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**Oil and the Great Moderation**

by Anton Nakov and Andrea Pescatori

We assess the extent to which the period of great U.S. macroeconomic stability since the mid-1980s can be accounted for by changes in oil shocks and the oil share in GDP. To do this we estimate a DSGE model with an oil-producing sector before and after 1984 and perform counterfactual simulations. We nest two popular explanations for the Great Moderation: (1) smaller (non-oil) real shocks; and (2) better monetary policy. We find that the reduced oil share accounted for as much as one-third of the inflation moderation and 13% of the growth moderation, while smaller oil shocks accounted for 11% of the inflation moderation and 7% of the growth moderation. This notwithstanding, better monetary policy explains the bulk of the inflation moderation, while most of the growth moderation is explained by smaller TFP shocks.

Key words: monetary policy, oil price, great moderation, bayesian estimation, OPEC.

JEL code: E32, E52, F0

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# 1 Introduction

Hamilton (1983) noticed that all US recessions but one since World War II were preceded by increases in the price of crude oil, suggesting that exogenous oil shocks were responsible for much of the post war volatility of US GDP growth (see Figure 1). Other authors found similar evidence of a link between oil price rises and US inflation, as well as a link between oil price fluctuations and both output growth and inflation in other industrialized countries (e.g. Darby (1982), Burbidge and Harrison (1984)).

The relevance of oil as a source of macroeconomic fluctuations was established as conventional wisdom at least until Hooker (1999) pointed to a break in the oil price–GDP relationship and Hooker (2002) found a parallel break in the oil price–inflation relationship around 1981.<sup>1</sup> This break date roughly coincides with (but precedes) the beginning of a period of remarkable macroeconomic stability, dubbed by some economists as the “Great Moderation,” and reflected in a sharp decline in the volatility (and sometimes the persistence) of key macro variables in a number of industrialized economies, including the US (see Table 1 and figures 2 and 3).<sup>2</sup>

Since evidence suggests that the moderation is spread across a number of countries<sup>3</sup>, and oil supply shocks are likely to affect many oil-importing countries in a similar way, a reduction in oil sector volatility or a dampening of the transmission of that volatility to the rest of the world economy is a natural candidate (perhaps working alongside other factors) for explaining the rise of macroeconomic stability in the advanced world. One possibility is that oil supply shocks have simply become smaller or less frequent in the period after 1984; at the same time, diversification towards less oil-intensive sectors and increased energy efficiency may have reduced the share of oil in GDP and thus diminished the importance of oil supply shocks.

We assess the extent to which the macroeconomic moderation in the US can be accounted for by changes in oil shocks and the oil share, by performing counterfactual simulations based on Bayesian estimation of the model of Nakov and Pescatori (2007) for the periods pre- and post-1984. In doing so, we nest two popular explanations for the Great Moderation: (1) “good luck” in the form of a shift in the distribution of TFP and other (non-oil) real shocks, as claimed for example by Ahmed, Levin and Wilson (2002) and Stock and Watson (2002); and (2) an improvement in the conduct of monetary policy, as argued

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<sup>1</sup>Specifically, Hooker (1999) found that two widely used transformations of the oil price do not Granger cause output in the post-1980 period, while Hooker (2002) identified a structural break in core US inflation Phillips curves such that oil prices contributed substantially to core inflation before 1981, but since that time the pass-through has been negligible.

<sup>2</sup>The “Great Moderation” was noticed by Kim and Nelson (1999) and McConnell and Perez-Quiros (2000), and its beginning is usually dated around 1984.

<sup>3</sup>Cecchetti et al. (2006) find evidence of moderation in 16 out of 25 industrialized countries, and Stock and Watson (2003) report similar evidence for 6 of the G-7 countries; on the other hand, see Canova et al. (2007) for evidence that the moderation has been more of an Anglo-Saxon phenomenon.

by Clarida, Gali and Gertler (2000) and Boivin and Giannoni (2003).<sup>4</sup>

We find that oil played a non-trivial role in the moderation. In particular, the reduction of the oil share alone can explain around one-third of the inflation moderation and 13% of the GDP growth moderation. In turn, oil-sector shocks alone can account for 7% of the growth moderation and 11% of the inflation moderation. Yet the dominant role was played by non-oil shocks and by monetary policy. In particular, smaller TFP shocks account for two-thirds of GDP growth moderation, while better monetary policy alone can explain two-thirds of the inflation moderation.

Related to this, we find evidence that the inflation–output gap trade-off has become more benign after 1984 due to the smaller share of oil in GDP. More generally, oil sector shocks have become less important for US macroeconomic fluctuations relative to US-originating shocks to TFP, preferences and policy.

The rest of the paper is organized as follows. The next section puts our work in the context of the related literature; section 3 presents the stylized volatility facts; section 4 sketches a log-linearized version of the oil pricing model of Nakov and Pescatori (2007) and illustrates how different factors could cause moderation; section 5 covers the data and estimation methodology; section 6 describes our priors and the estimation results; section 7 contains counterfactual analysis decomposing the volatility moderation into contributions by each factor and discusses the implied changes in the Phillips curve; section 8 relates our results to those of the literature and the last section concludes.

## 2 Related Literature

Our paper is related to several distinct lines of research. One is the empirical literature on the link between oil and the macroeconomy starting with Darby (1982) and Hamilton (1983). Bernanke, Gertler and Watson (1997) challenged Hamilton’s finding, documenting that essentially all U.S. recessions in the post-war period were preceded by both oil price increases as well as a tightening of monetary policy. Using a modified VAR methodology, they found that the systematic monetary policy response to inflation (presumably caused by oil price increases) accounted for the bulk of the depressing effects of oil price shocks on the real economy. What is more, Barsky and Killian (2001) and Killian (2005) argued that even the major oil price increases in the 1970s were not an essential part of the mechanism that generated stagflation, and that the latter is attributable instead to monetary factors. Unlike these studies, our analysis is based on a structural model featuring optimal oil price setting, estimated with Bayesian methods. This allows us to disentangle the contribution of policy from the effects of oil shocks and the oil share without running into the Lucas critique.

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<sup>4</sup>We do not control for other possible explanations involving structural changes in private sector behavior, such as better inventory management (McConnell and Perez-Quiros, 2000), or financial innovation (Dynan, Elmendorf and Sichel, 2005).

Another strand of research deals with theoretical models of the link between oil and the macroeconomy. Some of the more recent contributions include Kim and Loungani (1992), Rotemberg and Woodford (1996), Finn (1995, 2000), Leduc and Sill (2004), and Carlstrom and Fuerst (2005). While these studies differ in the way oil is employed in the economy (as a consumption good, as a standard productive input, or as a factor linked to capital utilization), and hence in the implications of oil shocks, they all share the assumption that the oil price (or oil supply) is exogenous, and hence unrelated to any economic fundamentals. This is not only unappealing from a theoretical point of view as Killian (2007) pointed out, it is also inconsistent with the evidence presented in Killian (2007), Mabro (1998), and Hamilton (1983).<sup>5</sup> The issue is that with an exogenous (or a perfectly competitive) oil sector, and absent any real rigidities (e.g. real wage rigidities as in Blanchard and Gali, 2007), there is no meaningful trade-off between inflation and output gap stabilization, implying that full price stability is optimal even in the face of oil sector shocks. The fact that inflation in the 1970s was highly volatile suggests that either policy was very far from optimal, or that indeed there was an important policy trade-off. In contrast to existing models, ours features a dominant oil exporter that charges an endogenously varying (optimal) oil price markup, which enters the Phillips curve as a “cost-push” term and induces a trade-off between the output gap and inflation (Nakvo and Pescatori, 2007).

