP method, which is estimated as a smooth transition between different states of economic environment. The procedure is non-parametric in nature but needs additional information from the data for identifying the shocks - i.e. instruments which are variables correlated with a particular shock of interest.

This leads to a second literature that focuses on episodic switches in DSGE frameworks incorporating Markov chains for macroeconomic volatility and structural parameters in which agents take into account the nonlinear nature of the system and of the switching process. Using data from the US and the UK, a number of empirical studies have estimated regime-switching DSGE models and found substantial evidence of structural shifts (see, for example, Schorfheide, 2005, Liu and Mumtaz, 2011, Liu et al., 2011, Chen and Macdonald, 2012, Bianchi, 2013, Davig and Doh, 2014, Bianchi and Ilut, 2017, Bianchi and Melosi, 2017, among others). More recently, Bjornland et al. (2018) construct and estimate such a regime-switching model that directly studies the role of oil price volatility in the US economy for the timing of the Great Moderation. Best and Hur (2019) evaluate the role of monetary policy with time-varying volatilities of non-policy shocks. Maih et al. (2021) investigate the implications of asymmetric monetary policy rules for the Euro area and the US based on a sample that encompasses periods of financial distress.

In our paper, studying the underlying shifts in an economy is not at the heart of the problem; rather, it is evaluating the role of the central bank in response to episodic oil price fluctuations that takes centre stage. We assess the empirical relevance of such policy interactions by estimating a SOE/rest-of-the-world model containing key features of emerging oil-producing economies. In contrast to the previous papers, and Bjornland et al. (2018) in particular, the switch in our model assumes that responses of the real economy depend on the volatility and persistence of oil price shocks. In addition, we study the role of an implicit fuel subsidy programme in our regime-switching models which affects the monetary policy environment.

Another issue associated with the VAR literature or the literature estimating nonlinear multivariate models is that it does not provide much information about the mechanisms through which oil price shocks affect the macroeconomy. As a result, a class of SOE

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[7] See, for a detailed discussion, Levine et al. (2019) and Levine et al. (2022).

[8] Pal and Mitra (2015), Nusair (2016) and Jawadi and Ftiti (2019) are some examples in the recent empirical literature for modelling nonlinearities of the oil shock.

structural models have recently been developed to investigate the macroeconomic impacts of oil price shocks and policy design in small open oil-importing and -exporting countries including Nigeria. This is the third strand of literature. Omotosho (2019) develops and estimates an open-economy model using Nigerian data and focuses on sources of macroeconomic fluctuations and inflation dynamics. A comprehensive review is provided by Omotosho (2022) which provides several mixed results reporting varied monetary policy responses to an oil price shock.

Furthermore, many attempts have failed to replicate the stylized facts for oil-exporting emerging economies. The variations in findings are explained by the varying nature of monetary policy response, prevailing exchange rate regimes, dependence of oil intensity and modelling assumptions: see, for example, Medina and Soto (2005), Allegret and Benkhodja (2015), Bergholt et al. (2019), Ferrero and Seneca (2019), Algozhina (2022) and Omotosho (2022).[9] However, this literature has not examined the macroeconomic implications through the interactions among oil price volatility, consumption subsidies, consumers that are financially constrained, and economic transitions between states, which is the focus of this paper. We aim to explicitly disentangle the potentially alternative sources of nonlinearities from economic shifts by embedding the oil sector effects, while incorporating the policymakers' behaviour with changing policy stances, in our estimated structural model.

3. A nonlinear dynamic structural model

To motivate our system estimation approach (and the resulting impulse responses - henceforth IRFs), we first formally examine the relationship between oil price changes and real GDP growth. We estimate the following stationary recursive model with censored regressors introduced by Kilian and Vigfusson (2011), by the method of least squares, to study the response of output to unexpected changes in oil prices

$$x_t = a_{10} + \sum_{i=1}^{p} a_{11,i} x_{t-i} + \sum_{i=1}^{p} a_{12,i} y_{t-i} + \epsilon_{1,t} \tag{1}$$

$$y_t = a_{20} + \sum_{i=0}^{p} a_{21,i} x_{t-i} + \sum_{i=1}^{p} a_{22,i} y_{t-i} + \sum_{i=0}^{p} b_{21,i} x_{t-i}^{cen} + \epsilon_{2,t} \tag{2}$$

where x_t denotes the log growth in the oil price and y_t is real GDP growth. $\epsilon_t = (\epsilon_{1,t}, \epsilon_{2,t})' \sim (0, \Sigma)$ is uncorrelated orthogonal white noise. x_{t-i}^{cen} is one of the nonlinear transformations that provide the censoring of the oil price series. The literature widely accepts that the most appropriate specification of oil prices involves some measure of oil price increases. This consensus is based on Mork (1989)'s oil price increase (OPI_t) measure and a censored indicator that is proposed by Hamilton (2003)

$$\text{Mork}: \quad x_t^{cen} = OPI_t = \max(0, \ln(o_t) - \ln(o_{t-1})) \tag{3}$$

$$\text{Hamilton}: \quad x_t^{cen} = NOPI_t = \max(0, \ln(o_t) - \max(\ln(o_{t-1}), \ldots, \ln(o_{t-4}))) \tag{4}$$

where $\ln(o_t)$ is the logarithm of the real oil price. $NOPI_t$ indicates that any increases that did not exceed the maximum price observed in the past 4 quarters are also censored at zero. Herrera et al. (2015), Kilian and Vigfusson (2017) and Agboola et al. (2024) estimate the same model for the OECD countries, the US, and a group of oil-exporting emerging economies, respectively, and discuss the benefits of using these indicators. Not only do they produce relatively stable relationship between oil prices and macroeconomic variables, they also tend to predict declines in US real GDP growth.

Based on Kilian and Vigfusson (2011) and Kilian and Vigfusson (2017), to identify the structural system, the following restrictions, $a_{12,0} = 0$ and $a_{21,0} \neq 0$, are imposed, which are similar to restrictions used in the structural VAR literature. The assumption that the price of oil is a predetermined (contemporaneously exogenous) variable with respect to real GDP can be justified as Nigeria is a small open-economy and does not have the market power to influence global oil prices. This assumption rules out instantaneous feedback from y_t to x_t and is consistent with empirical evidence in Agboola et al. (2024).

The response to the exogenous oil price innovation $\epsilon_{1,t}$ depends on the past history of the system as well as the sign and magnitude of $\epsilon_{1,t}$. Since the corresponding IRFs are nonlinear functions of $b_{21,i}$ as well as the other parameters of the model, they are computed by Monte Carlo integration conditional on the history $\mathbb{I}_t$. The conditional response $IR_y(h, \delta, \mathbb{I}_t)$ is calculated to an innovation of size δ in $\epsilon_{1,t}$ for a given horizon h. We average 100,000 draws for each response function of the level of real GDP and compute the effect of an oil price innovation of magnitude $\delta = -\sigma$ (one standard deviation shock) and $\delta = -2\sigma$ (two standard deviation shock). The model allows us to make a distinction between positive and negative shocks and nests the linear structural VAR model (where $b_{21,i} = 0 \forall i \in \{0, \ldots, p\}$ and the usual identification restrictions apply). The latter can be estimated to obtain the unconditional $IR_y^{VAR}(h, \delta)$ from which varying δ produces symmetric effects of oil price shocks on GDP. Our exercise also includes the estimated response from the linear model for comparison.

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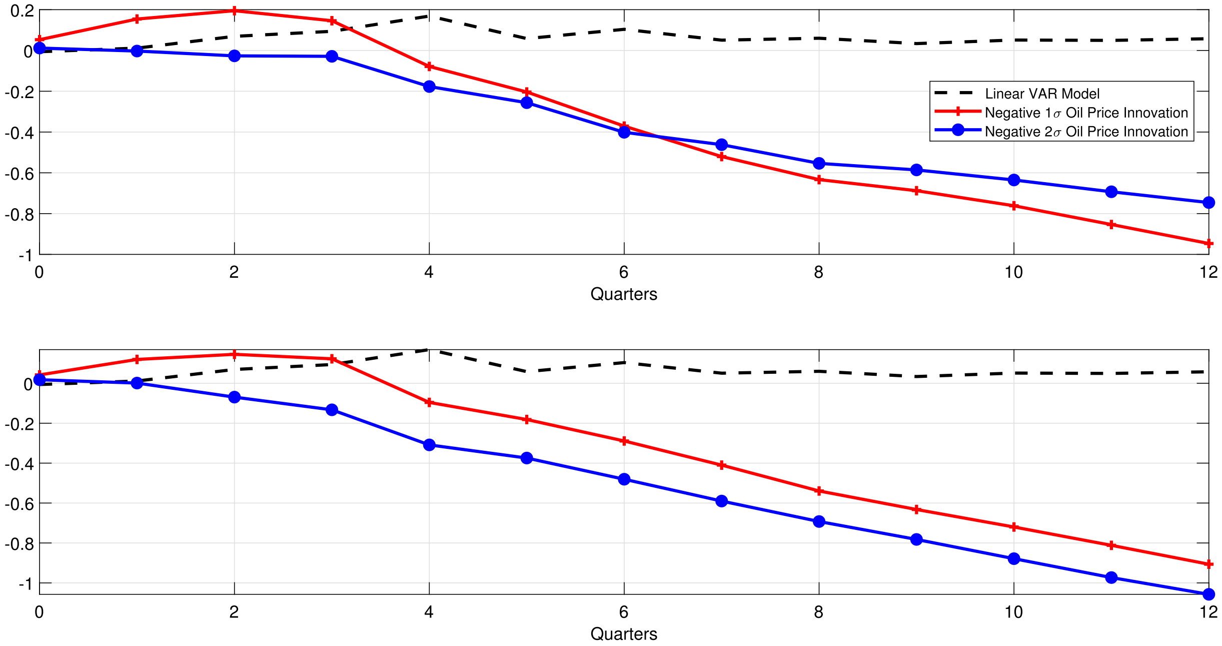
[9] These models capturing interactions between oil prices and macroeconomic policy are based on the assumption that the data generating processes of the associated variables have no breaks or mean shifts or switching mechanism embedded in them.



Notes: The upper panel is plotted using the model with oil price increases (OPI_t); the lower panel is based on the model with net oil price increases ($NOPI_t$). The figure plots the mean response of real GDP corresponding to a 1 s.d. and 2 s.d. (σ) of the oil price shock's innovation (i.e. $IR_y(h, -\sigma, \mathbb{I}_t)$ and $0.5 * IR_y(h, -2\sigma), \mathbb{I}_t)$. For simulating paths of x_t and y_t, we use 100,000 draws of simulations for computing the IRF given the history $\mathbb{I}_t$. Each response is for a 12 period (3 years) horizon and is computed by cumulating the responses of the growth rate.

Fig. 2. Impulse response functions of real GDP.

3.1. *Impulse responses of GDP to oil price shocks*

The quarterly data series used in the estimation include the percentage changes in the real price of oil using the OPEC benchmark of Brent crude oil price and the growth rate of real GDP.[10] The oil price series is transformed and deflated using the nominal exchange rate and domestic CPI. The sample runs from 2000Q2 to 2018Q2. The lag order $p = 6$ is set to capture the dynamic effects of oil price on the real economy and determined by performing residual diagnostic checks on each of the estimated models following the procedure set out in Agboola et al. (2024).

In Fig. 2, we focus on the estimated IRFs of the observable GDP to negative oil price shocks and each response is for a 12-period horizon (3 years). The aim of this exercise is two-fold. First, we evaluate nonlinearity in the response across our structural models by understanding how the IRF trajectories may be affected by the magnitude of the shock, the response horizons, and the type of the censored variables; second, we assess the impact of shocks (1σ and 2σ) on the model dynamics. These allow us to study the importance of oil price shocks to the level of output in order to gain a better understanding of the innovation and forecasting uncertainties and, thus, the model uncertainties faced by policymakers.

Overall, in terms of the cumulative level effect, an unexpected oil price decrease leads to an output contraction at long horizons, although a 1σ shock has a positive effect on real GDP in the short run (about three quarters). As expected, there are marked differences in IRFs when there are strong asymmetric effects (i.e. on the responses to a large shock). A 2σ negative innovation has stronger (contractionary) effects on real GDP than a 1σ one suggested by the net oil price increase model. Using both measures, doubling the magnitude of the negative oil price innovation amplifies the conditional response and would result in a 1-year cumulative output contraction of about 0.2-0.3% in Nigeria.

An obvious question is how the IRFs have evolved over time. The dynamics can be significantly magnified or altered depending on certain country-specific characteristics that exacerbate their vulnerabilities to the shock. Such characteristics can include on-going economic policy changes.[11] Given that the growing industrial sector in Nigeria depends on oil production, an oil price decrease can initially promote aggregate demand and hence output growth (through the supply side). The net effect generally shows a contraction in output. In the NOPI model, the effect is greater and more persistent when considering a large oil price shock.

At this stage, an interesting question is why a 2σ large shock would cause a more severe output contraction than a 1σ typical shock at short horizons ($h < 6$)? Mechanically, the shock is large enough to activate the nonlinear features of the model. One possible explanation is that, depending on energy intensity in production, through the supply-side effect, oil production often responds with a lag to a price shock, followed by production expansion, as a decrease in oil prices decreases production costs. Moreover, given

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[10] Section 6 describes the data in more detail.

[11] For example, the intervening role of monetary policy.

Nigeria's large volume of oil exports and its nature of being a primary sector-based economy, an oil price decrease deteriorates its current account balance and pushes the exchange rate downwards which might positively affect revenues from the agricultural sector, thus aggregate demand is likely to be positively affected on impact (Agboola et al., 2024). This may explain the initial expansion seen from the GDP responses to a typical shock which seems to be persistent for about two quarters.

3.2. *Oil price shocks in nonlinear models*

Now, considering the discussion above conditional on $\mathbb{I}_t$, suppose that we allow the magnitude of oil price innovations to vary between $\delta = -\sigma$ and $\delta = -2\sigma$, i.e., the latter innovations are rare implying large and persistent decreases in the real price of oil, but do not consider the variance of the shock to be non-constant. Given the evidence in Fig. 2, it is unambiguous that there is considerable wedge between the response in the linear VAR and those in the nonlinear model, and that it is possible to believe that a large shock would result in output reacting more and differently to shocks. But whether this is caused by merely the size of the shock or the changing/amplifing transmission mechanisms in propagating the shock is unclear. For example, empirical evidence shows that the outcomes associated with an oil price shock are different conditional on the variance of the shock before the shock hits (Kilian and Vigfusson, 2017) which would lead us to believe that the transmission mechanisms may also be affected. This motivates us to take into consideration the possibility of the variance of shocks changing over time, i.e., taking heteroskedasticity into consideration.

While being able to identify some nonlinear dynamics in the output responses to oil prices, our empirical analysis is unable to provide any information about the mechanisms through which oil price shocks affect the economy through, for example, the connection between regime-switching and policy, particularly in the Taylor rule model. Thus, it leaves *unanswered*, the more fundamental question of what leads the economy or policymakers to behave differently over time. Answering this question requires a model with richer dynamics, accounting for the key features of resource-rich emerging economies. We now turn to the open-economy DSGE model that is estimated using a larger data set encompassing more observable variables for Nigeria.

4. Theoretical framework for the baseline model

We set up a two-agent New Keynesian model that incorporates: (i) an oil sector that is owned by the government and foreign investors as in Algozhina (2022); (ii) oil in household consumption basket and firms' production technology as in Medina and Soto (2005) and Allegret and Benkhodja (2015); (iii) five different measures of inflation as in Medina and Soto (2005); (iv) an inefficient financial sector as in Smets and Wouters (2007); (v) a fiscal policy rule as in Algozhina (2022); (vi) a fuel pricing rule that connotes an implicit subsidy regime as in Allegret and Benkhodja (2015); and (vii) non-Ricardian consumers to capture credit constraints. Furthermore, we allow for the law of one price gap in imports and, by implication, assume incomplete exchange rate pass-through into import prices as in Monacelli (2005) and Senbeta (2011). As standard in most DSGE models, we assume that wages as well as prices of domestically produced goods are sticky. Finally, an investment adjustment cost is incorporated into the model to generate hump-shaped investment responses to shocks. We agnostically subject our model to the following regime-switching behaviour: stochastic switches in (i) volatility and persistence of oil price shocks; and (ii) parameters in the monetary policy rule. The main elements of the model are as follows.[12]

4.1. *Consumption and prices*

Household consumption, C_t, is a composite index comprising non-oil consumption bundle, $C_{no,t}$, and oil consumption, $C_{o,t}$

$$C_t = \left[\left(1-\gamma_o\right)^{\frac{1}{\eta_o}} \left(C_{no,t}\right)^{\frac{\eta_o-1}{\eta_o}} + \gamma_o^{\frac{1}{\eta_o}} \left(C_{o,t}\right)^{\frac{\eta_o-1}{\eta_o}} \right]^{\frac{\eta_o}{\eta_o-1}} \tag{5}$$

where $\eta_o > 0$ measures the degree of substitution between core and fuel consumption and γ_o represents the share of domestic consumption devoted to fuel consumption, $C_{o,t}$.

Expenditure minimization subject to (5) yields the demands for core consumption and fuel consumption as follows

$$C_{no,t} = \left(1-\gamma_o\right) \left[\frac{P_{no,t}}{P_t}\right]^{-\eta_o} C_t, \quad C_{o,t} = \gamma_o \left[\frac{P_{ro,t}}{P_t}\right]^{-\eta_o} C_t \tag{6}$$

where $P_{ro,t}$ represents the subsidized price of imported fuel,[13] $P_{no,t}$ is the price of non-oil (core) goods, and P_t is the aggregate consumer price index.

Furthermore, core consumption bundle, $C_{no,t}$, is defined as a composite index given by a constant elasticity of substitution aggregator that combines imported bundle, $C_{f,t}$, and domestically produced goods, $C_{h,t}$, as follows

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[12] To save space, parts of the model associated with the wage setting dynamics, behaviours of non-oil firms, interaction between the SOE and the foreign economy, and analogous 'foreign' variables are largely omitted in the exposition. See, for details, Online Appendices A–C.

[13] The price of imported fuel is not simply the domestic currency price of fuel but rather a convex combination of the landing price of fuel and the domestic price of fuel in the previous period. Thus, following Allegret and Benkhodja (2015), $P_{ro,t}$ is determined based on a fuel pricing rule given as $P_{ro,t} = P^{1-\nu}_{ro,t-1} P^{\nu}_{lo,t}$ where the landing price of fuel, $P_{lo,t}$, is the current world price of fuel expressed in local currency.

$$C_{no,t}=\left[\left(1-\gamma_c\right)^{\frac{1}{\eta_c}}\left(C_{h,t}\right)^{\frac{\eta_c-1}{\eta_c}}+\gamma_c^{\frac{1}{\eta_c}}\left(C_{f,t}\right)^{\frac{\eta_c-1}{\eta_c}}\right]^{\frac{\eta_c}{\eta_c-1}} \tag{7}$$

where $\eta_c>0$ represents the elasticity of substitution between home and foreign goods in the core consumption basket and γ_c measures the share of domestic consumption sourced from the rest of the world by way of non-oil imports.

Minimizing the household's expenditure subject to (7) yields the demands for $C_{h,t}$ and $C_{f,t}$

$$C_{h,t}=\left(1-\gamma_c\right)\left[\frac{P_{h,t}}{P_{no,t}}\right]^{-\eta_c}C_{no,t},\quad C_{f,t}=\gamma_c\left[\frac{P_{f,t}}{P_{no,t}}\right]^{-\eta_c}C_{no,t} \tag{8}$$

where $P_{h,t}$ represents the price of domestically produced goods, $P_{f,t}$ is the price of imported goods (expressed in domestic currency), and $P_{no,t}$ is the core consumption price index. The corresponding equations for the aggregate consumer price index, P_t, and core consumption price index, $P_{no,t}$, are standard

$$P_t=\left[\left(1-\gamma_o\right)P_{no,t}^{1-\eta_o}+\gamma_o P_{ro,t}^{1-\eta_o}\right]^{\frac{1}{1-\eta_o}},\quad P_{no,t}=\left[\left(1-\gamma_c\right)P_{h,t}^{1-\eta_c}+\gamma_c P_{f,t}^{1-\eta_c}\right]^{\frac{1}{1-\eta_c}} \tag{9}$$

4.2. Ricardian consumers

We consider two types of consumers in the model economy: Ricardian (R) and non-Ricardian (NR). The Ricardian consumers comprise a fraction (γ_R) who are optimizers and have unconstrained access to the financial markets. A representative household in this category is able to smooth out its consumption over time by buying and selling financial assets without any form of constraints (Galí, 2018). On the other hand, the non-Ricardian consumers represent the remaining fraction $(1-\gamma_R)$ who are non-optimizers and financially constrained. Thus, they completely consume their labour income within the period (Melina et al., 2016; Gabriel et al., 2012). However, both categories of households have identical preferences as each representative household derives utility from private consumption, C_t, and dis-utility from labour, N_t.

In order to make inter-temporal consumption and savings decisions, the representative optimizing household maximizes an expected discounted utility function given by

$$U_0^R=E_0\sum_{s=o}^{\infty}\beta^s\left[\frac{\left(C_{t+s}^R-\phi_c C_{t+s-1}\right)^{1-\sigma}}{1-\sigma}-\frac{\left(N_{t+s}^R\right)^{1+\varphi}}{1+\varphi}\right] \tag{10}$$

where E_0 denotes the mathematical expectation operator, C_t^R is the representative Ricardian household's current level consumption, C_t is the economy-wide consumption level, N_t^R is the number of hours worked, $\beta\in(0,1)$ is a discount factor, σ is relative risk aversion coefficient, and $\varphi>0$ is the inverse of the Frisch elasticity of labour supply. While (10) is separable in both consumption goods and labour effort, we assume that consumption is subject to external habit formation, implying that the habit stock is proportional to aggregate past consumption. $\phi_c\in(0,1)$ measures the degree of external habit formation in consumption.

The representative household makes its inter-temporal decisions by maximizing (10) subject to a per period budget constraint

$$P_tC_t^R+P_{i,t}I_{no,t}+\frac{B_{t+1}}{R_t\mu_t}+\frac{\varepsilon_tB_{t+1}^*}{R_t^*\mu_t^*}=W_tN_t^R+R_{h,t}K_{h,t}+B_t+\varepsilon_tB_t^*+D_t-TX_t \tag{11}$$

where the Ricardian consumer supplies N_t^R hours of work at a nominal wage rate, W_t, yielding a labour income, $W_tN_t^R$. The household owns an amount of non-oil capital, $K_{h,t}$, which it leases to the domestic (non-oil) firms at a rental rate, $R_{h,t}$, to generate a capital income, $R_{h,t}K_{h,t}$. The household receives an aliquot share, D_t from the profits of the firms. The household also enters the period with the stock of nominal domestic bonds, B_t, and foreign bonds, B_t^*, maturing in period $t+1$. B_{t+1} and B_{t+1}^* represent the household's investments in domestic and foreign bonds at the end of period t, respectively; while the nominal exchange rate is denoted by ε_t. Each domestic bond pays a gross nominal rate of return, R_t, in domestic currency while its foreign counterpart pays an exchange rate adjusted nominal rate of return, R_t^*.

Following Smets and Wouters (2007) and Gupta et al. (2016), we allow for a domestic risk premium, μ_t, over the monetary policy rate when households hold domestic assets as well as a stochastic disturbance term that represents the risk premium faced by households when borrowing abroad, μ_t^*. As described in Smets and Wouters (2007), μ_t is a wedge between the central bank controlled interest rate and the return on assets held by households. Thus, a positive shock to the domestic risk premium has the potentials of reducing consumption and increasing the cost of capital. It is assumed that μ_t and μ_t^* evolve as first-order autoregressive processes. The income received by the household is used to finance the purchase of consumption goods, C_t^R, at the cost of P_t per unit; and non-oil investment goods, $I_{no,t}$, at the cost of $P_{i,t}$ per unit. Lastly, TX_t represents per-capita lump-sum net taxes from the government.

The non-oil investment goods, $I_{no,t}$ in (11), comprise home-produced goods, $I_{h,t}$, and foreign-produced goods, $I_{f,t}$, which are combined as follows

$$I_{no,t}=\left[\left(1-\gamma_i\right)^{\frac{1}{\eta_i}}\left(I_{h,t}\right)^{\frac{\eta_i-1}{\eta_i}}+\gamma_i^{\frac{1}{\eta_i}}\left(I_{f,t}\right)^{\frac{\eta_i-1}{\eta_i}}\right]^{\frac{\eta_i}{\eta_i-1}} \tag{12}$$

where γ_i is the share of imports in aggregate non-investment goods and η_i is the elasticity of intra-temporal substitution between domestically produced and imported investment goods.

Cost minimization by the representative Ricardian household subject to (12) yields the demand equations for home-produced and imported investment goods

$$I_{h,t} = \left(1-\gamma_i\right)\left[\frac{P_{h,t}}{P_{i,t}}\right]^{-\eta_i} I_{no,t}, \quad I_{f,t} = \gamma_i \left[\frac{P_{f,t}}{P_{i,t}}\right]^{-\eta_i} I_{no,t} \tag{13}$$

and the aggregate investment price deflator, $P_{i,t}$, is given by

$$P_{i,t} = \left[\left(1-\gamma_i\right) P_{h,t}^{1-\eta_i} + \gamma_i P_{f,t}^{1-\eta_i}\right]^{\frac{1}{1-\eta_i}} \tag{14}$$

Finally, the representative Ricardian household accumulates non-oil capital as follows

$$K_{h,t+1} = \left(1-\delta_h\right) K_{h,t} + I_{no,t}\left[1 - S\left(\frac{I_{no,t}}{I_{no,t-1}}\right)\right] \tag{15}$$

where $0 < \delta_h < 1$ represents the rate at which capital depreciates. The investment adjustment cost function, $S\left(\frac{I_{no,t}}{I_{no,t-1}}\right)$, is defined as

$$S\left(\frac{I_{no,t}}{I_{no,t-1}}\right) = \frac{\chi}{2}\left(\frac{I_{no,t}}{I_{no,t-1}} - 1\right)^2 \tag{16}$$

where $\chi \geq 0$ is the sensitivity parameter governing the size of adjustment cost.

4.3. Non-Ricardian consumers

In view of the fact that the non-Ricardian consumers are incapable of inter-temporal optimization, we assume that the representative consumer in that category chooses its consumption, C_t^{NR}, by maximizing

$$U_0^{NR} = E_0 \sum_{s=0}^{\infty} \beta^s \left[\frac{\left(C_{t+s}^{NR} - \phi_c C_{t+s-1}\right)^{1-\sigma}}{1-\sigma} - \frac{\left(N_{t+s}^{NR}\right)^{1+\varphi}}{1+\varphi}\right] \tag{17}$$

subject to the budget constraint

$$P_t C_t^{NR} = W_t N_t^{NR} - TX_t \tag{18}$$

4.4. Oil-producing firms

There are four categories of firms operating in the economy, namely: the final goods firms, the intermediate goods producing firms, the foreign goods importing firms and the oil-producing firm. The economic environments in which the first three categories of firms operate are standard and discussed in Online Appendix B. In this section, we focus on the oil-producing firm.

The oil firm's profit maximization problem is similar to that of Ferrero and Seneca (2019). This firm combines materials sourced from the domestic economy, M_t, and oil-related capital, $K_{o,t}$, to produce oil output, $Y_{o,t}$. The oil output is exported to the rest of the world at a price, $p_{o,t}^*$, determined in the international crude oil market. To produce oil, the firm employs a constant return to scale Cobb-Douglas extraction technology given by

$$Y_{o,t} = A_{o,t} K_{o,t}^{\alpha_o^k} M_t^{\alpha_o^m} \tag{19}$$

where $A_{o,t}$ represents the oil technology. α_o^k and $\alpha_o^m \in (0,1)$ represent the elasticities of oil output with respect to oil-related capital and material inputs, respectively.

We assume that $K_{o,t}$ is accumulated by foreign direct investment, FDI_t^*, as follows

$$K_{o,t} = \left(1-\delta_o\right) K_{o,t-1} + FDI_t^* \tag{20}$$

where δ_o represents the rate at which $K_{o,t}$ depreciates. Foreign direct investment inflows to the oil sector respond to the real international price of oil as follows

$$\widetilde{FDI_t^*} = \rho_{fdi}\widetilde{FDI_{t-1}^*} + (1-\rho_{fdi})\widetilde{p_{o,t}^*} \tag{21}$$

where the tildes over each of the variables, hereafter, denote the deviations from their steady state. ρ_{fdi} measures the extent of inertia in the accumulation of FDI_t^*.