Finally, our paper is related to the literature on the Great Moderation, starting with Nelson (1999) and McConnell and Perez-Quiros (2000). With some simplification, most of the explanations for the stability can be classified into three broad categories: (a) “good practices,” that is, changes in private sector behavior unrelated to stabilization policy, for instance improved inventory management (McConnell and Perez-Quiros, 2000) or financial innovation (Dyman, Elmendorf and Sichel, 2005); (b) “good policy,” notably better monetary policy as argued by Clarida, Gali and Gertler (2000), Boivin and Giannoni (2003), and Gali and Gambetti (2007); and (c) “good luck,” meaning a favorable shift in the distribution of real shocks, as in Ahmed, Levin and Wilson (2002), Stock and Watson (2002), and Justiniano and Primiceri (2006). Explanations of “good luck” in particular often give smaller oil shocks as an example (e.g., Summers, 2005).<sup>6</sup>

Our framework allows us to separate oil from non-oil factors, while nesting the “better policy” and “smaller non-oil shocks” explanations. In this regard, our work is most closely related to Leduc and Sill (2007), who assess the role played by monetary policy relative to TFP and oil shocks in the Great Moderation. The main advantage of our approach lies in modeling the oil sector from

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<sup>5</sup>When testing the null hypothesis that the oil price is not Granger-caused collectively by US output, unemployment, inflation, wages, money, and import prices, Hamilton (1983) obtained a rejection at the 6% significance level.

<sup>6</sup>Not all studies fit the above classification. For example, Canova et al. (2007) claim that it is impossible to account for both the Great Inflation of the 1970s and the strong output growth in the 1990s with a single explanation. Using a different approach, Canova (2007) finds that the fall in variances of output and inflation had different causes, and that the quest for a single explanation is likely misplaced. See section 8 for more on this.

optimizing first principles rather than assuming an exogenous process for the oil supply. Another difference is that we estimate most of the model’s parameters separately for each sample with Bayesian techniques, which allows us to fit the volatility reduction facts better compared to Leduc and Sill, who calibrate their model. In addition, compared to their paper, we put special focus on the role played by the oil share and not only on oil shocks.

### 3 Volatility Reduction Facts

Table 1 shows the standard deviations of three quarterly US macro series: GDP growth, deflator inflation, and the federal funds rate, for two subsamples, pre- and post-1984. “The Great Moderation” refers to the pronounced decline in the volatility of these (and other) macro variables in the post-1984 sample. In particular, the volatility of GDP growth declined by about 55%, inflation by 60%, and the nominal interest rate by 30%. For comparison, the last row of the table shows the standard deviation of the quarterly percentage change in the real price of oil. While there is a reduction in its volatility by 20%, this is somewhat less pronounced than for the other three variables.

Clearly, the volatility reduction facts reported in Table 1 are not insensitive to the choice of break year. Different studies have estimated different break dates for the different variables, but usually they lie in the range around 1982 to 1986. Redoing the calculations with 1982:I as the break date, we obtain volatility reductions of 45%, 57%, 20%, and 25%, respectively. And doing the same with 1986:I, we obtained 54%, 62%, 36%, and 13%. While the differences are nontrivial, by and large all three sample splits tell the same story.

The aim of this paper is to evaluate empirically the contribution of oil sector volatility and transmission, and compare it with alternative explanations for the volatility reduction (better monetary policy and non-oil-related “good luck”). While the Great Moderation is sometimes associated also with a reduction in the persistence of macro variables (e.g., Canova et al. 2007), we will not attempt to replicate this phenomenon or attribute it to the various factors.

	Standard deviation (x 100)		Volatility reduction
	1965:I – 1983:IV	1984:I – 2006:IV	
GDP growth	1.126	0.508	55%
Inflation	0.609	0.244	60%
Interest rate	0.847	0.583	31%
Real oil price	16.33	12.99	20%

Table 1. US volatility reduction since 1984

## 4 The Log-Linearized Model

We base our empirical analysis on the full version of the model in Nakov and Pescatori (2007), outlined for convenience in the Appendix. Here we sketch a compact representation of the more important equations, expressed in terms of log-deviations from the efficient equilibrium. For equal treatment of the household sector with four other types of agents (firms, the monetary authority, OPEC, and non-OPEC countries), we include a shock to the time discount factor as an additional source of aggregate demand disturbance. In addition, we allow for monetary policy to react to the output gap as well as inflation, which in our model is an appropriate objective for a central bank concerned with the welfare of the representative household.

With these modifications we are able to match the volatility facts reported in Table 1 without the need to introduce additional features such as habit formation or price indexation. As explained below, the optimal commitment solution of our model entails sufficient history-dependence to account for the sluggishness of inflation and output.

### 4.1 The Dynamic IS curve

Log-linearizing the consumer's Euler equation, replacing consumption with the value added of final goods (that is, GDP), and casting the resulting expression in deviation from the efficient allocation, we obtain

$$\hat{y}_t = E_t \hat{y}_{t+1} - (\hat{\lambda}_t - E_t \pi_{t+1} - \hat{r}r_t^e), \quad (1)$$

where  $\hat{y}_t = y_t - y_t^e$  is the (log) distance between actual value added and its efficient level (which we refer to it as the "output gap" for simplicity).

The IS curve thus relates the current output gap positively to its expected future level, and negatively to the distance between the ex-ante real interest rate  $\hat{\lambda}_t - E_t \pi_{t+1}$ , and the efficient real interest rate,  $\hat{r}r_t^e$ . The latter is defined as the expected growth rate of efficient GDP and in equilibrium is given by the expression

$$\hat{r}r_t^e = (1 - \rho_b) \hat{b}_t - \left( \frac{1 - \rho_a}{1 - s_o} \right) \hat{a}_t - \left( \frac{s_o (1 - \rho_z)}{1 - s_o} \right) \hat{z}_t, \quad (2)$$

which depends negatively on shocks to technology,  $\hat{a}_t$  (in final goods) and  $\hat{z}_t$  (in the oil sector), and positively on the shock to the discount factor,  $\hat{b}_t$ , where  $s_o$  is the share of oil in GDP.<sup>7</sup> The driving variables  $\hat{a}_t$ ,  $\hat{z}_t$ , and  $\hat{b}_t$  are assumed to follow independent stationary AR(1) processes

$$\hat{a}_t = \rho_a \hat{a}_{t-1} + \epsilon_t^a, \quad (3)$$

$$\hat{z}_t = \rho_z \hat{z}_{t-1} + \epsilon_t^z, \quad (4)$$

$$\hat{b}_t = \rho_b \hat{b}_{t-1} + \epsilon_t^b, \quad (5)$$

<sup>7</sup>In the notation of Nakov and Pescatori (2007),  $s_o \equiv 1 - \alpha_1 - \alpha_2$ .



where

$$\hat{a}_t \equiv \log(A_t), \quad (6)$$

$$\hat{z}_t \equiv \log(Z_t), \quad (7)$$

$$\hat{b}_t \equiv \log(\beta_t) - \log(\beta). \quad (8)$$

$\rho_a$ ,  $\rho_z$ , and  $\rho_b$  are shock persistence parameters, and  $\epsilon_t^a$ ,  $\epsilon_t^z$ , and  $\epsilon_t^b$  are *i.i.d.* innovations to US total factor productivity, oil technology, and the time discount factor, all of them mean zero and with standard deviations  $\sigma_a$ ,  $\sigma_z$ , and  $\sigma_b$ , respectively.

Notice that the observable GDP growth rate is given by

$$\Delta y_t = \Delta \hat{y}_t + \Delta y_t^e. \quad (9)$$

## 4.2 The Phillips curve

Aggregating the optimal staggered price-setting decision of final goods firms, we obtain the following first-order approximation to the dynamics of inflation around the deterministic steady-state with zero inflation

$$\pi_t = \beta E_t \pi_{t+1} + (1 - s_o) \lambda \hat{y}_t + s_o \lambda \hat{\nu}_t, \quad (10)$$

where  $\pi_t$  denotes inflation,  $\hat{y}_t$  is the output gap,  $\hat{\nu}_t \equiv \hat{p}_{ot} + \hat{z}_t$  is the optimal oil price markup (determined below),  $\beta$  is the mean time discount factor; and parameter  $\lambda$  is related to the structural parameters of the underlying model as follows

$$\lambda = \frac{(1 + \psi)(\mu - s_o)(1 - \theta)(1 - \beta\theta)}{[\mu\alpha_1 + (\mu - 1)(1 + \psi)s_o]\theta}, \quad (11)$$

where  $\psi$  is the inverse of the Frisch labor supply elasticity,  $\mu$  is the average markup in the final goods sector,  $1 - \theta$  is the frequency of price adjustment, and  $\alpha_1$  is the labor share in final goods production.