As in Algozhina (2022), we assume that the oil firm (which is jointly owned by foreign direct investors and the government) receives its revenues net of royalties levied by the government on production quantity at a rate τ as follows

$$\Pi_{o,t} = (1-\tau)\,\varepsilon_t p^*_{o,t} Y_{o,t} \tag{22}$$

We assume that the real international price of oil and the oil technology evolve according to the following $AR(1)$ processes with exogenous shocks

$$p^*_{o,t} = \left(p^*_{o,t-1}\right)^{\rho_{p^*_o}(s^{vo}_t)} \exp\left(\sigma_{p^*_o}(s^{vo}_t)\xi^{p^*_o}_t\right), \quad A_{o,t} = \left(A_{o,t-1}\right)^{\rho_{a_o}} \exp\left(\xi^{A_o}_t\right) \tag{23}$$

In order to capture possible nonlinearities in the response of the resource-rich economy to oil price instabilities, we allow the volatility of the oil price shock to change from one regime to another as follows

$$s^{vo}_t \in \{High, Low\} \tag{24}$$

To take into consideration the possibility where the responses of the real economy may also depend on the persistence of the shock, we restrict the persistence parameter, $\rho_{p^*_o}$, to follow a Markov chain that switches at the same time, but not necessary in the same direction.

4.5. Fiscal policy

Each period, the government receives revenues from lump-sum taxes, TX_t, issues one period bonds that results in a net debt position, B_t, and receives oil revenues in form of royalties from the oil firm, OR_t. These receipts are used to finance government expenditure on public goods, $G_{c,t}$, and interest payments, $\frac{B_{t+1}}{R_t}$. Finally, when the need arises, the government makes subsidy payments, OS_t, within a framework that allows for the stabilization of domestic fuel price. Consequently, we assume that the government respects a budget constraint given by

$$TX_t + OR_t + B_t = P_{g,t}G_{c,t} + OS_t + \frac{B_{t+1}}{R_t} \tag{25}$$

where (25) shows that an increase in government spending, $G_{c,t}$, can be financed either by increasing taxes, generating more oil revenues, or issuing more debt. As in Medina and Soto (2007), we assume that the government consumption basket consists of imported goods, $G_{f,t}$, and domestically produced goods, $G_{h,t}$

$$G_{c,t} = \left[\left(1-\gamma_g\right)^{\frac{1}{\eta_g}} G_{h,t}^{\frac{\eta_g-1}{\eta_g}} + \gamma_g^{\frac{1}{\eta_g}} G_{f,t}^{\frac{\eta_g-1}{\eta_g}}\right]^{\frac{\eta_g}{\eta_g-1}} \tag{26}$$

where η_g is the elasticity of substitution between imported and domestically produced goods consumed by the government and γ_g is the share of foreign goods in government's consumption basket.

Cost minimization by the government subject to (26) yields the demands for home and foreign goods as follows

$$G_{h,t} = \left(1-\gamma_g\right)\left(\frac{P_{h,t}}{P_{g,t}}\right)^{-\eta_g} G_{c,t}, \quad G_{f,t} = \gamma_g\left(\frac{P_{f,t}}{P_{g,t}}\right)^{-\eta_g} G_{c,t} \tag{27}$$

while the government consumption price index is given by

$$P_{g,t} = \left[\left(1-\gamma_g\right)P_{h,t}^{1-\eta_g} + \gamma_g P_{f,t}^{1-\eta_g}\right]^{\frac{1}{1-\eta_g}} \tag{28}$$

where $P_{g,t}$ is the deflator of government expenditure.

In order to allow for fuel consumption subsidies in the SOE, we follow Allegret and Benkhodja (2015). We assume that aggregate refined oil, O_t, is produced abroad and imported into the SOE at a landing price, $P_{lo,t}$, by the government.[14] In turn, the government sells the imported fuel at a regulated price, $P_{ro,t}$, based on a fuel pricing regime given by

$$P_{ro,t} = P_{ro,t-1}^{1-\nu} P_{lo,t}^{\nu} \tag{29}$$

where the landing price of imported fuel is given by[15]

$$P_{lo,t} = \varepsilon_t \frac{P^*_{o,t}}{P^*_t}\Psi^o_t \tag{30}$$

In (30), $P^*_{o,t}$ is the foreign currency price of oil abroad and Ψ^o_t is the law of one price gap associated with the import price of fuel. The parameter $0 < \nu < 1$ governs the extent to which the government subsidizes fuel consumption. When $\nu = 1$, the implicit subsidy regime ceases to exist while $\nu = 0$ implies complete price regulation. Thus, the implicit fuel subsidy payment by the government is

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[14] This is the cost of importing a litre of fuel into the domestic economy, expressed in domestic currency.

[15] This is similar to the specification in Poghosyan and Beidas-Strom (2011).

given by the difference between the value of fuel imports expressed in domestic currency and the amount realized from fuel sales in the domestic economy as follows

$$OS_t = \left(P_{lo,t} - P_{ro,t}\right) O_t \tag{31}$$

where total imported fuel, O_t, comprises fuel consumption by households, $C_{o,t}$, and consumption by domestic firms, $O_{h,t}$.

On the revenue side of the budget constraint, (25), the government collects lump-sum taxes and oil revenues. The amount of oil revenues, OR_t, accruing to the government is given by

$$OR_t = \tau \varepsilon_t p^*_{o,t} Y_{o,t} \tag{32}$$

Following Algozhina (2022), we consider backward looking fiscal policy reaction functions that allow government consumption and taxes to respond to lagged debt, oil revenues and oil subsidy payments. Thus, our linearized fiscal policy rules are specified as follows

$$\widetilde{g}_{c,t} = \rho_g \widetilde{g}_{c,t-1} + \left(1 - \rho_g\right) \left[\omega_b \widetilde{b}_{t-1} + \omega_{gy} \widetilde{y}_{t-1} + \omega_{os} \widetilde{os}_t + \omega_{or} \widetilde{or}_t\right] + \xi_t^{gc} \tag{33}$$

$$\widetilde{tx}_t = \rho_{tx} \widetilde{tx}_{t-1} + \left(1 - \rho_{tx}\right) \left[\varphi_b \widetilde{b}_{t-1} + \varphi_g \widetilde{g}_{c,t} + \varphi_{os} \widetilde{os}_t - \varphi_{or} \widetilde{or}_t\right] + \xi_t^{tx} \tag{34}$$

where ρ_g and ρ_{tx} represent the degree of smoothing in the government spending and tax rules, respectively. ω_b, ω_{gy}, ω_{os} and ω_{or} are the government consumption feedback coefficients with respect to lagged domestic debt, lagged output, oil subsidy payments and oil revenues, respectively. In (34), taxes respond to lagged debt, government consumption, oil subsidy payments and oil revenues with the feedback parameters, φ_b, φ_g, φ_{os} and φ_{or}, respectively. The tax shock and government spending shock are represented by ξ_t^{tx} and ξ_t^{gc}, respectively, and given by an exogenous process.

4.6. Monetary policy

In setting the short term nominal interest rate, R_t, the central bank follows a simple Taylor rule by gradually responding to aggregate inflation, $\pi_t = \frac{P_t}{P_{t-1}}$, domestic output, $y_{h,t}$, and the real exchange rate, q_t. The linearized monetary policy rule is specified as follows

$$\widetilde{R}_t = \rho_r(s_t^{mp})\widetilde{R}_{t-1} + \left(1 - \rho_r(s_t^{mp})\right) \left[\omega_\pi(s_t^{mp})\widetilde{\pi}_t + \omega_y(s_t^{mp})\widetilde{y}_{h,t} + \omega_q(s_t^{mp})\widetilde{q}_t\right] + \xi_t^r \tag{35}$$

where ρ_r is the interest rate smoothing parameter capturing monetary policy inertia. ω_π, ω_y and ω_q are the policy coefficients chosen by the central bank with respect to inflation, domestic output and the real exchange rate, respectively. The monetary policy shock, ξ_t^r, is assumed independent and identically distributed ($i.i.d.$). (35) is consistent with a managed floating exchange rate regime (Sangare, 2016).

In order to accommodate time-varying behaviour of the central bank subject to the state of the economy, we allow the parameters in the Taylor rule to switch between two regimes as follows

$$s_t^{mp} \in \{Hawkish, Dovish\} \tag{36}$$

We allow for independent changes in the conduct of monetary and fiscal policy. In line with the Taylor principle, the feedback coefficient on inflation is expected to be greater than unity, i.e., $\omega_\pi > 1$. Under such circumstances, the monetary authority is unconstrained and can thus respond most to inflation in order to achieve price stability (the "Hawkish" regime). This is consistent with the notion of active monetary policy in the categorization of equilibrium policies by Leeper (1991). On the other hand, monetary policy is "Dovish" if it is constrained by private and fiscal policy behaviour in such a way that money stock is allowed to respond to deficit shocks (Leeper, 1991). In this case, the fiscal authority independently determines its budget while the monetary authority is required to adjust monetary policy in order to satisfy the government budget constraint. This is usually the case when the central bank pursues macroeconomic objectives other than price stability, such as output growth. We follow Bjornland et al. (2018) and assume that the policy regimes differ in the central bank's responsiveness to inflation and that the prior mean for the dovish regime allows $\omega_\pi < 1$.

4.7. Aggregation, market clearing and the rest of the world

The aggregate demand equations are derived from the model setup, where domestic output, $Y_{h,t}$, is absorbed by households consumption of domestically produced goods, $C_{h,t}$; materials input used up by oil-producing firms, M_t; government consumption of domestically produced goods, $G_{h,t}$; non-oil exports, $C^*_{h,t}$; and domestic investment, $I_{h,t}$.[16] Consequently, the domestic resource constraint is given by $P_{h,t}Y_{h,t} = P_{h,t}C_{h,t} + \varepsilon_t P^*_{h,t}C^*_{h,t} + P_{h,t}M_t + P_{h,t}I_{h,t} + P_{h,t}G_{h,t}$.

On the other hand, the aggregate GDP, Y_t, which combines both oil ($Y_{o,t}$) and non-oil output ($Y_{h,t}$) is given by $P_tY_t = P_{h,t}Y_{h,t} + \varepsilon_t P^*_{o,t}Y_{o,t} = P_{h,t}C_{h,t} + P_{h,t}M_t + P_{h,t}I_{h,t} + P_{h,t}G_{h,t} + NX_t$. Net exports ($NX_t$) is given by $NX_t = EX_t - IM_t$, where EX_t is aggregate

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[16] $I_{h,t}$ is used to augment the stock of physical capital available for use in the production process in period $t+1$.

exports and IM_t represents aggregate imports. The former comprise oil exports ($EX_{o,t}$ measured as $\varepsilon_t P_{o,t}^* Y_{o,t}$) and non-oil exports ($EX_{no,t}$ measured as $\varepsilon_t P_{h,t}^* C_{h,t}^*$). Similarly, the latter comprise oil imports ($IM_{o,t}$ measured as $P_{lo,t} O_t$) and non-oil imports ($IM_{no,t}$ measured as $P_{f,t} Y_{f,t}$), where the quantity of non-oil goods imported into the economy is given by $Y_{f,t} = C_{f,t} + I_{f,t} + G_{f,t}$. Setting the current account equal to the financial account, we obtain the following expression for the Balance of Payments

$$\frac{q_t b_t^*}{R_t^* \mu_t^*} = q_t b_{t-1}^* + nx_t - (1-\tau)\, q_t p_{o,t}^* y_{o,t} + q_t f di_t^* \tag{37}$$

The labour and capital markets clear as follows

$$N_t = \int_0^1 N_t^R(j)\, dj + \int_0^1 N_t^{NR}(j)\, dj \qquad \text{and} \qquad K_{h,t} = \int_0^1 K_{h,t}(j)\, dj$$

The demand for domestic goods by the foreign economy (the rest of the world), $C_{h,t}^*$, is given by

$$C_{h,t}^* = \gamma^* \left(\frac{P_{h,t}^*}{P_t^*} \right)^{-\eta^*} C_t^* \tag{38}$$

and the IS curve for the foreign economy is specified as

$$\frac{1}{R_t^* \mu_t^*} = \beta E_t \left[\left(\frac{C_{t+1}^{R*} - \phi_c^* C_t^*}{C_t^{R*} - \phi_c^* C_{t-1}^*} \right)^{-\sigma^*} \frac{1}{\pi_{t+1}^*} \right] \tag{39}$$

with the analogous parameters and variables for the foreign economy.

The central bank in the foreign economy sets the interest rate in a similar fashion as the domestic economy by following a Taylor rule with the analogous policy parameters and variables. The linearized monetary policy rule for the foreign economy is specified as follows

$$\tilde{R}_t^* = \rho_{r^*} \tilde{R}_{t-1}^* + \left(1 - \rho_{r^*}\right) \left[\omega_{\pi^*} \tilde{\pi}_t^* + \omega_{y^*} \tilde{y}_{h,t}^* \right] + \xi_t^{r^*} \tag{40}$$

Finally, the inflation rate in the foreign economy is assumed to follow an $AR(1)$ process as follows $\pi_t^* = \left(\pi_{t-1}^*\right)^{\rho_{\pi^*}} \exp\left(\xi_t^{\pi^*}\right)$. This completes the model.

Overall, the SOE is driven by 11 stochastic shocks relating to (i) 3 oil shocks: real international oil price ($\xi_t^{p_o^*}$), oil sector productivity ($\xi_t^{a_o}$), LOP in oil price ($\xi_t^{\psi^o}$); (ii) 2 domestic supply shocks: domestic total factor productivity ($\xi_t^{a_h}$), domestic risk premium (ξ_t^{μ}); (iii) 1 monetary policy shock: domestic monetary policy (ξ_t^{r}); (iv) 2 fiscal policy shocks: government consumption ($\xi_t^{g_c}$), tax (ξ_t^{tx}); and (v) 3 external shocks: foreign monetary policy ($\xi_t^{r^*}$), foreign inflation ($\xi_t^{\pi^*}$), foreign risk premium ($\xi_t^{\mu^*}$).

5. The regime-switching models

In this section, we take an agnostic approach in regime-switching, assuming that the model economy switches exogenously between regimes. We describe the solution procedure (in Online Appendices D and E) and then discuss the constant-probability switching assumptions.