Notice that the oil price markup enters the Phillips curve like a “cost-push” term. Namely, a rise in the oil price markup leads to a rise in inflation and/or a negative output gap, implying a trade-off between the two policy objectives. This contrasts with the case of perfect competition in the oil sector (or an exogenous oil price), in which oil price shifts are necessarily associated with an opposite movement in the efficient level of output and imply no tension between inflation and output gap stabilization (for more details we refer the reader to Nakov and Pescatori, 2007).

Iterating the Phillips curve forward, we obtain the expression

$$\pi_t = \lambda \sum_{k=0}^{\infty} \beta^k E_t [(1 - s_o) \hat{y}_{t+k} + s_o \hat{\nu}_{t+k}], \quad (12)$$

which shows that inflation is a weighted average of current and expected future output gaps and oil price markups.

### 4.3 Monetary policy

The central bank follows a Taylor-type rule of the form

$$\hat{i}_t = \phi_i \hat{i}_{t-1} + (1 - \phi_i) (\phi_\pi \pi_t + \phi_y \hat{y}_t) + \hat{r}_t, \quad (13)$$

where  $\pi_t$  is inflation,  $\hat{y}_t$  is the output gap,  $\hat{r}_t$  is a zero mean *i.i.d.* monetary policy shock, and  $\phi_i$ ,  $\phi_\pi$ , and  $\phi_y$  are policy reaction coefficients.

### 4.4 Oil sector

Nakov and Pescatori (2007) model OPEC as the dominant supplier of oil, which seeks to maximize the welfare of its owner, internalizing the effect of its pricing decision on global output and oil demand. Operating alongside a competitive fringe of price-taking oil suppliers, the dominant oil exporter sells its output to an oil-importing country (the United States), which uses it to produce final goods.

A first-order approximation of the optimal oil price-setting rule of the dominant oil supplier takes the form

$$\hat{\nu}_t = \hat{p}_{ot} + \hat{z}_t = \gamma' \begin{bmatrix} \hat{y}_{t-1} \\ \hat{i}_{t-1} \\ \hat{\lambda}_{t-1} \\ \hat{\xi}_t \end{bmatrix}, \quad (14)$$

where  $\hat{\xi}_t = [\hat{a}_t, \hat{b}_t, \hat{r}_t, \hat{z}_t, \hat{\omega}_t]'$  is a vector of exogenous states, and  $\gamma$  is a vector of nonlinear functions of the structural parameters of the model. Notice that while the behavior of households and firms of the oil importer is fully forward-looking in the model, the optimal commitment solution of OPEC's problem is history-dependent. In particular, it is a function of past value added,  $\hat{y}_{t-1}$ , and the nominal interest rate,  $\hat{i}_{t-1}$ , both of which are state variables; in addition, it depends on past promises about future oil supply, captured by the vector  $\hat{\lambda}_{t-1}$  of Lagrange multipliers.

Competitive fringe producers seek to maximize profits while taking the oil price as given. In equilibrium, competitive fringe output,  $\hat{x}_t$ , is an increasing function of the oil price,  $\hat{p}_{ot}$ , oil technology,  $\hat{z}_t$ , and the shock to fringe capacity,  $\hat{\omega}_t$

$$\hat{x}_t = \hat{p}_{ot} + \hat{z}_t + \hat{\omega}_t. \quad (15)$$

The total capacity of the competitive fringe is assumed to follow a stationary AR(1) process with persistence  $\rho_\omega$

$$\hat{\omega}_t = \rho_\omega \hat{\omega}_t + \epsilon_t^\omega, \quad (16)$$

where  $\hat{\omega}_t \equiv \log(\Omega_t/\bar{\Omega})$ , and  $\epsilon_t^\omega$  is *i.i.d.* with mean zero and standard deviation  $\sigma_\omega$ .

## 4.5 What factors could cause moderation?

We illustrate how different factors may contribute to the moderation of different variables based on the above model.

Perhaps the simplest explanation could be that the distribution of real disturbances hitting the economy has changed so that real shocks have become smaller. Notice that smaller real shocks would reduce the volatility of  $r\hat{r}_t^e$ , while smaller oil-sector shocks in particular are likely to diminish the variance of the oil price markup,  $\hat{\nu}_t$ . Since these are the two driving variables in our model, for any given interest rate rule and oil share, the volatility of output, inflation, and the interest rate would be reduced.

An alternative (or complementary) explanation has to do with better monetary policy. This includes smaller monetary surprises ( $\hat{r}_t$  shocks), as well as a more stabilizing policy rule. Smaller monetary shocks reduce the volatility of the interest rate, which is transmitted through the IS and Phillips curves to actual output and inflation. At the same time, stronger systematic reaction of the policy instrument to inflation and output deviations from target results in better stabilization of these variables over the cycle.<sup>8</sup>

Finally, part of the moderation may be due to the fact that oil — perhaps once an important source of volatility — now accounts for a smaller fraction of GDP than in the past. The latter can be due to increased energy efficiency and diversification away from oil-intensive sectors.

The oil share affects the volatility of  $r\hat{r}_t^e$  as well as the coefficient on the cost-push term in the Phillips curve. Other things equal, a smaller oil share is likely to reduce the volatility of output and the pass-through from the oil price to inflation.

To see how the oil share affects the inflation–output gap trade-off, notice that a policy of strict price stability ( $\pi_t = 0$ ) implies

$$\hat{y}_t = -\frac{s_o}{1-s_o}\hat{\nu}_t, \tag{17}$$

while a policy aimed at strict output gap stability ( $\hat{y}_t = 0$ ) implies,

$$\pi_t = s_o\lambda \sum_{k=0}^{\infty} \beta^k E_t \hat{\nu}_{t+k}. \tag{18}$$

In both cases, the extent to which stabilizing one variable induces inefficient fluctuations in the other is a function of the oil share. Finally, the oil share affects the elasticity of demand for OPEC’s oil and thus the volatility of the oil price markup itself.

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<sup>8</sup>Strictly speaking, stronger reaction to the output gap would result in better alignment of output with its efficient level, which need not imply smaller volatility of the growth rate of output, especially if real shocks are large.

## 5 Data and Methodology

We assess the extent to which the macroeconomic moderation in the United States can be accounted for by changes in oil shocks and the oil share by performing counterfactual simulations based on Bayesian estimation of the model of Nakov and Pescatori (2007) for the periods pre- and post-1984. Our estimation methodology is similar to Smets and Wouters (2003), Gali and Rabanal (2005), and An and Shorfheide (2005). The observable variables (the moderation of which we want to explain) are US GDP growth, inflation, the nominal interest rate, and the percentage change of the real price of oil. Quarterly data on real GDP, the GDP deflator, the federal funds rate and the West Texas Intermediate oil price from 1965:I to 2006:IV are taken from FRED II.<sup>9</sup> GDP growth and inflation are computed as quarterly percentage changes of real GDP and the GDP deflator<sup>10</sup>; the nominal interest rate is converted to quarterly frequency to render it consistent with the model; and the oil price is detrended by the GDP deflator and cast in quarterly percentage changes. The resulting series are demeaned by their subsample means prior to estimation.