5.1. Regime shifts in time-varying oil price volatility

We first consider only two states with two distinct values: $s_t^{vo} \in (High, Low)$ where the time variation is modelled by the means of stochastic volatility. As defined by (23), this is done by augmenting the AR(1) process for the oil price shock with a regime-dependent variance term $\sigma_{p_o^*}^2(s_t^{vo})$ so that the disturbance term, $\xi_t^{p_o^*} \sim N(0, \sigma_{p_o^*}^2(s_t^{vo}))$, and the persistence parameter, $\rho_{p_o^*}(s_t^{vo})$, follows the same chain. The first-order Markov chain for the unobserved s_t^{vo}, which gives the probability that state s_{High}^{vo} is followed by state s_{Low}^{vo}: $p_{i,j}$ where $\{i, j\} \in \{High, Low\}$, assumes the usual implication for inter-temporal interdependency, given by $Pr\{s_{t+1}^{vo} = j | s_t^{vo} = i\} = p_{i,j}$ where $\sum_{j=1}^{N} p_{i,j} = 1$ and $i = 1, 2, ..., N$. The transition probability plays an important role in determining the real outcome of the economy because it is taken into account by agents in the model when forming expectations and making decisions. For the stochastic volatility, letting subscripts $1 = Low$ and $2 = High$ denote the two volatility regimes, respectively, the transition probability matrix is

$$P^{vo} = \begin{bmatrix} p_{11}^{vo} & p_{12}^{vo} \\ p_{21}^{vo} & p_{22}^{vo} \end{bmatrix} \tag{41}$$

This is the first switching model with constant probabilities of Markov-switching, $p_{i,j}^{vo}$, which is assumed to be entirely independent of other parts of the underlying model.

5.2. Regime shifts in volatility and policy parameters

In this section, we consider two versions of the Markov-switching DSGE model. First, we allow regime-switching in our SOE Taylor rule in order to assess how the monetary policy reaction function responds to inflation - i.e. based on the two monetary policy states as defined by (35) and (36). The policy parameters switch together with s^{vo}, following a synchronized two-state Markov process (Model 1).[17] The alternative model is broader and assumes that both the price volatility and monetary policy rule are governed by two discrete-state Markov chains. In this case, we assume the transition probabilities for an independent chain where the variations in the oil price and policy stance are not synchronized and estimate a four-regime model.

To introduce the Markov regimes in this DSGE specification, we follow Bianchi and Ilut (2017) and Liu and Mumtaz (2011) by partitioning the parameter vector: $\Theta = \{\Theta^{s,mp}; \Sigma^{s,vo}; \bar{\Theta}\}$, where $\Theta^{s,mp}$ denotes the policy parameters subject to regime shifts, and $\{s, mp\} = 1, 2$ for *Hawkish* and *Dovish* monetary policy, respectively, and $\Theta^{s,vo}$ is for the price volatility that is subject to regime shifts. The discrete values $\{s, mp\} = 1, 2 = Hawkish, Dovish$ can either evolve independently of $\{s, vo\} = 1, 2 = Low, High$ or be governed by the previous chain, as assumed by our Model 1. $\bar{\Theta}$ contains the time-invariant parameters in the model. As a result, there can be two transition matrices for four possible regimes which are both 2×2, respectively

$$P^{vo} = \begin{bmatrix} p_{11}^{vo} & p_{12}^{vo} \\ p_{21}^{vo} & p_{22}^{vo} \end{bmatrix} \qquad P^{mp} = \begin{bmatrix} p_{11}^{mp} & p_{12}^{mp} \\ p_{21}^{mp} & p_{22}^{mp} \end{bmatrix} \tag{42}$$

The solution to the Markov-switching model, defined by Farmer et al. (2011), follows the regime-dependent system[18]

$$\mathbb{Y}_t = \Omega^*(s_t^{mp}, P^{mp})\mathbb{Y}_{t-1} + \Gamma^*(s_t^{mp}, P^{mp}, s_t^{vo}, P^{vo})\xi_t \qquad \mathbb{O}_t = L\mathbb{Y}_t \tag{43}$$

where Ω^* depends on the parameters that can be switched and the probability of moving across the two states; Γ^* is a function of vector of the volatility parameters as well as the policy parameters.

6. Data and methodology

Next, we turn to Bayesian methods for estimating the model parameters and explain our data and calibration used in the quantitative analysis.

6.1. Data, calibration and priors

The model developed in the previous section is estimated for the Nigerian economy using 73 quarterly observations on 15 selected macroeconomic variables over the sample period of 2000Q2 - 2018Q2.[19] While Nigeria represents the small open-economy in our model setup, the rest of the world consists of Nigeria's major trading partners of the Euro area, the US, and India.[20]

The domestic variables are: per capita real domestic GDP ($y_{h,t}$), per capita real consumption (c_t), per capita real investment ($i_{no,t}$), real effective exchange rate (q_t), headline consumer price index (p_t), core consumer price index ($p_{no,t}$), nominal interest rate (R_t), oil output ($y_{o,t}$), government debt (b_t), tax revenue (tx_t) and government consumption ($g_{c,t}$). The data set for these variables are sourced and constructed from the National Bureau of Statistics and the CBN Statistics database.

The foreign economy variables include trade-weighted foreign real GDP per capita (y_t^*), foreign aggregate consumer price index (p_t^*), and foreign interest rate (R_t^*). The data set used for the computation of the trade-weighted foreign variables as well as the real international price of oil ($p_{o,t}^*$) are retrieved from the Federal Reserve Bank of St. Louis and the International Financial Statistics.

We carry out necessary transformations on the data set in order to make them model consistent. First, as in Section 3.1, we demean and deseasonalize the relevant variables. Since the variables implied by our model are stationary, we remove trend from the data by taking first difference in the logarithm of the variables with the exception of the domestic and foreign interest rates. In order to avoid the problem of stochastic singularity when evaluating the likelihood function (and also to account for possible inaccuracies in national accounts data for the domestic economy), we balance the number of observables with the number of stochastic disturbances in our model by incorporating four measurement errors relating to domestic output (ξ_t^{yobs}), consumption (ξ_t^{cobs}), investment (ξ_t^{iobs}), and oil output (ξ_t^{yoobs}). Details of the calibrated parameters and priors are appended to the paper in Online Appendix F.

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[17] Our assumption of the synchronized-switching model is based on the observation that the monetary authority in Nigeria has responded differently to different oil price shocks in the past, depending on the persistence of the shock and the state of the economy prior to the shock. It aligns with the above setup where variances are subject to stochastic switches between low- and high-variance states and allows us to study the behaviour of policy that is affected by these variances. In other words, the heteroscedasticity in oil price shocks highlights the time variation in the amount of uncertainty faced by policymakers. This is particularly relevant to their responses that are affected by high-variance episodes.

[18] The rational expectations solution to the state-space form of Model 0 (the non-switching model) is discussed in Online Appendix D.

[19] This choice of the estimation sample was based on data availability for Nigeria, but we carry out an additional check based on an extended sample in Section 8 below.

[20] These three regions account for about 65% of Nigeria's total external trade over the last two decades. In the normalized weights for the computation of the foreign variables, the Euro area is predominant with a trade weight of 0.39 while the weights for the US and India are 0.36 and 0.25, respectively.

6.2. Bayesian estimation and filtering

We estimate the model variants (including the baseline model) by Bayesian methods which entail obtaining the posterior distribution of the model's parameters, θ, conditional on the data $\mathbb{Y}^T$. Using the Bayes' theorem, the posterior distribution is obtained as

$$p(\theta, P, S^T | \mathbb{Y}^T) = \frac{L(\mathbb{Y}^T | \theta, P, S^T) p(S^T | P) p(\theta, P)}{\int L(\mathbb{Y}^T | \theta, P, S^T) p(S^T | P) p(\theta, P) d(\theta, P, S^T)} \tag{44}$$

where S^T collects the history of the realized states of the system, $p(\theta, P)$ denotes the prior density of the parameter vector θ, $p(S^T | P)$ is the prior density of the states and P denotes the transition probability matrix, $L(\mathbb{Y}^T | \theta, P, S^T)$ is the likelihood of the sample $\mathbb{Y}^T$ with T observations, and $\int L(\mathbb{Y}^T | \theta, P, S^T) p(S^T | P) p(\theta, P) d(\theta, P, S^T)$ is the marginal data density which is useful for measuring the model fit and used in our Bayesian model comparisons.[21] Since there is no closed form analytical expression for the posterior, this must be simulated.[22]

For evaluating the likelihood function when regime-switching is involved, an exact filtering procedure such as the Kalman filter that can be used for updating the unobservable variables is impracticable because the likelihood depends on the histories of all possible regimes and it is not feasible to trace all the updates in the filtering procedure which can grow exponentially with the size of T. A computationally efficient solution to this is to use the Kim and Nelson (1999) filter which can collapse the updates by averaging at each step of the filtering procedure.

The joint posterior distribution of θ is then obtained in two steps. First, the posterior modes and the Hessian matrix are obtained via standard numerical optimization routines. The Hessian matrix is then used in the Metropolis-Hastings (MH) algorithm to generate a sample from the posterior distribution. The Monte-Carlo Markov Chain Metropolis-Hastings (MCMC-MH) algorithm is used for simulating 100,000 random draws from the posterior density,[23] with the variance-covariance matrix of the perturbation term in the algorithm being adjusted in order to maintain a reasonable acceptance ratio (between 29%-31%). These draws are then used for inference in the estimations and robustness checks below.

7. Empirical results and analysis

Table 1 reports the parameter estimates, summarizing posterior means of the estimated parameters and 90% high posterior density intervals for all the model specifications, as well as the posterior marginal likelihood. Overall, the parameter estimates are plausible and robust across specifications. In what follows, we first discuss the estimates. Second, we evaluate the model's empirical fit using the estimated log-likelihoods and second moments.[24] Third, we compute the impulse responses and carry out the moment analysis in order to assess the impact of the oil price shock and model-implied dynamics.

7.1. Parameter estimates

First, the posterior means of Model 0 are broadly consistent with the findings from recent empirical research conducted for emerging market economies and for Nigeria in particular (see, for example, Gabriel et al., 2016, Omotosho, 2019, among others). Our estimation delivers that, based on the posterior estimates of γ_R, about 20% of the households is liquidity constrained. These households in Nigeria do not trade on financial markets and consume entirely their wage income each period. This is slightly below the prior value and those usually found in earlier empirical studies. The estimate of v implies that there is about 55% pass-through of international oil price to domestic prices and the government subsidizes about half of the consumption of fuel in the domestic economy.

In terms of fiscal policy, the estimated feedback parameter with respect to oil output, ω_{yo}, is -0.25, suggesting evidence of countercyclical government expenditure. The fiscal policy is 'active' for demand stabilization, implying that the country is able to sustain increased government spending even during periods of oil price drop. The tax policy response is, on the other hand, 'passive'. Our estimated $\varphi_b = 2.1$ means that the fiscal authority strongly adjusts taxes in order to ensure debt stability in the regime that passively accommodates the monetary authority.[25]

It is interesting to note that the estimated values of the key switching parameters are very different between the various regimes. The standard deviation of the oil price shock, $\xi_t^{p_o^*}$, is estimated to be nearly two times higher in the high volatility regime than in the

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[21] We compute the log marginal data density approximated by the modified harmonic mean sampling from the posterior distribution.

[22] Our Bayesian estimation and filtration are obtained using the RISE toolbox in Matlab. See Maih (2015) for further details.

[23] The first 20% 'burn-in' observations are discarded to remove any dependance from the initial conditions. The number of replications is sufficiently large to explore the whole parameter space and asymptotically move to its ergodic distribution.

[24] Discussed in Online Appendix G in which we also conduct an invertibility test on the form of RE solution for validating our impulse response results.

[25] Following the work by Bianchi and Ilut (2017) and Jin and Xiong (2021), one could allow the possibility of switches in fiscal policy to capture the time-varying nature of fiscal policy for oil-exporting countries in which fiscal spending and planning can heavily depend on oil revenues. For example, one could assume a tax policy active regime under which the fiscal authority becomes active and is not committed to keep debt stable ($\varphi_b = 0$). Furthermore, combinations of fiscal and monetary policy states can be prone to indeterminacy which can affect the behaviour of policymakers. However, as previously noted, in view of the lack of central bank communications combined with weak governance and the political inflexibility faced by the fiscal authorities in developing countries with fuel subsidy regulations, our focus, in terms of the scope of the paper, is on the role of monetary policy in managing aggregate demand and examining how monetary policy plays a role in the macroeconomic response to oil price shocks.

Table 1
Prior and posterior distributions.