Since our model is meant to describe the behavior of OPEC, we start the sample in 1965, which marks the year in which OPEC based its secretariat in Vienna. Before that the international oil industry was dominated by seven major oil companies of Anglo-Saxon origin, known as the “Seven Sisters.” Of these, five belonged to the US (Esso, Mobil, Chevron, Texaco, and Gulf), one to the UK (BP), and one was Anglo-Dutch (Shell). Even though OPEC was created in 1960, in the first few years of its existence its activities were of a low-profile nature, as it set out its objectives, established a secretariat, and engaged in negotiations with the oil companies.<sup>11</sup> Thus, throughout the period 1959–1964 the nominal oil price remained unchanged at just below 3\$ a barrel.

The sample is split in 1984:I. This corresponds to the break in US output volatility estimated by McConnell and Perez-Quiros (2000), Cecchetti et al. (2006), and others. A break in inflation volatility was found around that date as well (Kahn, McConnell, and Perez-Quiros, 2002); a break in the oil–GDP link (Hooker, 1999) and the oil–inflation relationship (Hooker, 2002) was identified around 1981; and a break in the conduct of monetary policy around 1979–1982 (Gali and Gertler, 2000).

We fix several parameters of the model based on historical averages over the full sample (as in the case of the time discount factor), or on values which are standard in the literature (as with the elasticity of substitution among final goods). These calibrated parameter values are given in table 2 below.

The elasticity of oil in production is calibrated separately for each subsample based on the average nominal expenditure on oil as a share of nominal GDP,

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<sup>9</sup>The original series names are GDPC96, GDPDEF, FEDFUNDS, and OILPRICE.

<sup>10</sup>Our model does not distinguish between the GDP deflator and CPI inflation.

<sup>11</sup>Source: [www.opec.org](http://www.opec.org).

that is

$$s_o = \sum_t \frac{(\text{barrels of oil consumed in the US})_t \times (\$ \text{ per barrel})_t}{(\text{nominal GDP})_t}, \quad (19)$$

where  $t$  runs from 1965 to 1983 in the first sample and from 1984 to 2006 in the second. This yields a value of 0.036 for the first period and 0.022 for the second, which we fix prior to estimation.<sup>12</sup> The reason we choose to calibrate the oil share in this way rather than letting the estimation procedure tell us about its distribution is that we do not expect the variables we use in the estimation to be informative about this parameter. Instead, we use a formula for the oil share which is consistent with our model, and for which we have accurate data.

Quarterly discount factor	$\beta$	0.9926	Avg. annual real rate 3%
Steady-state markup	$\mu$	1.15	Avg. markup 15%
Mean of non-OPEC capacity	$\bar{\Omega}$	0.004925	OPEC market share 40%
Inflation target	$\bar{\Pi}$	1	Optimal long-run inflation
Capital share	$\alpha_2$	0.33	Avg. capital income share
Oil share, 1965–1983	$s_o$	0.036	Avg. oil income share
Oil share, 1984–2006	$s_o$	0.022	

Table 2. Calibrated parameters

The above procedure leaves us with fourteen parameters to estimate: the frequency of price adjustment ( $\theta$ ), the Frisch labor supply elasticity ( $\psi$ ), the parameters of the monetary policy rule ( $\phi_i, \phi_\pi, \phi_y$ ), the shocks' autoregressive parameters ( $\rho_a, \rho_b, \rho_z, \rho_\omega$ ), and standard deviations of the innovations ( $\sigma_a, \sigma_b, \sigma_z, \sigma_\omega, \sigma_r$ ).

We approximate our model to first-order and solve it with a standard method for linear rational expectations models (e.g., Sims, 2002, and Klein, 2000). Given the state-space representation, we use the Kalman filter to evaluate the likelihood of the four observable variables. From Bayes's rule, the posterior density function is proportional to the product of the likelihood and the prior density of the parameters. We use a random walk Metropolis-Hastings algorithm to obtain 5 chains of 50000 draws from the posterior distribution. We choose a scale for the jumping distribution in the MH algorithm which yields an acceptance rate of around 30%. The posterior distributions are obtained by discarding the first half of the draws from each chain.

Once we obtain the estimates for each sample period, we perform counterfactual simulations, isolating the effect of a change in a single factor (e.g., the oil share) on the volatility moderation.

<sup>12</sup>We do this by setting the share of labor to 0.634 in the first sample and 0.648 in the second, while keeping the share of capital fixed at 0.33.

## 6 Priors and Estimation Results

### 6.1 Choice of priors

The first four columns of tables 3a and 3b show the assumed prior densities for the parameters whose posterior distributions we want to characterize. We use the same prior densities for each parameter in both samples, except for the parameter on inflation in the monetary policy rule. For this parameter we assume a normal (1.5, 0.5) distribution in the second sample, but a gamma prior with mean 1.1 and a standard deviation of 0.5 in the first sample. Following Lubik and Schorfheide (2004) and Justiniano and Primiceri (2007), this assigns roughly equal probability on the inflation coefficient being either less or greater than one, while restricting it to be positive.<sup>13</sup>

We should stress that the conditions for local determinacy of equilibria in our model are not the standard ones. In particular,  $\phi_\pi > 1$  is not a necessary condition for local uniqueness, and indeed there is a large region of determinacy for values of  $\phi_\pi$  sufficiently below 1 (see Figure 4). The reason is that, in contrast to the standard three-equation New Keynesian framework, in our model the Phillips curve includes an additional term — the oil price markup — which responds (optimally) to other endogenous variables, and in particular to the past output gap. This explains why we can solve and estimate our model for values of  $\phi_\pi$  below 1.

For the other parameters of the monetary policy rule we use normal prior densities in both samples. For the price adjustment probability we assume a beta prior with mean 0.75 and standard deviation of 0.1. For the inverse Frisch labor supply elasticity we assume a gamma prior with mean 1 and standard deviation of 0.25.<sup>14</sup> The autocorrelation coefficients of the shocks are assumed to be beta with mean 0.9 and standard deviation of 0.05. And for the standard deviation of the innovations we assume an inverted gamma distribution (which ensures nonnegativity) and use prior information from the calibrated model in Nakov and Pescatori (2007) to specify the mean.

### 6.2 Estimation results

Comparing the two sets of estimated posterior modes in tables 3a and 3b we notice several important parameter shifts. First, the mode of the inflation coefficient of the monetary policy rule is larger in the second sample, implying that monetary policy was reacting more strongly to inflation than in the first period. At the same time, the estimated standard deviation of the interest rate innovation in the pre-1984 sample is more than double that in the post-1984 sample, suggesting that policy was more erratic in the first period.

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<sup>13</sup>The estimation results turn out to be almost identical if instead we assume the same normal prior density for the coefficient on inflation in both samples.

<sup>14</sup>We base our estimation on the full model, in which the Frisch labor supply elasticity enters in several equations independently from the Calvo parameter. Hence, we are able to identify these two parameters separately, not like in the simple three-equation New Keynesian model.

Second, the mode of the Calvo parameter governing the frequency of price adjustment is smaller in the post-1984 period, suggesting that prices have become more flexible.

Third, there is evidence of changes in the volatility (and persistence) of real shocks. In particular, the volatility of the US technology innovation was cut by half in the post-1984 period, while preference shocks became more persistent. Finally, oil sector shocks (especially oil technology shocks) became smaller in the latter period.