Parameter	Prior distribution			Posterior distribution		
	Density	Mean	SD/DoF	Model 0	Model 1	Model 2
Ricardian consumers: γ_R	Beta	0.60	0.10	0.8234 [0.7932:0.8556]	0.8258 [0.7700:0.8981]	0.8253 [0.8036:0.8473]
Labour supply elasticity: φ	Gamma	1.45	0.10	1.4314 [1.4302:1.4325]	1.4685 [1.3575:1.5983]	1.4376 [1.4154:1.4694]
Relative risk aversion: σ	Inv. Gamma	2.00	0.40	1.2654 [1.2260:1.3051]	1.2021 [1.0761:1.3458]	1.4227 [1.3662:1.5083]
External habit: ϕ_c	Beta	0.70	0.10	0.4332 [0.3826:0.4795]	0.3490 [0.2858:0.4125]	0.4096 [0.3858:0.4303]
Investment adj. cost: χ	Gamma	4.00	3.00	16.6782 [15.6640:17.8428]	18.6519 [13.7652:22.1644]	16.7882 [14.4645:19.2569]
Fuel pricing parameter: ν	Beta	0.30	0.10	0.5207 [0.4595:0.5951]	0.5460 [0.4698:0.6208]	1
Oil - core cons. elast.: η_o	Gamma	0.20	0.10	0.1627 [0.1484:0.1772]	0.2053 [0.1329:0.2789]	0.1145 [0.0706:0.1466]
For. - dom. cons. elast.: η_c	Gamma	0.60	0.20	0.4972 [0.4215:0.5795]	0.5242 [0.3907:0.6461]	0.5564 [0.5071:0.5898]
For. - dom. inv. elast.: η_i	Gamma	0.60	0.20	0.5760 [0.5629:0.5870]	0.4351 [0.3170:0.5367]	0.4923 [0.4599:0.5222]
Calvo - domestic goods: θ_h	Beta	0.70	0.10	0.5855 [0.5594:0.6278]	0.6244 [0.5737:0.6840]	0.6248 [0.6099:0.6417]
Calvo - imported goods: θ_f	Beta	0.70	0.10	0.6401 [0.6246:0.6557]	0.6571 [0.5815:0.7317]	0.6707 [0.6022:0.6573]
Calvo - exported goods: θ_{hf}	Beta	0.70	0.10	0.6946 [0.6139:0.7747]	0.7500 [0.6616:0.8476]	0.7374 [0.6846:0.7945]
Monetary policy						
Taylor rule - inflation: ω_π = Hawkish	Gamma	1.500	0.25	3.5875 [3.5391:3.6328]	3.2061 [2.8738:3.5370]	3.5016 [3.3536:3.6253]
Taylor rule - inflation: ω_π = Dovish	Gamma	0.800	0.25		1.2827 [1.0839:1.4662]	1.1995 [1.1624:1.2409]
Taylor rule - output: ω_y = Hawkish	Gamma	0.125	0.05	0.0828 [0.0683:0.0984]	0.1262 [0.0573:0.1917]	0.0906 [0.0666:0.1285]
Taylor rule - output: ω_y = Dovish	Gamma	0.125	0.05		0.1099 [0.0450:0.1684]	0.1042 [0.0805:0.1366]
Taylor rule - exch. rate: ω_q = Hawkish	Gamma	0.125	0.05	0.0887 [0.0842:0.1053]	0.1067 [0.0654:0.1440]	0.0767 [0.0522:0.0988]
Taylor rule - exch. rate: ω_q = Dovish	Gamma	0.125	0.05		0.1242 [0.0404:0.2184]	0.1415 [0.0871:0.1919]
Interest rate smoothing: ρ_r = Hawkish	Beta	0.500	0.25	0.2071 [0.1359:0.2772]	0.1116 [0.0489:0.1596]	0.1500 [0.0461:0.2547]
Interest rate smoothing: ρ_r = Dovish	Beta	0.500	0.25		0.4385 [0.1371:0.7298]	0.4505 [0.3381:0.5800]
Fiscal policy						
Tax - fiscal debt: φ_b	Normal	0.80	1.00	2.1016 [2.0965:2.1068]	2.1968 [2.0145:2.4067]	2.0916 [2.0640:2.1178]
Tax smoothing: ρ_{tx}	Beta	0.50	0.25	0.6959 [0.6276:0.7450]	0.6940 [0.6486:0.7390]	0.6502 [0.5925:0.6939]
Tax - gov. exp.: φ_g	Normal	1.90	1.00	1.8952 [1.7727:1.9742]	1.8015 [1.5781:2.0062]	1.8128 [1.7444:1.8646]
Tax - subsidies: φ_{os}	Normal	0.20	1.00	1.5518 [1.4694:1.6362]	1.4569 [1.3064:1.6233]	1.4385 [1.3442:1.5346]
Tax - oil revenue: φ_{or}	Normal	0.60	1.00	1.8109 [1.7327:1.8618]	1.7682 [1.5362:1.9792]	1.6867 [1.5627:1.7616]
Govt. cons. - output: ω_{yo}	Normal	0.00	0.50	-0.2573 [-0.2927:-0.2235]	-0.2444 [-0.2969:-0.1934]	-0.2839 [-0.3093:-0.2630]
Govt. cons. smoothing: ρ_{g_c}	Beta	0.50	0.25	0.3398 [0.2806;0.4057]	0.2674 [0.2121:0.3201]	0.3306 [0.2647:0.3880]
Persistence of shocks						
Int'l oil price shock: $\rho_{p_o^*}$ = High	Beta	0.50	0.25	0.9318 [0.8948:0.9750]	0.9586 [0.9226:0.9895]	0.9383 [0.9021:0.9635]
Int'l oil price shock: $\rho_{p_o^*}$ = Low	Beta	0.50	0.25		0.3613 [0.0131:0.7339]	0.2737 [0.2007:0.3344]
Law of one price gap - oil: ρ_{ψ^o}	Beta	0.50	0.25	0.7040 [0.6440:0.7665]	0.7620 [0.6845:0.8526]	0.8416 [0.7935:0.8906]
Dom. productivity: ρ_{a_h}	Beta	0.50	0.25	0.8117 [0.7268:0.8950]	0.8058 [0.7519:0.8571]	0.8210 [0.7744:0.8732]
Oil productivity: ρ_{a_o}	Beta	0.50	0.25	0.9587 [0.9280:0.9909]	0.9568 [0.9241:0.9926]	0.9684 [0.9441:0.9961]
Dom. risk premium: ρ_μ	Beta	0.50	0.25	0.7298 [0.6826:0.7827]	0.7817 [0.6975:0.8468]	0.8032 [0.7441:0.8768]
For. monetary policy: ρ_{r^*}	Beta	0.50	0.25	0.4769 [0.3976:0.5533]	0.3962 [0.3191:0.4670]	0.4637 [0.3313:0.5781]
For. risk premium: ρ_{μ^*}	Beta	0.50	0.25	0.7930 [0.7447:0.8532]	0.8244 [0.7684:0.8716]	0.8024 [0.7521:0.8623]
For. inflation: ρ_{π^*}	Beta	0.40	0.25	0.1401 [0.0003:0.2353]	0.0803 [0.0191:0.1371]	0.1060 [0.0554:0.1680]
Standard deviation of shocks						
Int'l oil price: $\xi_t^{p_o^*}$ = High	Inv. Gamma	0.10	4.00	0.1525 [0.1391:0.1686]	0.2076 [0.1107:0.3297]	0.1646 [0.1093:0.2311]
Int'l oil price: $\xi_t^{p_o^*}$ = Low	Inv. Gamma	0.10	4.00		0.1209 [0.1062:0.1403]	0.1229 [0.1080:0.1388]
Dom. productivity: $\xi_t^{a_h}$	Inv. Gamma	0.10	4.00	0.1497 [0.1223:0.1753]	0.1721 [0.1385:0.2057]	0.1500 [0.1271:0.1660]
Law of one price gap - oil: $\xi_t^{\psi^o}$	Inv. Gamma	0.10	4.00	0.6240 [0.5301:0.7140]	0.6266 [0.4960:0.7503]	0.3859 [0.3481:0.4293]
Dom. monetary policy: ξ_t^r	Inv. Gamma	0.10	4.00	0.3812 [0.3360:0.4277]	0.4154 [0.3612:0.4708]	0.4092 [0.3495:0.4746]
Oil productivity: $\xi_t^{a_o}$	Inv. Gamma	0.10	4.00	0.1987 [0.1774:0.2272]	0.2037 [0.1807:0.2287]	0.2024 [0.1844:0.2211]
Dom. fiscal policy: $\xi_t^{g_c}$	Inv. Gamma	0.10	4.00	0.1348 [0.1214:0.1477]	0.1340 [0.1179:0.1598]	0.1428 [0.1263:0.1555]
Dom. risk premium: ξ_t^μ	Inv. Gamma	0.10	4.00	0.1967 [0.1756:0.2234]	0.1602 [0.1312:0.1879]	0.1743 [0.1558:0.1919]
Tax: ξ_t^{tx}	Inv. Gamma	0.10	2.00	0.1349 [0.1215:0.1473]	0.1368 [0.1191:0.1557]	0.1392 [0.1253:0.1523]
For. monetary policy: $\xi_t^{r^*}$	Inv. Gamma	0.10	4.00	0.0946 [0.0814:0.1057]	0.1047 [0.0866:0.1242]	0.1001 [0.0794:0.1183]
For. risk premium: $\xi_t^{\mu^*}$	Inv. Gamma	0.10	4.00	0.0446 [0.0386:0.0508]	0.0425 [0.0346:0.0511]	0.0486 [0.0380:0.0592]
For. inflation: $\xi_t^{\pi^*}$	Inv. Gamma	0.01	4.00	0.0053 [0.0047:0.0059]	0.0049 [0.0042:0.0055]	0.0050 [0.0042:0.0057]
Transition probability - volatility						
p_{12}^{vo} [Low, High]	Beta	0.50	0.28	–	0.0325 [0.0018:0.0583]	0.0261 [0.0004:0.0600]
p_{21}^{vo} [High, Low]	Beta	0.50	0.28	–	0.3438 [0.1027:0.5634]	0.3463 [0.2739:0.4185]
Marg. data density				756.2058	778.2268	744.3944

low volatility regime in Model 1. The persistence parameter, $\rho_{p_o^*}$, however, moves in the other direction, with high persistence in the low volatility regime than that in the high volatility regime. The periods of major oil price fluctuations do not tend to be long-lasting. The difference clearly suggests evidence of distinct oil price movements that are time-varying in our model-implied dynamics. Model 0 appears to over-estimate the persistence of an oil price shock, and hence the central bank's response to inflation.

The difference between the policy parameters is also clear and substantial in Model 1. We find that the estimated central bank reaction function shows strong responses to inflation and the response is very aggressive under the high response regime (hawkish). Evidence from all three models shows moderate feedback of the central bank to output (ω_y) and the exchange rate (ω_q). In the low response (dovish) regime, the estimated ω_π is 1.28, still satisfying the Taylor principle. Monetary policy is much less responsive with the lower feedback coefficient for inflation. This suggests that the policymakers were concerned with inflation volatility, in line with their primary mandate of price stability throughout the sample period.

The interest rate smoothing parameter and ω_q move in the other direction, with higher values in the less responsive state than those in the high policy response (hawkish) regime. The CBN should respond more aggressively to changes in output and the exchange rate to stabilize the economy than it would in the hawkish regime. Turning to the transition probabilities for the off-diagonal terms of P^{vo}, we find that the probability of moving from high to low oil price volatility ($p_{21}^{vo} = 0.34$) is much higher than the probability of the opposite movement ($p_{12}^{vo} = 0.03$).

Importantly, our models are able to deliver plausible estimates of the remaining structural parameters that are in line with the empirical DSGE literature on emerging economies. For example, the estimates of risk-aversion (σ) indicate that the intertemporal elasticity of substitution in consumption is less than one (0.6-0.8) - our estimates are similar to those usually found in earlier empirical studies. The posterior means of the estimated Calvo parameters imply that the average price contract length is less than 2 quarters, broadly consistent with the findings from recent empirical research conducted for emerging economies (e.g. Gabriel et al., 2016). The remaining parameters are broadly consistent with our prior assumption.

The differences in marginal data densities or the posterior odds ratio (Bayes Factors) are important as decisive evidence in favouring one model over others. Model 1 clearly wins the likelihood ranking and attains the highest posterior odds, thus providing the most comprehensive form of assessment suggesting that our model with switching is empirically relevant and statistically improves the fit to the data. Our finding clearly rejects models with time-invariant parameters and variances in terms of explaining the data using the SOE DSGE structure for Nigeria over the sample period.[26] The discussion of our key output that allows us to quantitatively study the degree and effects of nonlinearity and varying policy stance in the response to an oil price shock is what we turn to next.

7.2. Smoothed transition probabilities

In this section, we report and discuss the smoothed transition probabilities computed based on the posterior estimates (means and medians). The top panel of Fig. 3 shows the filtered probabilities for the high volatility state with regime-switching in the variance of the international oil price identified in the model. As expected, high volatility is detected in the Nigerian economy in two distinct but recurrent periods: throughout 2008-09 as a result of the US credit crisis and in 2014 to 2016. This is consistent with the result under the alternative assumption discussed in Section 8 which identifies the same periods in which high oil price volatility is predominant. The first period corresponds to the 2008 sharp price fall but does not seem to be very persistent. The second period is associated with the 2014 price fall which seems long-lasting, and culminated into an economic recession witnessed in the country in 2016.

Looking at the top row of Fig. 3 in more detail, our model detects some episodic oil price movements in the early period of our sample. This may be explained by the oil-supply shocks driven by OPEC (political) events, as historical series of exogenous OPEC events may affect oil prices. For example, the civil crisis in Venezuela at the beginning of the millennium led to a drop in oil production. This in turn has implications for the measure of oil shocks that considers price disruptions due to these events. This issue has been studied for the case of the US by Kilian (2009) and Kumar and Mallick (2023) using a SVAR model.

The second row of Fig. 3 depicts the smoothed probabilities based on Model 1, which captures possibly synchronized regime shifts in the monetary policy rule that respond to the oil price volatility states. In the early 2000s, the economy mostly stayed in the hawkish policy regime with a high probability as the CBN responded strongly to inflation as intended and in line with its core mandate of price stability. However, we identify a switch to a dovish state that coincides with the first oil price volatility episode with a high probability, albeit for a relatively brief period, when monetary policy becomes much less responsive. Inflation in Nigeria was brought under control during the financial crisis period, although monetary policy seems to have played a role in stabilizing output during this distinct episode (i.e. in sustaining the high GDP growth around the crisis period).

The CBN appears to have been less sensitive to movements in headline inflation since the 2008-09 global financial crisis as the Monetary Policy Rate becomes more persistent during the period, reflecting a transition to a multiple-mandate regime. Thus, in recent times, the CBN has been involved in quasi-fiscal operations aimed at boosting output, with the belief that its interventions would positively impact the supply-side drivers of inflation. This explains the observed switch in the monetary policy regime after the financial crisis. Our result showing that the economy operates mostly under the more responsive monetary policy state for the remainder of the sample, except for the first oil price episode, can perhaps be rationalized by the arguments presented based on the estimated IRFs discussed in the next section.

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[26] Although the likelihood ranking provides the most comprehensive form of assessment for the relative merits of alternative models, we further compare some selected second moments implied by the estimated models with the dynamics seen in the actual data in Online Appendix G.

Notes:
Top Panel: The figure presents the smoothed probabilities for being in the high oil price volatility regime in the model that allows independent switching in the standard deviations $(\sigma_{p_o^*})$ and persistence $(\rho_{p_o^*})$ of the oil price shock. Their priors are assumed to be inverse gamma with $(0.1, 4)$ and beta with $(0.5, 0.25)$, respectively, for both the high and low regimes. Observed data: international oil price.
Middle Panel: Model 1 $(\nu = 0.546)$. The figure presents the smoothed probabilities for being in the high oil price volatility regime and dovish monetary response regime in the model that allows synchronized switching in the standard deviations and persistence of the oil price shock and the Taylor rule coefficients. See Table 1 for details of their priors. Observed data: core inflation.
Bottom Panel: Model 2 $(\nu = 1)$. The figure presents the smoothed probabilities for being in the high oil price volatility regime and dovish monetary response regime in the model that allows synchronized switching in the standard deviations and persistence of the oil price shock and the Taylor rule coefficients. See Table 1 for details of their priors. Observed data: core inflation.