Parameter	Prior distribution				Posterior distribution		
	Density and domain	Mean	Std	Mean	Std	Mode	
$\theta$	Beta	$[0, 1)$	0.75	0.100	0.649	0.076	0.627
$\psi$	Gamma	$\mathbb{R}^+$	1.00	0.250	1.097	0.397	0.901
$\phi_i$	Normal	$\mathbb{R}$	0.60	0.100	0.557	0.075	0.543
$\phi_\pi$	Gamma	$\mathbb{R}^+$	1.10	0.500	1.887	0.292	2.096
$\phi_y$	Normal	$\mathbb{R}$	0.50	0.125	0.596	0.105	0.586
$\rho_a$	Beta	$[0, 1)$	0.90	0.050	0.957	0.015	0.974
$\rho_b$	Beta	$[0, 1)$	0.90	0.050	0.883	0.035	0.894
$\rho_z$	Beta	$[0, 1)$	0.90	0.050	0.933	0.026	0.940
$\rho_\omega$	Beta	$[0, 1)$	0.90	0.050	0.931	0.024	0.947
$100\sigma_a$	Inv. Gamma	$\mathbb{R}^+$	0.70	$\infty$	1.220	0.098	1.180
$100\sigma_b$	Inv. Gamma	$\mathbb{R}^+$	0.70	$\infty$	2.170	0.480	1.900
$100\sigma_z$	Inv. Gamma	$\mathbb{R}^+$	10.0	$\infty$	18.27	1.870	18.59
$100\sigma_\omega$	Inv. Gamma	$\mathbb{R}^+$	10.0	$\infty$	31.74	5.300	28.64
$100\sigma_r$	Inv. Gamma	$\mathbb{R}^+$	0.10	$\infty$	0.430	0.053	0.430

Table 3a. Prior and posterior distributions, 1965–1983

Table 4 shows that the estimated model does quite a good job at matching the second moments and the post-1984 volatility reduction of the variables of interest. To be precise, the model slightly overestimates the volatility of GDP growth and inflation in both periods but matches quite well the post-1984 reduction in volatility of these variables. The moderation of the nominal interest rate is somewhat overestimated, but the volatility and moderation of the oil price is matched pretty well.

Parameter	Prior distribution				Posterior distribution		
	Density and domain	Mean	Std	Mean	Std	Mode	
$\theta$	Beta	$[0, 1)$	0.75	0.100	0.529	0.067	0.543
$\psi$	Gamma	$\mathbb{R}^+$	1.00	0.250	1.328	0.405	1.248
$\phi_i$	Normal	$\mathbb{R}$	0.60	0.100	0.684	0.057	0.704
$\phi_\pi$	Normal	$\mathbb{R}$	1.50	0.500	3.115	0.290	3.012
$\phi_y$	Normal	$\mathbb{R}$	0.50	0.125	0.549	0.101	0.572
$\rho_a$	Beta	$[0, 1)$	0.90	0.050	0.978	0.009	0.984
$\rho_b$	Beta	$[0, 1)$	0.90	0.050	0.950	0.015	0.950
$\rho_z$	Beta	$[0, 1)$	0.90	0.050	0.870	0.040	0.867
$\rho_\omega$	Beta	$[0, 1)$	0.90	0.050	0.948	0.021	0.955
$100\sigma_a$	Inv. Gamma	$\mathbb{R}^+$	0.70	$\infty$	0.595	0.044	0.590
$100\sigma_b$	Inv. Gamma	$\mathbb{R}^+$	0.70	$\infty$	2.108	0.512	1.880
$100\sigma_z$	Inv. Gamma	$\mathbb{R}^+$	10.0	$\infty$	13.70	1.708	14.45
$100\sigma_\omega$	Inv. Gamma	$\mathbb{R}^+$	10.0	$\infty$	28.70	5.134	25.63
$100\sigma_r$	Inv. Gamma	$\mathbb{R}^+$	0.10	$\infty$	0.226	0.033	0.200

Table 3b. Prior and posterior distributions, 1984–2006

	1965–1983		1984–2006		Volat. reduction	
	Data	Model	Data	Model	Data	Model
GDP growth	1.126	1.381	0.508	0.669	55%	52%
Inflation	0.609	0.658	0.244	0.279	60%	58%
Interest rate	0.847	0.860	0.583	0.455	31%	47%
Real oil price	16.32	15.71	12.99	12.92	20%	18%

Table 4. Second moments of model and data

## 7 Implications

### 7.1 What accounts for the Moderation?

In this section we attribute the volatility reduction implied by the model (the last column of Table 4) to counterfactual changes in each factor in isolation, including: (1) the oil share; (2) monetary policy; (3) real shocks, including oil sector shocks and US shocks; (4) a shift in the frequency of price adjustment or (5) in the Frisch labor supply elasticity; and (6) the residual due to the interaction of all factors (this is just to say that the contributions of factors 1 to 5 are not linearly additive and do not sum up exactly to 100%).

Table 5a presents the percentage reduction in volatility that would be achieved by a change in any single factor keeping the rest of the parameters at their pre-1984 values.<sup>15</sup> Thus, had the oil share in the period 1965–1983 been at its

<sup>15</sup>We do not model transition dynamics here; Canova and Gambetti (2007) propose an



post-1984 value (that is, 0.022 instead of 0.036), GDP growth would have been 6.5% less volatile, the nominal interest rate 10.7% less volatile, and inflation 23% less volatile, while the oil price would have been 0.4% more volatile. Expressed in percent of the actual reduction in the volatility of these variables (reproduced in the last column), the change in the oil share alone could explain around one-tenth of the GDP growth moderation, one-quarter of the interest rate moderation, and one-third of the inflation moderation. This points to the oil share decline having played a considerable role in the moderation, especially of inflation.

By the same token, better monetary policy (meaning both better systematic reaction and smaller monetary shocks) could explain about two-thirds of the inflation moderation, one-half of the interest rate moderation, but only 5% of the GDP growth moderation. And smaller real shocks explain around three-quarters of the GDP growth moderation, one-quarter of inflation moderation, and one-third of the interest rate moderation. Smaller oil shocks in particular account for 7% of GDP growth moderation, 11% of inflation moderation, and all of the oil price moderation.

Table 5b shows that around two-thirds of the GDP growth moderation can be accounted for by smaller TFP shocks alone, while smaller time preference shocks account for around one-tenth of the inflation moderation and a quarter of the interest rate moderation. Interestingly, smaller oil technology shocks were responsible for the bulk of the oil price moderation, with fringe (or cartelization) shocks playing a smaller role.

Our findings ascribe to monetary policy quite a modest role in the moderation of GDP *growth*. This could be for several reasons. One is the proximity of our simple model to the RBC paradigm: apart from nominal price rigidities (with a Calvo parameter estimated at 0.63 in the first period) and imperfect competition in oil, our model features no other imperfections or real rigidities (e.g., as in Blanchard and Gali, 2007) that would raise the relative importance of the interest rate channel. Second, we assume that the central bank reacts to the output *gap* (and not to output *growth*), which in our model is a relevant target variable for a central bank concerned with the welfare of the representative household. Given this rule, better monetary policy does not necessarily imply smaller output fluctuations, especially if real disturbances are large. Third, the estimated reaction to the output gap is not much different across the two samples (it is the reaction to inflation, which increases substantially in the second period), so even if the fluctuations of efficient output were not large, the post-1984 rule would not have stabilized output much better than the pre-1984 one.

The bottom line of this analysis is that the reduced oil share and smaller oil

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alternative method of performing counterfactual simulations based on re-estimating all the model's parameters conditional on the chosen counterfactual value for any given parameter. Essentially this amounts to treating all model parameters as reduced-form rather than deep behavioral parameters independent of the experiment. While this can be a useful alternative methodology, we stick to the more standard approach of Stock and Watson (2003), treating our parameters as behavioral.

shocks have played a nontrivial role in the volatility reduction even if the other two factors — smaller TFP shocks and better monetary policy — have played the dominant role for the moderation of GDP and inflation, respectively.

	Oil share	Monet. policy	Real shocks			Calvo param	Frisch elast.	All factors
			Oil	US	All			
GDP growth	6.49	2.29	3.40	34.9	40.3	1.07	0.37	52
Inflation	23.0	40.2	6.06	6.43	13.0	-6.89	-2.28	58
Interest rate	10.7	26.5	1.22	15.8	17.3	-1.98	-0.71	47
Real oil price	-0.42	0.01	17.9	0.02	18.0	0.05	0.01	18

Table 5a. Percent moderation by factor<sup>16</sup>

	Real shock				All factors
	$\hat{a}$	$\hat{b}$	$\hat{z}$	$\hat{\omega}$	
GDP growth	34.1	0.54	3.13	0.27	52
Inflation	0.88	5.50	4.64	1.37	58
Interest rate	2.98	12.4	0.52	0.70	47
Real oil price	0.02	0.00	14.8	2.65	18

Table 5b. Percent moderation by shock

## 7.2 Changes in the Phillips curve

Hooker (2002) finds evidence of a break in standard (backward-looking) core US inflation Phillips curves regressions, with oil price changes making a substantial contribution to core inflation before 1981 but having little or no pass-through since that time. Similarly, estimating the standard New Keynesian model via maximum likelihood, Ireland (2004) finds that “cost-push” shocks have become smaller since the 1980s.

Our model, estimated with Bayesian techniques, is in broad agreement with these claims. Indeed, it points to the decrease in the oil share as a likely cause of the improvement in the Phillips curve trade-off as inflation and the output gap have become more aligned with each other and less sensitive to oil price fluctuations. In particular, the last column of Table 6 shows that conditional on a 40% reduction of the oil share from 3.6% to 2.2% (and keeping all other factors unchanged), the volatility of the output gap is reduced by around 40% (as is the instantaneous pass-through from the cost-push term to inflation), resulting in a 23% decline in the volatility of inflation.

<sup>16</sup>The numbers indicate by how much the volatility of a (row) variable would have been reduced by a change in a single (column) factor. A negative sign means that the factor alone would have raised volatility post-1984

In addition, thanks mostly to smaller oil shocks, the volatility of the oil price markup itself has decreased by around 15% in the period after 1984. This, together with increased price flexibility (in the form of higher  $\lambda$ ) since the mid-1980s and a stronger transmission channel, has made it possible for monetary policy to stabilize better both the output gap (see row 7 of Table 6) and inflation.

		1965–1983	1984–2006	Counterf $s_o$
Oil share	$s_o$	0.036	0.022	0.022
Common slope coeff.	$\lambda$	0.643	1.337	0.641
Oil markup pass-through	$s_o\lambda$	0.023	0.029	0.014
Output gap coefficient	$(1 - s_o)\lambda$	0.620	1.312	0.627
Oil markup volatility	$\text{std}(\hat{\nu}_t)$	29.35	25.08	28.77
Oil markup persistence	$\rho(\hat{\nu}_t)$	0.946	0.947	0.946
Output gap volatility	$\text{std}(\hat{y}_t)$	1.072	0.562	0.678
Output gap persistence	$\rho(\hat{y}_t)$	0.902	0.925	0.817

Table 6. Changes in the Phillips curve

### 7.3 Changes in the relative importance of shocks

Tables 7a and 7b show the asymptotic variance decomposition of the four variables of interest in the first and second samples.<sup>17</sup>

Notably, the last two columns of both tables reveal that the contribution of oil sector shocks to US GDP growth and inflation variability has been considerable, both before and after 1984. In particular, oil shocks ( $\hat{z}$  and  $\hat{\omega}$ ) contributed to around 17% of GDP growth volatility, and as much as 60% of inflation volatility and 32% of interest rate volatility in the period 1965–1983. Thereafter, oil shocks continued to account for around 17% of growth volatility but were responsible for “only” 33% percent of inflation volatility and 14% of interest rate volatility. Interestingly, the shock to oil productivity turns out to be more important for GDP growth and oil price volatility, while the fringe shock is more relevant for the volatility of inflation and the interest rate.

<sup>17</sup>This is obtained by solving the equation  $\Sigma_y = A\Sigma_y A' + B\Sigma_u B'$  in  $\Sigma_y$ , the unconditional variance of  $y$ , where  $y_t$  is the solution to the linear rational expectations model of the form  $y_t = Ay_{t-1} + Bu_t$ . It is thus the decomposition of the unconditional variance of endogenous variables, given that shocks occur in every period from today to infinity.

	US shocks			Oil shocks	
	Real		Nom.	$\hat{z}$	$\hat{\omega}$
	$\hat{a}$	$\hat{b}$	$\hat{r}$		
GDP growth	75.6	1.38	5.76	14.4	2.84
Inflation	1.95	24.4	10.4	9.86	53.4
Interest rate	6.77	57.5	3.77	1.34	30.6
Real oil price	0.04	0.01	0.04	74.0	25.9

Table 7a. Variance decomposition, 1965–1983

Turning to US-originating disturbances, the shock to TFP ( $\hat{a}$ ), which accounts for the bulk of GDP growth volatility before 1984, has become even more important for GDP growth, but has decreased its impact on inflation, the interest rate, and the oil price after that year. The preference shock ( $\hat{b}$ ) was important for inflation and the nominal interest rate before 1984 and has become even more relevant for these variables, but less important for GDP growth, in the more recent sample; and the interest rate shock ( $\hat{r}$ ) has increased its relative importance for inflation but has become less relevant for GDP, the interest rate, and the oil price.

	US shocks			Oil shocks	
	Real		Nom.	$\hat{z}$	$\hat{\omega}$
	$\hat{a}$	$\hat{b}$	$\hat{r}$		
GDP growth	79.0	0.76	3.53	12.3	4.39
Inflation	0.60	33.1	32.8	0.55	32.9
Interest rate	2.59	82.1	1.41	0.76	13.2
Real oil price	0.02	0.00	0.01	70.0	30.0

Table 7b. Variance decomposition, 1984 – 2006

Finally, Figure 5 shows the imputed series for the structural innovations based on the more recent sample period. The shocks are signed so that a positive value is associated with an increase in the oil price. Interestingly, the figure suggests that the recent oil price increases (starting after the Asian crisis and interrupted temporarily around the recession of 2001), are reflecting to a greater extent “fringe” shocks (that is, reduced availability of oil outside OPEC’s control) rather than increases in the marginal cost of oil production.

## 8 Comparison of the Results with the Literature

Based on a calibrated model with an exogenous oil supply, Leduc and Sill (2007) conclude that improved monetary policy can account for 45% of the decline in

inflation volatility but only 5% to 10% of the reduction in output volatility, the bulk of which can be explained by smaller TFP shocks. In this regard, our findings are similar to theirs: we find that better policy can explain around two-thirds of the inflation moderation but only around 5% of the GDP growth moderation. However, our results are distinct when it comes to attributing the Great Moderation to oil shocks. While we find that smaller oil-sector shocks have contributed to 7% of the GDP growth moderation and 11% of the inflation moderation, Leduc and Sill claim that oil shocks became larger after 1984 and hence led to rising volatility. This discrepancy is likely due to the different way in which Leduc and Sill identify oil shocks, namely, by treating the oil supply as constant except for four episodes of military conflict, with larger average production drops after 1984. This contrasts with our modeling of the oil -sector as the dominant player with competitive fringe, and identifying oil shocks as disturbances to oil productivity or fringe capacity. In addition, we find that reduced *oil share* can explain about one-third of the inflation moderation and 13% of the GDP growth moderation, a question which is not addressed by Leduc and Sill.

Gali and Blanchard (2007) introduce real wage rigidities to generate an inflation–output gap trade-off. They demonstrate how a reduction in oil’s share of consumption and production shifts inward the policy frontier and goes some way towards explaining the observed reduction in inflation and output volatility. Our model, in comparison, generates a policy trade-off by assuming imperfect competition in the oil market while ignoring real wage rigidities. We also attempt to quantify more precisely the contribution of each factor by estimating the model with Bayesian techniques and performing counterfactual simulations.

Canova (2007) investigates the causes of output and inflation moderation in the US by estimating the benchmark small-scale New Keynesian model with Bayesian techniques over rolling samples. He finds instability in the posterior of the parameters that describe private sector behavior, the coefficients of the policy rule, and the covariance structure of shocks. Canova further shows that even though changes in the parameters of the private sector are largest, they cannot account by themselves for the full decline in the volatility of output and inflation, while changes in the parameters of the policy rule and the covariance of the shocks can. Our findings are similar to Canova in that the bulk of GDP growth moderation is attributed to changes in real shocks, while most of the inflation moderation is due to monetary policy. Yet we find that as much as one-third of the inflation moderation and 13% of the moderation of output is attributable to the smaller share of oil in GDP, which is not directly measurable in the benchmark New Keynesian model estimated by Canova.