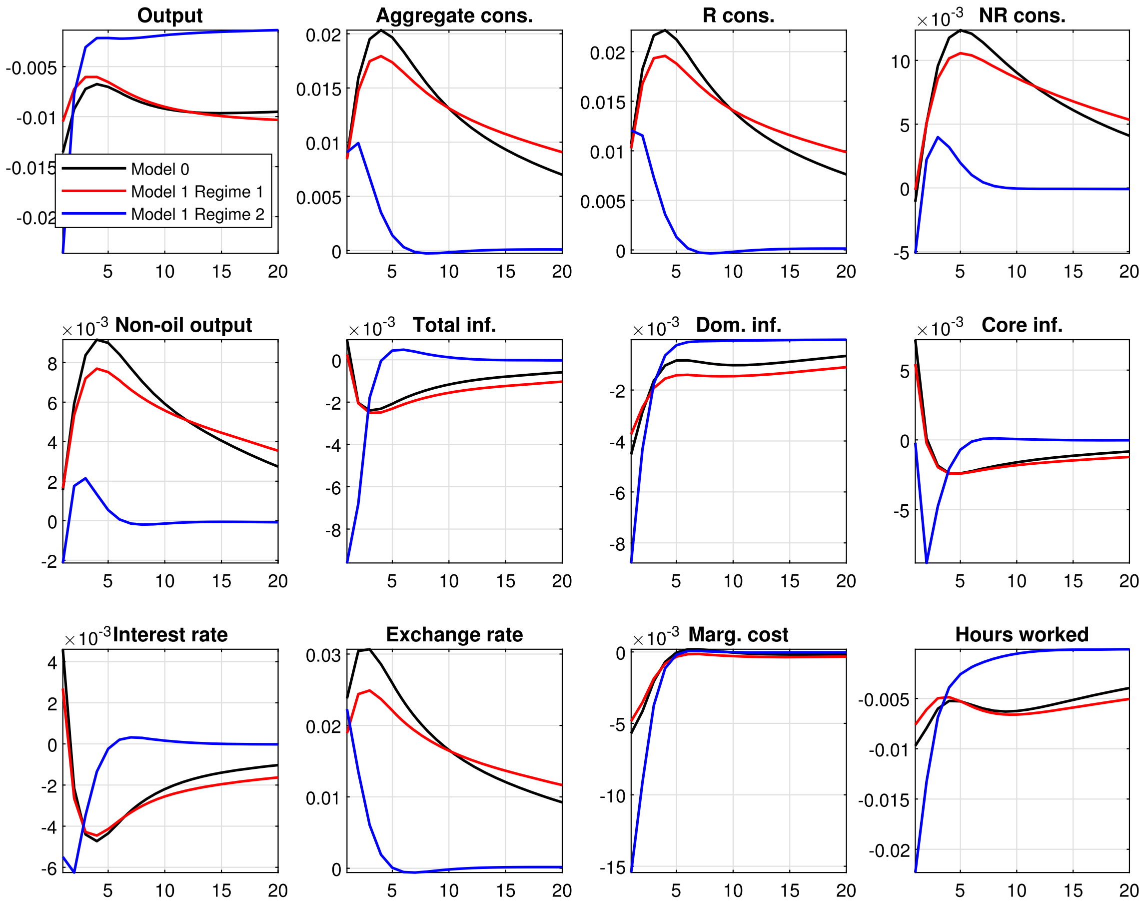
Fig. 3. Smoothed state probabilities.

7.3. Posterior impulse response analysis

We now focus on the (estimated posterior) impulse responses for the international oil price shocks $(\xi_t^{p_o^*})$. To illustrate the role of different regimes identified in the previous section, Fig. 4 plots the mean responses corresponding a negative one standard deviation (s.d.) of the shock's innovation and compares the low and high oil price volatility regimes with synchronized policy reactions (Regime 1: Low Volatility/High Response; Regime 2: High Volatility/Low Response).

The Nigerian economy is heavily import-dependent, especially for raw materials. Thus, a negative oil price shock acts as a negative productivity shock to the economy as firms are unable to import necessary production inputs. Output declines initially within a couple of quarters but rises subsequently as the cost of production decreases. This subsequently increases capital accumulation and investment by firms, and consumption by households. Overall, the effects are generally stronger and more persistent under the high volatility regime and weaker in the low volatility state (except for consumption and the exchange rate). Private consumption rises as more resources become available to agents following the negative shock, but the impacts are smaller and short-lived as predicted by Regime 2 under which the shock leads to a sharp initial decline in output, lower marginal cost faced by domestic firms, and labour demand.

A negative oil price shock in Nigeria also acts as a labour demand shifter. The decreased production cost shrinks labour demand (firms wishing to substitute away from labour), pushing marginal cost down, and lowers prices and the interest rate. When firms experience a decline in their marginal cost as a result of a shock that decreases the cost of production, they adjust prices downwards



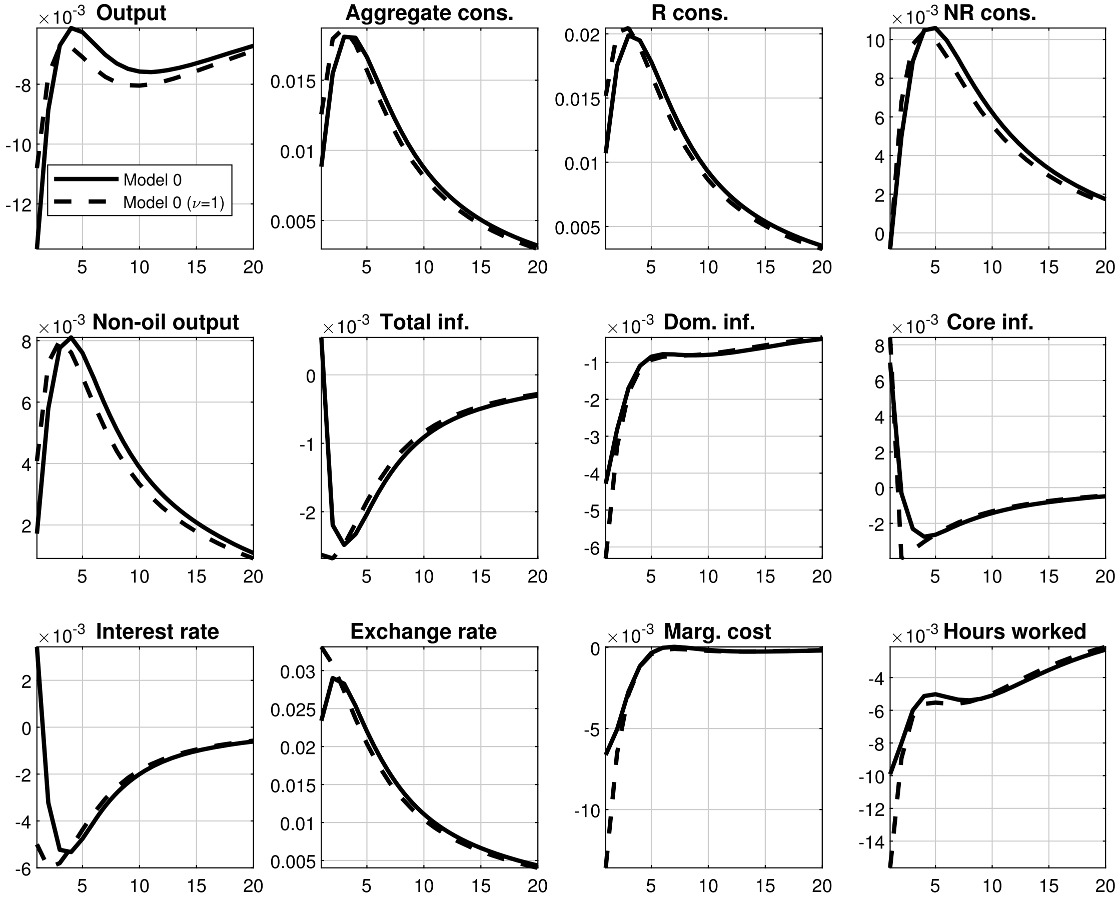
Notes: The figure plots the mean response corresponding a *negative* one s.d. of the oil price shock's innovation. Each response is for a 20 period (5 years) horizon. Regime 1: Low Volatility/High MP Response. Regime 2: High Volatility/Low MP Response. Model 0: The baseline model with constant (time-invariant) parameters. Model 1: The model with switching in the volatility and persistence of oil price shocks and the monetary policy rule.

Fig. 4. Impulse responses to an oil price shock: Model 1.

only partially in the short run. The responses are short-lived and can return to pre-shock levels after a short period depending on the state of oil price volatility and policy response. The shock also contracts oil output and reduces debt and government consumption on impact (not reported), but the latter response shows a subsequent increase in deficit that comes about through a rise in government purchases. Their implication for fiscal cyclicality is consistent with the data but requires further empirical investigations in a separate paper.

In addition, the shock depreciates the currency, in response to a potentially adverse impact of the country's external reserves, thereby improving the terms of trade, which improves goods' competitiveness. The depreciation is much weaker and dies out rapidly under Regime 2 when monetary policy is less responsive. During 'normal times' (i.e. in Regime 1 with a high probability of occurrence), the exchange rate pass-through to domestic prices causes inflation to rise on impact due to higher imported prices (especially non-oil inflation), pushing up wage growth. However, the inflationary pressures triggered by a negative shock under the low volatility regime are relatively small. This may explain why the CBN does not respond to the shock by switching its policy stance, thereby not amplifying the decline in real output associated with the shock. This suggests that the incomplete pass-through effect of oil price changes to domestic retail price of fuel as estimated in Model 1 plays an important role for transmitting monetary policy responses.

From Fig. 4, as expected, there are marked differences in explaining the responses of the variables over time between the different regimes and policy scenarios. Interestingly, Model 1 also clearly predicts that there is an amplification effect in real output under Regime 2 where the oil price variance is high and the policy systematically reacts strongly to output and exchange rate stabilization. As a consequence of lower marginal cost, the total and core measures of inflation initially fall, the CBN responds by embarking on a brief period of expansionary policy, when the economy enters into a less responsive policy regime, in order to stabilize output growth, tackling the contractionary effect of reduced oil price on output. Domestic output is boosted as shown in Fig. 4 where the cumulative output responses are very different from those predicted under the alternative regime. This clearly suggests time-varying output responses in a state characterized by a combination of increased volatility (higher uncertainty about oil prices) and switched monetary stance (expansionary as the CBN responds by decreasing the interest rate in Fig. 4).



Notes: The figure plots the mean response corresponding a *negative* one s.d. of the oil price shock's innovation. Each response is for a 20 period (5 years) horizon. Model 0: The baseline model with constant (time-invariant) parameters. $\nu = 1$ provides us a counterfactual case for Model 0 where there is complete pass-through of international oil price movements to domestic retail price of fuel.

Fig. 5. Impulse response functions: Model 0 with $\nu = 0.546$ and $\nu = 1$.

7.4. Pass-through effect of international oil price

Our analysis so far has some interesting modelling implications, and suggests clear future research directions for modelling a SOE with an oil-exporting economy. For such an economy with fuel consumption subsidies, the subsidy regime distorts domestic price signals and this matters for the response of monetary policy to an exogenous oil price shock. As noted, assuming complete pass-through of international oil price movements to domestic retail price of fuel under our setup could alter the monetary transmission and suggest very different policy responses to the oil price fluctuations.[27]

All the models above estimating the fuel pricing rule, (29), suggest that the pass-through effect for Nigeria is around 52-55%. Such a coefficient with an implicit fuel subsidy programme in place limits the pass-through effect of oil price to domestic prices. Based on (29), the parameter $0 < \nu < 1$ governs the level to which the government subsidizes fuel consumption. A value of $\nu = 1$ provides us a counterfactual case where there is complete pass-through and the subsidy regime ceases to exist. In Fig. 5, we first simulate Model 0 based on the posterior estimates and report the IRFs comparing the transmission of the negative oil price shock when the subsidy programme is 'turned on' and 'turned off'.

We focus our discussion on the behaviour of monetary policy variables. For inflation, when $\nu = 1$, domestic inflation declines more as the prices of domestically produced goods are less sticky in their downward adjustment. Headline inflation also declines following a negative shock to oil prices while the decline is delayed and has a hump-shaped response with the subsidy programme which generates additional price rigidities (when $\nu < 1$). Comparing the two scenarios, the interest rate responses are found to be very different. Reacting to aggregate inflation, the CBN increases the interest rate following a negative oil price shock in the benchmark economy (i.e. a regime with incomplete oil price pass-through), aggravating the contractionary effects on output in the short run, but is able to cut the rate in the bid to boost aggregate demand without facing the immediate inflationary pressure in

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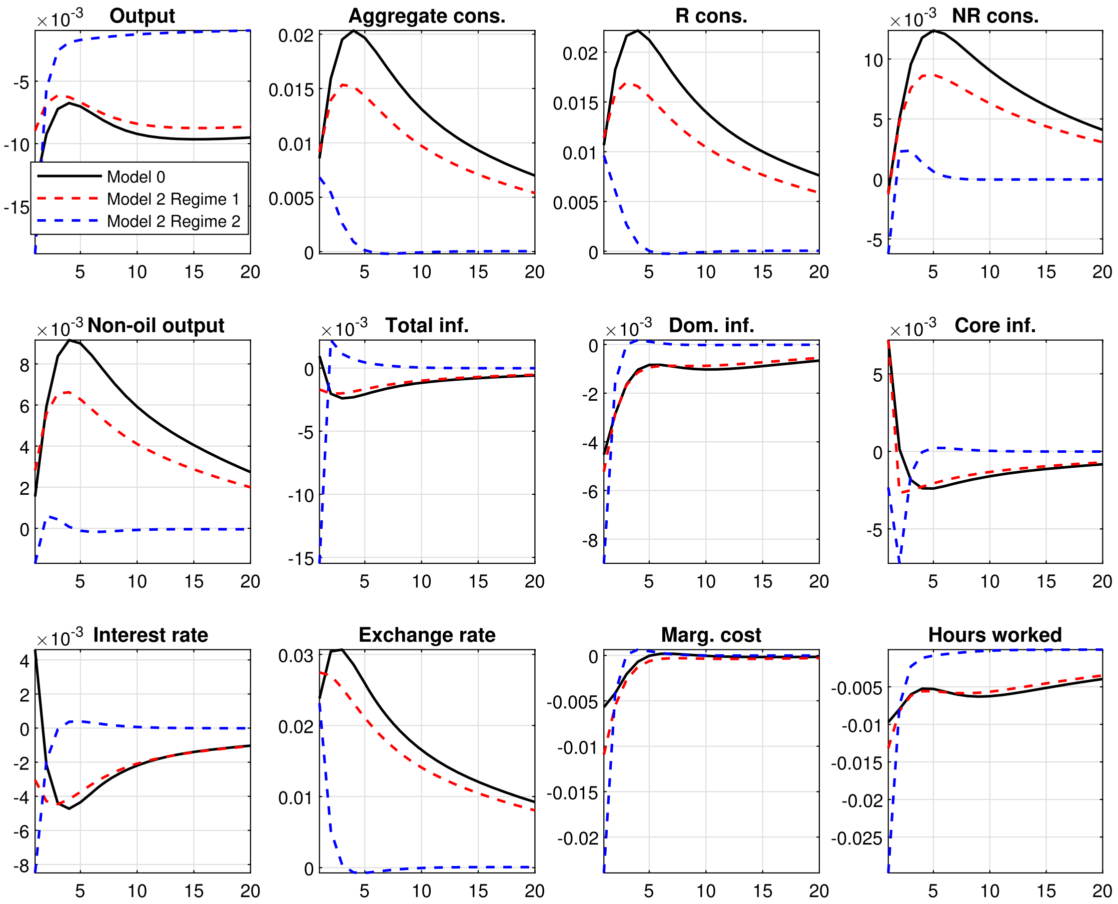
[27] On the 29th of May, the new administration of President Bola Tinubu announced the removal of fuel consumption subsidy, a fiscal reform that has been subject to intense policy debate in Nigeria.



Notes: The figure plots the mean response corresponding a *negative* one s.d. of the oil price shock's innovation. Each response is for a 20 period (5 years) horizon. Regime 1: Low Volatility/High MP Response; Regime 2: High Volatility/Low MP Response. Model 0: The baseline model with constant (time-invariant) parameters. Model 2: A variant of the regime-switching model (Model 1) that assumes complete pass-through of international oil price into the retail price of fuel ($\nu = 1$).

Fig. 6. Impulse responses to an oil price shock: Model 2 ($\nu = 1$).

the counterfactual, ameliorating the output contraction on impact. The latter move causes the real exchange rate to depreciate more under the assumption of no subsidies.

Following the results of our counterfactual simulations, we go back to the estimated model (Model 2) and look at Fig. 6 in more detail, where $\nu = 1$ is imposed in the estimation. The output contraction under this model without fuel subsidies is less severe in the short run. The associated real marginal cost faced by firms, compared with the benchmark case, is much lower, leading to a downward adjustment in the domestic retail prices. Headline inflation declines much further. The results are consistent with those reported in Fig. 5 and across the two Markov-regimes estimated here. In Fig. 5, where the pass-through effect is incomplete, when the economy is in 'normal times' (i.e. Regime 1), the inflationary pressure gives rise to an increase in the interest rate of 0.25 percentage point. However, when assuming the subsidy removal, the CBN under the same regime is able to cut the interest rate by nearly 0.3 percentage point.

Interestingly, following a 1 s.d. negative shock to the real oil price under Regime 2 (i.e. High Volatility/Low Response), the CBN responds by cutting the interest rate much further, and by roughly 0.2-0.3 percentage points more than the cut in the benchmark economy (where ν is estimated), but the reduction is more short-lived. This predicts a better outcome for the output trajectory, ameliorating its contractionary effect, after its initial decline as a result of the oil price fall. This is clearly evident in Table 1. The response to inflation in the Taylor rule is much more aggressive ($\omega_\pi = 3.5$) in Model 2 when hawkish policy is in place while the responses for output and the exchange rate stabilization are relatively stronger when the economy operates in the dovish state than it is in the more active regime.

Our results based on the counterfactual economy reveal another interesting finding. Upon impact, a negative oil price shock matters more for the Ricardian consumers than the non-Ricardian ones across the two oil volatility regimes, in a sense that the increase in aggregate consumption is mostly associated with that from the Ricardian consumers, arising from the additional income that is available to the latter. Consumption rises initially but the non-Ricardian (financially constrained) consumers see this happening

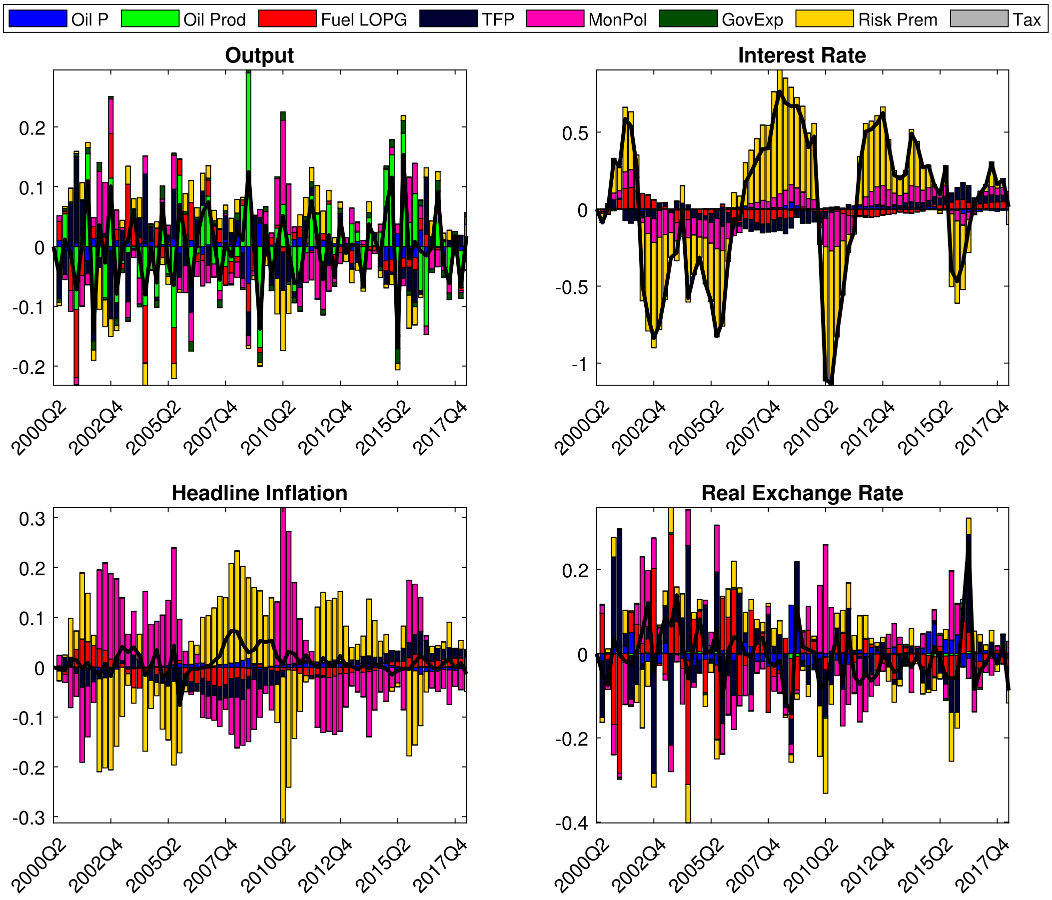


Fig. 7. Historical decomposition: Model 0.

with a much smaller increase in their consumption. These results are useful in helping us understand the issues of different welfare consequences as a result of removing the consumption subsidies and the uncertainty about oil price volatility.

Finally, the bottom panel of Fig. 3 suggests that there are two brief periods in the sample, including the one coinciding with the 2008-09 financial crisis, when the economy switches to a less aggressive policy state in response to a high oil price volatility episode. The first period seems to suggest that the response is triggered by the strength of the pass-through effect into domestic prices (i.e. the extent of policy-induced price rigidities) and the second monetary policy state seems to have lasted several quarters longer than the benchmark case in which a fuel subsidy programme is in place.

7.5. *Historical decomposition of business cycles*

In this section, we examine the historical decomposition of observed GDP, headline inflation, the interest rate and real exchange rate, over the sample period of 2000Q2 - 2018Q2, for the three model economies: the one with constant parameters and variances, the benchmark and the counterfactual ($\nu = 1$). Model 1 in Fig. 8 records a clear spike occurring in the aftermath of the financial crisis with a negative contribution to GDP from the oil price shock when oil price volatility is high. Fig. 8 also shows clearly that oil sector shocks (including the oil price shock) matter in specific periods, such as the one preceding the 2008-09 global financial crisis and the period around the 2015-16 decline in output growth, whereas the evidence is not as clear as shown in Fig. 7, implied by the estimated Model 0. In all three models, it is clear that the oil production shock contributes significantly to output fluctuations.

There is a clear, negative contribution from oil sector shocks to headline inflation when oil price volatility is heightened through the period after the outbreak of the financial crisis. It is worth noting that, under Model 2 with a no subsidy regime (Fig. 9), the contribution is even more substantial and persistent (on average, the contribution is more than twice the size of that implied by Model 1). As explained in the previous section, this is the counterfactual case with complete pass-through of global oil prices to domestic inflation in which price rigidities are reduced. Inflation declines more when $\nu = 1$ as domestic prices are less sticky in their downward adjustment. Clearly, these effects can be amplified and long-lasting when the economy experiences a high volatility state. The observed inflationary pressures over the sample period are also attributable to negative monetary policy and risk premium shocks.

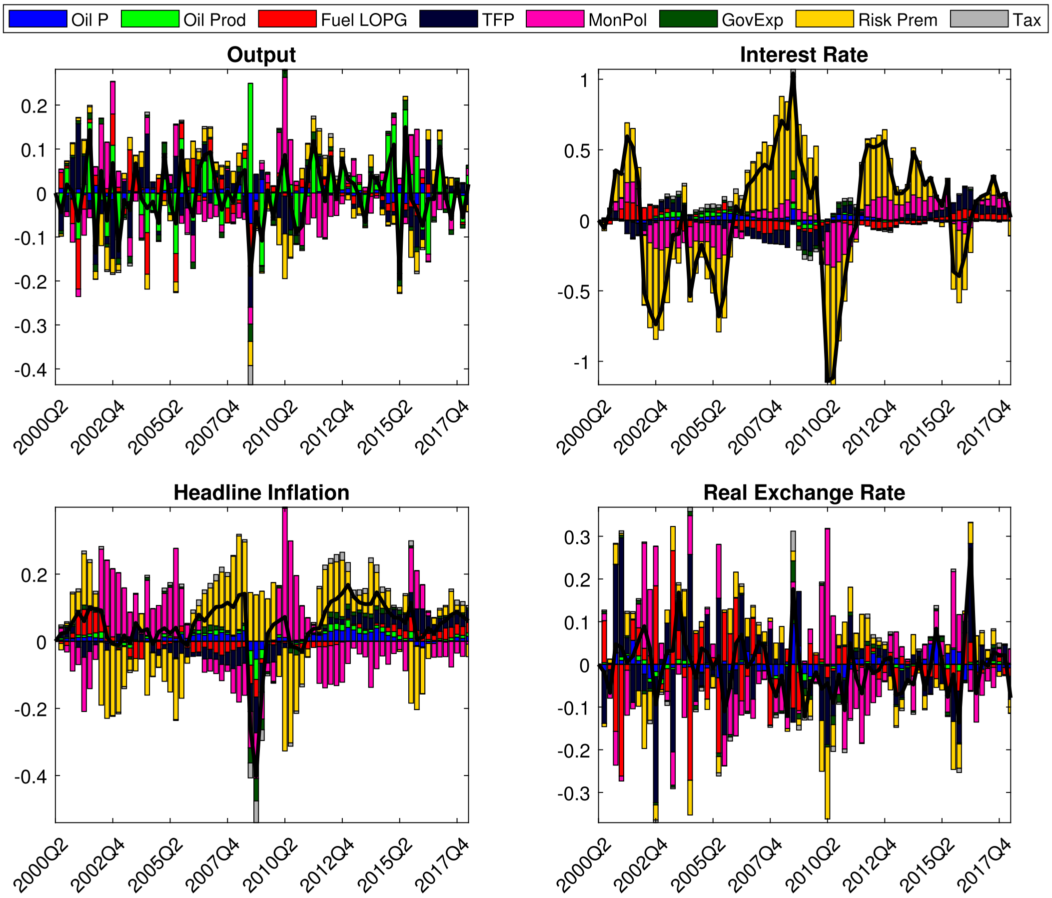


Fig. 8. Historical decomposition: Model 1.

Figs. 7–9 show that oil shocks and monetary policy innovations play non-trivial roles in the movements of real exchange rate in Nigeria. The exchange rate exhibits high volatility prior to the financial crisis and remains relatively stable between 2012 and the second quarter of 2015. In all three models, oil and monetary policy shocks play the dominant roles in the volatile movements in the foreign exchange market. The sharp depreciation recorded in the aftermath of the financial crisis is mainly explained by oil-related disturbances including the oil price shock (Fig. 9) which is followed by an exchange rate appreciation around 2010. The latter is mainly attributable to a positive monetary policy innovation. The heightened oil price volatility starting from the third quarter of 2014 triggers another sharp depreciation in 2015. Due to the ensuing reduction in oil revenues, the CBN responds to this period of crisis caused by oil-related volatility by devaluating the currency and maintaining a hawkish policy stance.

It is interesting to note that, there is also a negative contribution to the nominal interest rate around the same period from the oil price and oil production shocks suggested by Model 2 (Fig. 9), in particular, which would have been a much weaker one under Model 1. Indeed, the regulation of retail fuel price implied by the subsidy programme features in non-oil firms' real marginal cost and their price setting behaviour (i.e. (B.11) and (B.12) in Online Appendix B). Thus, it distorts price signals in the domestic economy and affects the response of monetary policy to inflationary developments. This provides further evidence for the important role of oil price shocks in affecting the macroeconomy.

Finally, as expected, the monetary policy and risk premium shocks play the dominant roles in the evolution of the nominal interest rate. Between the two subsidy regimes, the contributions of these two shocks are stronger in explaining the hawkish policy stance in Model 1 and are stronger in explaining the less active policy stance in Model 2, respectively. The latter captures the alternative inflationary scenario, as explained in Section 7.4, which is based on a value of unity for ν. This result further suggests that the direct effects of oil prices on the interest rate could be accounting for the nonlinearity and time variation in the relationship between the real economy and oil price shocks.