Gali and Gambetti (2007) look for the sources of the Great Moderation using a VAR with time-varying coefficients and stochastic volatility. Their findings point to structural change, as opposed to just good luck, as an explanation. In particular, they show that a significant fraction of the observed changes in comovements and impulse-responses can be accounted for by a stronger reaction of monetary policy to inflation, and an apparent end of short-run increasing returns to labor. On the other hand, using a VAR with time-varying coeffi-

cients identified through sign restrictions, Canova and Gambetti (2007) find no evidence that there was an increase in the response of the interest rate to inflation, and overall conclude that monetary policy was marginally responsible for the Great Moderation. Indeed, recent work by Benati and Surico (2007) casts doubt on the ability of VARs to distinguish between the “good policy” and “good luck” explanations for the Great Moderation.

Compared with these studies, our counterfactual analysis, based on estimation of a structural model, assigns an important role to monetary policy, especially in the moderation of inflation (and the nominal interest rate). At the same time, we point to the nontrivial role played by oil, especially in the moderation of inflation and in the improvement of the inflation–output gap trade-off.

## 9 Conclusions

We assess the extent to which increased macroeconomic stability in the US after 1984 can be accounted for by changes in oil shocks and the oil share, by taking the model of Nakov and Pescatori (2007) to the data with Bayesian techniques and performing counterfactual simulations. In doing so we nest two popular explanations for the Great Moderation, namely, smaller non-oil shocks, and better monetary policy.

Our estimates indicate that oil played a nontrivial role in the volatility decline. In particular, the reduced oil share alone can explain around one-third of the inflation moderation and 13% of the GDP growth moderation. Smaller oil-sector shocks account for 7% of the growth moderation and 11% of the inflation moderation. At the same time, we find that smaller TFP shocks can explain about two-thirds of the growth moderation, while better monetary policy alone can explain about two-thirds of the inflation moderation.

## 10 Appendix

### 10.1 Model equations

The dominant oil exporter seeks to maximize the present discounted utility of the household-owner

$$\max E_0 \sum_{t=0}^{\infty} \beta^t \log [p_{ot} O_t - O_t / Z_t], \quad (20)$$

subject to the constraints imposed by the optimal behavior of the competitive fringe

$$X_t = p_{ot} \Omega_t Z_t \quad (21)$$

of households and final goods firms in the oil-importing country

$$w_t = C_t L_t^\psi \quad (22)$$

$$1 = \beta R_t E_t \left[ \frac{\hat{b}_{t+1}}{\hat{b}_t} \frac{C_t}{C_{t+1}} \frac{P_t}{P_{t+1}} \right] \quad (23)$$

$$D_t = \hat{b}_t \frac{Q_t}{C_t} + \beta \theta E_t [\Pi_{t+1}^{\epsilon-1} D_{t+1}] \quad (24)$$

$$N_t = \mu m c_t \hat{b}_t \frac{Q_t}{C_t} + \beta \theta E_t [\Pi_{t+1}^\epsilon N_{t+1}] \quad (25)$$

$$1 = \theta \Pi_t^{\epsilon-1} + (1 - \theta) \left( \frac{N_t}{D_t} \right)^{1-\epsilon} \quad (26)$$

$$\Delta_t = \theta \Pi_t^\epsilon \Delta_{t-1} + (1 - \theta) \left( \frac{N_t}{D_t} \right)^{-\epsilon} \quad (27)$$

$$p_{ot} = s_o m c_t Q_t \Delta_t / (O_t + X_t) \quad (28)$$

$$L_t = \alpha_1 m c_t Q_t \Delta_t / w_t \quad (29)$$

$$Y_t = \frac{A_t}{\Delta_t} L_t^{\alpha_1} \bar{K}^{\alpha_2} (O_t + X_t)^{s_o}, \quad (30)$$

the rule followed by the monetary authority

$$\frac{R_t}{\bar{R}} = e^{r_t} \left( \frac{R_{t-1}}{\bar{R}} \right)^{\phi_i} \left( \frac{\Pi_t}{\bar{\Pi}} \right)^{\phi_\pi} \left( \frac{Y_t \bar{Y}^e}{Y_t^e \bar{Y}} \right)^{\phi_y} \quad (31)$$

and the global resource constraint

$$C_t = Y_t = Q_t - p_{ot} (O_t + X_t). \quad (32)$$

We assume that OPEC can commit to the optimal policy rule that brings about the equilibrium, which maximizes expression (20) above. Furthermore, we restrict our attention to Markovian stochastic processes for all exogenous variables and to optimal decision rules which are time-invariant functions of the state of the economy.

## 10.2 First-order conditions

$$0 = 1/O_t - (\lambda_{1t} + \lambda_{7t})p_{ot} + \lambda_{9t}s_o \frac{Q_t \Delta_t}{O_t + X_t} \quad (33)$$

$$0 = -\lambda_{1t} + \lambda_{2t}E_t \left[ \frac{\hat{b}_{t+1}}{\hat{b}_t} \frac{\beta R_t}{C_{t+1}\bar{\Pi}_{t+1}} \right] - \lambda_{2t-1} \frac{R_{t-1}C_{t-1}}{C_t^2 \bar{\Pi}_t} \frac{\hat{b}_t}{\hat{b}_{t-1}} \\ + \lambda_{3t}E_t [\beta\theta\Pi_{t+1}^{\epsilon-1}D_{t+1} - D_t] + \lambda_{4t}E_t [\beta\theta\Pi_{t+1}^\epsilon N_{t+1} - N_t] \\ + \lambda_{10t}L_t^\psi + \lambda_{11t}\phi_y \bar{R}^{1-\phi_R} R_t^{\phi_R} \left[ \frac{\Pi_t}{\bar{\Pi}} \right]^{\phi_\pi} \frac{Y_t^{\phi_y-1}}{(Y_t^e)^{\phi_y}} \left( \frac{\bar{Y}^e}{\bar{Y}} \right)^{\phi_y} \quad (34)$$

$$0 = \lambda_{1t} + \lambda_{3t}\hat{b}_t + \lambda_{4t}\mu mc_t \hat{b}_t + \lambda_{7t}s_o mc_t \Delta_t - \lambda_{8t}\alpha mc_t \Delta_t - \lambda_{9t}\Delta_t \quad (35)$$

$$0 = \lambda_{3t-1}\theta C_{t-1}\Pi_t^{\epsilon-1} - \lambda_{3t}C_t + \lambda_{5t}(1-\theta)(\epsilon-1)N_t^{1-\epsilon}D_t^{\epsilon-2} \\ + \lambda_{6t}(1-\theta)\epsilon N_t^{-\epsilon}D_t^{\epsilon-1} \quad (36)$$

$$0 = \lambda_{4t-1}\theta C_{t-1}\Pi_t^\epsilon - \lambda_{4t}C_t + \lambda_{5t}(1-\theta)(1-\epsilon)N_t^{-\epsilon}D_t^{\epsilon-1} \\ - \lambda_{6t}(1-\theta)\epsilon N_t^{-\epsilon-1}D_t^\epsilon \quad (37)$$

$$0 = \lambda_{8t}w_t + \lambda_{9t}\alpha_1 Q_t \Delta_t / L_t + \lambda_{10t}C_t \psi L_t^{\psi-1} \quad (38)$$

$$0 = \frac{1}{p_{ot} - Z_t^{-1}} - (O_t + 2X_t)(\lambda_{1t} + \lambda_{7t}) + \lambda_{9t}s_o \frac{Q_t \Delta_t}{O_t + X_t} \Omega_t Z_t \quad (39)$$