8. Robustness checks

In this section, we carry out robustness checks on key aspects of the model and data, respectively. We evaluate three additional specifications to test the robustness of the main results. The first section considers two alternative regime-switching variants accommodating independent regime shifts. The second check investigates the sensitivity of our results to an alternative model setup

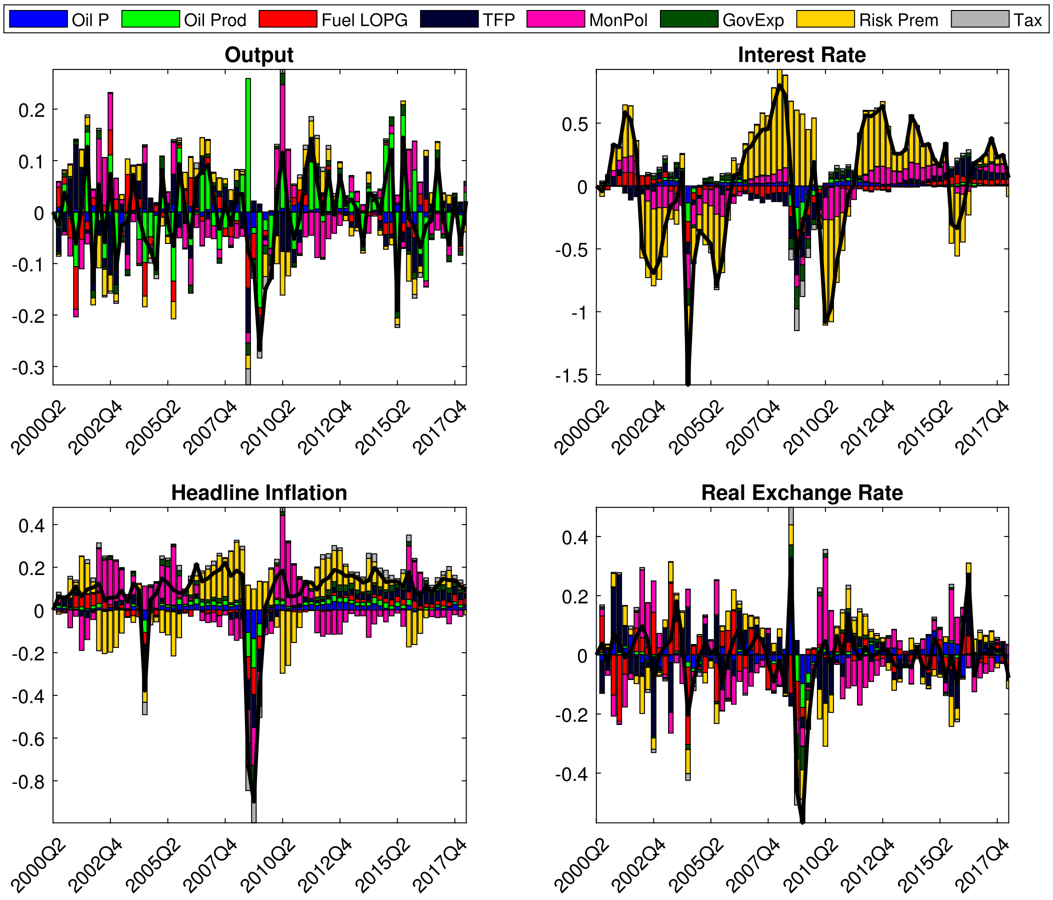


Fig. 9. Historical decomposition: Model 2 ($\nu = 1$).

where we reduce the share of oil in household consumption. As an additional robustness exercise, we re-estimate our model based on an extended sample to capture more recent events in the oil market. To focus the presentation, the latter two exercises are only performed for Model 1 and Model 0, i.e., the preferred model *vis-à-vis* the baseline model with time-invariant parameters.[28]

8.1. Regime-switching variants

Figure 2 in Online Appendix H presents the smoothed probabilities for being in the high macroeconomic volatility regime in the model that allows independent and simultaneous switching in the standard deviations of the 7 domestic shocks ($\xi_t^{a_h}$, $\xi_t^{\psi^o}$, ξ_t^{r}, $\xi_t^{a_o}$, $\xi_t^{g_c}$, ξ_t^{μ}, ξ_t^{tx}).[29] This seems to be in line with the finding of the heightened macroeconomic volatility for the latter period shown in Fig. 3. The economy shifts to a period of heightened volatility later in the sample, mostly coinciding with the latest oil price volatility episode. In Figure 2 in Online Appendix H, we also identify states of low and high volatilities in the structural macroeconomic shocks; the economy is mostly in a state of low macroeconomic volatility after the end of the financial crisis until the shift starting in 2014.

As described in Section 5.2, the second check in this section involves re-estimating Model 1 allowing two independent chains for switches in monetary policy and oil price volatility, respectively (four regimes). Figure 3 in Online Appendix H shows the result based on the posterior distribution of the model parameters. Followed by a shift from the low response to high response regime in early 2000, the economy mostly stays in the hawkish state with a high probability. It is clear that the oil price has been volatile and time-varying in our sample but there seems no evidence of increasing oil price volatility playing an independent role: i.e. the 'counterfactual' scenario suggests that the CBN monetary policy would act normally to stabilize prices being independent of the oil

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[28] Running a large number of MH-MCMC replications with regime-switching is very time intensive. To reduce the computational burden, the results in the two sub-sections are based on the posterior mode of θ computed using the search optimization routine described in Section 6.2. The key to log posterior optimization and robust estimation results is to use alternative optimizers and check whether we get to the point that has the highest posterior density which may not be improved by another optimization routine.

[29] As a further robustness check, we also estimate the model that allows regime shifts in both time-varying oil price volatility and macroeconomic volatility with two independent or synchronized Markov chains, the results are quantitatively very similar. To save space, we only report the estimated state probabilities here.

price movements and volatility. Indeed, the model is rejected by the data as the marginal density of this model is 751.9936 which is significantly lower than the value reported in the original specification for Model 1 (778.2268).

8.2. Additional impulse responses

To distinguish the possible effects between regimes shifts in oil price volatility and monetary policy, we provide the impulse responses computed from the estimated four-regime model in Online Appendix H. We briefly discuss these results as another counterfactual case.

Following a decline in oil prices, aggregate GDP falls and the effect is quite persistent. If the economy is in a high volatility regime (i.e. Regime 2 in Figure 4, Online Appendix H), the impulse response shows a strong, negative effect on GDP and the effect is much more persistent. This result is consistent with Kilian and Vigfusson (2017) who study the conditional response of US real GDP following an oil price shock. Our result also shows that a negative oil price shock generates a positive effect on the non-oil sector and lowers marginal cost, leading to an increase in non-oil output and a fall in domestic inflation. These effects would be stronger and more persistent in an economy when the real price of oil is volatile. When the decline in prices is long-lasting (e.g. the period associated with the 2014 price fall), private consumption rises more as households enjoy more income arising from lower prices. In an economy under Regime 2, the exchange rate would depreciate more, causing import prices and core inflation to rise. The interest rate would increase initially to respond to headline inflation, further exacerbating the contractionary effects on aggregate output.

Turning to the responses under Regime 3 (dovish) and Regime 4 (hawkish) in Online Appendix H, the latter economy responds most to inflation in order to achieve price stability. This policy stance would generate lower marginal cost, leading to a larger reduction in domestic inflation, and in the headline and core measures of inflation, even though the exchange rate depreciation would cause import prices to rise. The increased private consumption and reduced marginal cost would lead to an increase in non-oil output but the increase is suppressed initially following a negative oil price shock. Aggregate output would fall but the model would predict a modestly negative effect on output after an unexpected oil price decrease if the economy was governed by certain policy rules specific to the dovish regime.

8.3. Share of oil in household consumption

This robustness check is implemented to gauge the sensitivity of our results to an alternative assumption that reduces the share of oil in household consumption. This is the γ_o parameter in (5) which is calibrated to be 0.085 in our estimations according to Online Appendix F. We conduct an experiment on our estimated models by considering a lower value of $\gamma_o = 0.0425$, representing -50% of the benchmark calibration, which also changes the weight of oil in Nigeria's consumer price index basket and should imply that the real marginal cost is sensitive to this change (i.e. through the subsidized price of imported oil).

In line with our findings under the original model, the estimates of the structural parameters do no change significantly under the alternative calibration. In particular, our main conclusions, especially with regards to the oil price volatility regime and the behaviour of monetary policy, are very similar to the earlier finding. In Figure 5 in Online Appendix H, we present the smoothed probabilities for being in the high oil price volatility state, and for being in the high oil price volatility regime and more dovish regime, respectively. The results are broadly consistent with those depicted in Fig. 3, based on the benchmark scenario, including the policy shift coinciding with the financial crisis. In other words, our earlier finding regarding the distinct movements of volatility and policy responses remains valid under the different share of domestic consumption devoted to oil consumption considered.

It is also interesting to note that, similar to the case where $\nu = 1$, this counterfactual scenario identifies a brief monetary policy state around the same period which seems to suggest that the response is triggered by the level of oil share. As in the previous case, the second monetary policy state seems to have lasted several quarters longer than the benchmark economy represented by Model 1. This is an intuitive result as the oil share parameter affects oil consumption directly. Reducing the value of this parameter in domestic consumption moderates the impact of oil price shocks on aggregate demand and domestic output, and thus can cause a switch of monetary policy to a less responsive state.

8.4. Extended sample period (2000Q2 - 2021Q4)

In this section, we retain our benchmark model calibration and perform our final check to verify the robustness of the results discussed above. In light of recent events in the oil market, we extend the baseline sample period (2000Q2 - 2018Q2), adding 14 observations which improve the available degrees of freedom in the estimation, and compare the results with respect to the previously preferred model. The extended sample runs from 2000Q2 to 2021Q4.[30]

Figure 6 in Online Appendix H presents the smoothed probabilities for the states of oil price volatility and monetary responses. We briefly discuss how the estimation results may be different based on the extended sample period. Two results are worth noting. First, the estimated Model 1 identifies qualitatively another distinct period of oil price volatility starting from 2019Q3 where regime-changing is probabilistic and determined by the data. The result clearly shows recurrent spikes in the oil price movements over the sample. The lower panel of the figure confirms our previous results discussed in Section 7.2 based on our regime-switching Model 1. In line with the first oil price volatility episode, there is another synchronized switch to a less responsive policy state that is triggered

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[30] The extended sample period ends before the outbreak of the Russo-Ukrainian conflict.

by the latest volatility episode with a high probability. Monetary policy would have played a significant role in affecting the business cycle dynamics.[31]

Second, we uphold our main finding that Model 1 significantly outperforms Model 0 in terms of their empirical relevance in explaining the data. As we carry out the estimations for both models in this section, we uphold this result with both the extended sample and shorter sample periods during which the country experiences time-varying oil price volatility and associated policy reactions. Importantly, we compare the Laplace approximation of log marginal data density around the estimated posterior mode and our likelihood comparison exercise confirms our earlier results that there is a significant difference in the estimated posterior likelihoods: 943.6452 (Model 0) and 991.3649 (Model 1), providing yet again decisive evidence in favouring the latter.

9. Conclusions and future research

This paper found ample evidence in favour of time-varying switches in the parameters and variances of an estimated open-economy DSGE model for Nigeria. The data fit of the baseline (constant parameter) model improved significantly with the addition of regime-changing assumptions. We obtained plausible and tight posterior estimates for the key switching parameters; thus, confirming their empirical relevance. Consequently, our results rejected the assumption that the volatility and persistence of oil price shocks is constant over time. Indeed, there are clearly recurrent spikes in the oil price movements that contribute to the nonlinear effect of oil price shock on the real economy. These findings have interesting modelling implications and suggest future research directions for analyzing the macroeconomic effects of oil price shocks in oil-exporting SOEs.

We found evidence of time-varying monetary policy responses to oil price shocks as our estimated model identified (brief) breaks in the policy responses that are associated/synchronized with major oil price fluctuations, especially since 2008. By carefully studying a monetary authority with changing policy states identified through the nonlinear dynamics, rather than relying on inference based on an identified VAR or nonlinear empirical models, we are able to explicitly explain the potential sources of nonlinearities arising from monetary policy shifts that characterize the different behaviours of the central bank over time. Furthermore, our results provide evidence that monetary policy can reinforce the propagation of oil price shocks in resource-rich emerging economies; thus contributing important insights to the debate in the literature on the time-varying response of economic activities to an oil shock.

Our SOE model was carefully developed to provide a novel and flexible benchmark for future policy analysis, especially when studying the possible consequences of global commodity shocks on resource-exporting countries. Also, the empirical strategy is novel and comprehensive in terms of estimating a SOE-DSGE model that incorporates a number of key switching assumptions and features that are specific to oil-producing emerging economies. Our major findings withstand a number of robustness checks and provide important insights for designing stabilization policies to address the possible consequences of energy price shocks in emerging economies.

We recognize that there are possible avenues for future research. In terms of the modelling framework, the model could also be enriched by considering possible switches in the fuel subsidy process as well as in the volatility of shocks. These adjustments would allow for the investigation of possible evidence in the data regarding whether the subsidy policy has been more active in periods of high oil price volatility in order to promote domestic price stability. However, this requires the data sample to be extended to cover the period when the programme was institutionalized in the context of the Great Inflation, which is likely to be problematic for emerging economies.

Another issue that deserves further attention is fiscal policy, which is a key transmission mechanism for the oil price shocks to the aggregate economy. Fiscal policy is important for oil-dependent countries as they tend to benefit from the windfall profits from oil price increases or have an incentive to finance partly their expenditure through non-oil sources during a price drop. Under such circumstances, it is possible that fiscal adjustments play a unique role in how monetary policy is conducted. Fiscal policy states and monetary-fiscal interactions can also be examined as in Batini et al. (2009), Kliem et al. (2016), Bianchi and Ilut (2017) and Jin and Xiong (2021).

CRediT authorship contribution statement

Babatunde S. Omotosho: Data curation, Formal analysis, Methodology, Resources, Writing – original draft, Writing – review & editing, Conceptualization. **Bo Yang:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

We declare that we have no relevant, personal, or material financial interests that relate to the research described in this paper.

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[31] As the extended sample encompasses the COVID-19 observations, the impact of COVID-specific shocks on inflation and economic activities implies that state transitions are associated with these global shocks which can then potentially impact on monetary policy transmission. This should be taken further by proper consideration of COVID-specific shocks, introducing an additional channel for the propagation of monetary or external shocks, as in Cardani et al. (2022), or empirical models that assume that the errors are non-Gaussian and depend on stochastic volatility, as in Bobeica and Hartwig (2021). These features, however, are beyond the scope of the present paper and we leave this for future research.

Data availability

Data will be made available on request.

Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jimonfin.2024.103082.

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