$$0 = -\lambda_{2t-1}R_{t-1} \frac{\hat{b}_t}{\hat{b}_{t-1}} \frac{C_{t-1}}{C_t} \bar{\Pi}_t^{-2} + \lambda_{3t-1}\theta(\epsilon-1)C_{t-1}\Pi_t^{\epsilon-2}D_t \\ + \lambda_{4t-1}\theta\epsilon C_{t-1}\Pi_t^{\epsilon-1}N_t + \lambda_{5t}(\epsilon-1)\theta\Pi_t^{\epsilon-2} \\ + \lambda_{6t}\theta\epsilon\Pi_t^{\epsilon-1}\Delta_{t-1} + \lambda_{11t}\bar{R}^{1-\phi_R} R_t^{\phi_R} \phi_\pi \Pi_t^{\phi_\pi-1} \bar{\Pi}^{-\phi_\pi} \left( \frac{Y_t \bar{Y}^e}{Y_t^e \bar{Y}} \right)^{\phi_y} \quad (40)$$

$$0 = E_t [\lambda_{6t+1}\beta\theta\Pi_{t+1}^\epsilon] - \lambda_{6t} + \lambda_{7t}s_o mc_t Q_t - \lambda_{8t}\alpha_1 mc_t Q_t - \lambda_{9t}Q_t \quad (41)$$

$$0 = \lambda_{4t}\mu_t \hat{b}_t + \lambda_{7t}s_o \Delta_t - \lambda_{8t}\alpha_1 \Delta_t \quad (42)$$

$$0 = \lambda_{2t}\beta E_t \left[ \frac{C_t}{C_{t+1}\bar{\Pi}_{t+1}} \frac{\hat{b}_{t+1}}{\hat{b}_t} \right] - \lambda_{11t} \\ + E_t \left[ \lambda_{11t+1}e^{r_t}\beta\phi_R \left( \frac{R_t}{\bar{R}} \right)^{\phi_R-1} \left( \frac{\Pi_{t+1}}{\bar{\Pi}} \right)^{\phi_\pi} \left( \frac{Y_t \bar{Y}^e}{Y_t^e \bar{Y}} \right)^{\phi_y} \right] \quad (43)$$

$$0 = \lambda_{8t}L_t - \lambda_{10t} \quad (44)$$

The set of equations (21) to (44), together with the laws of motion of the exogenous states (3), (4), (5), and (16), constitute a full description of the model.



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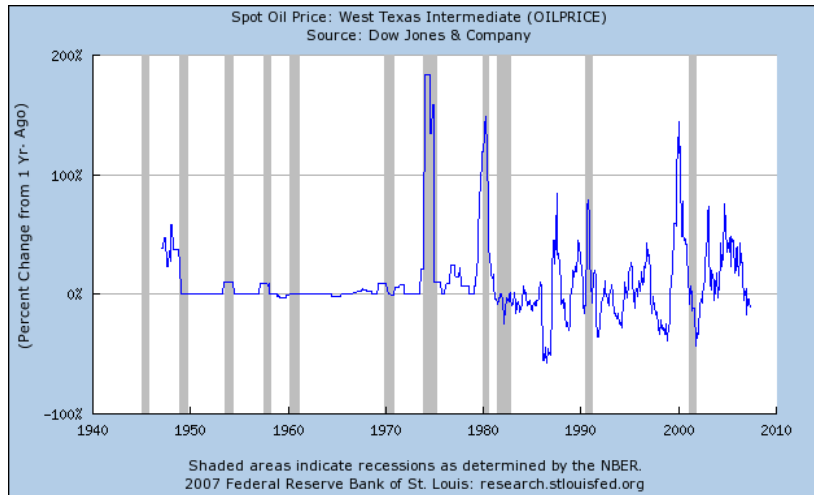


Figure 1: Oil price and US recessions

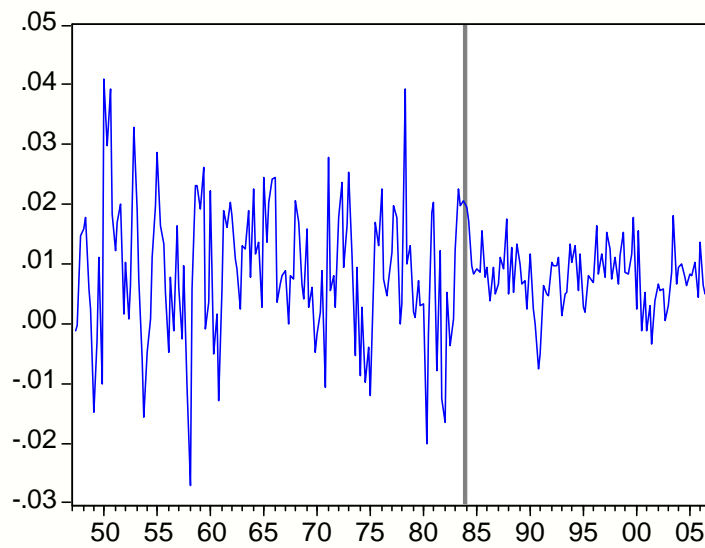


Figure 2: US GDP growth moderation

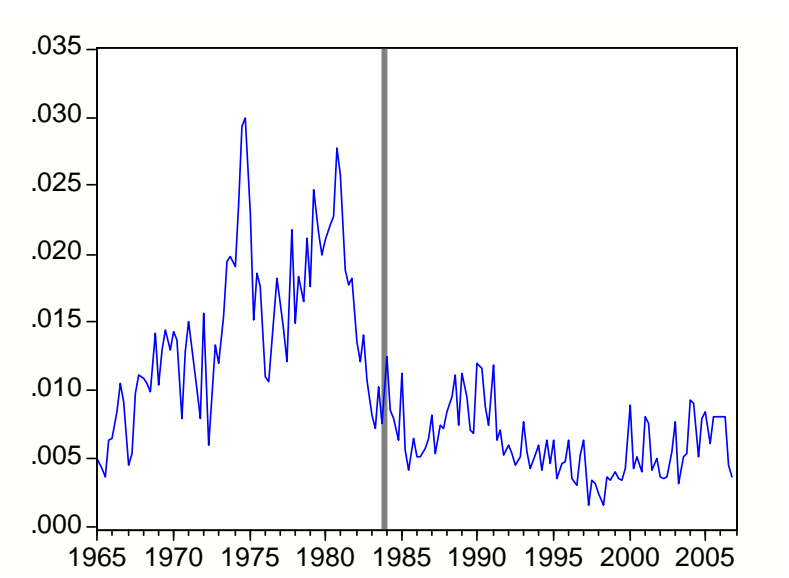


Figure 3: US inflation moderation

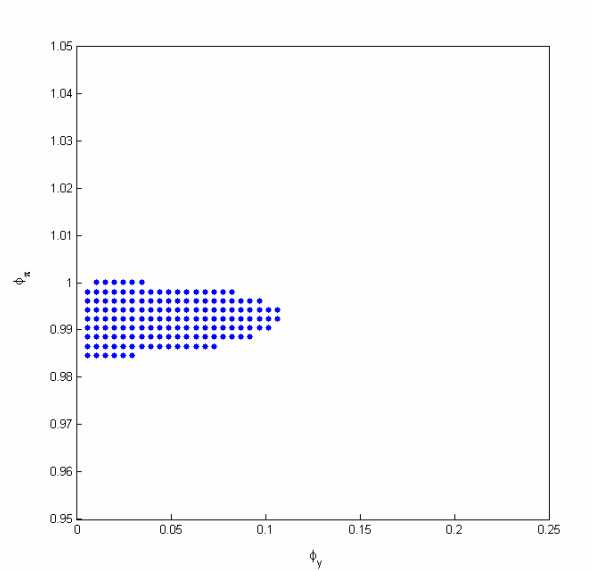


Figure 4: Instability (dark) and determinacy (white) regions of the model

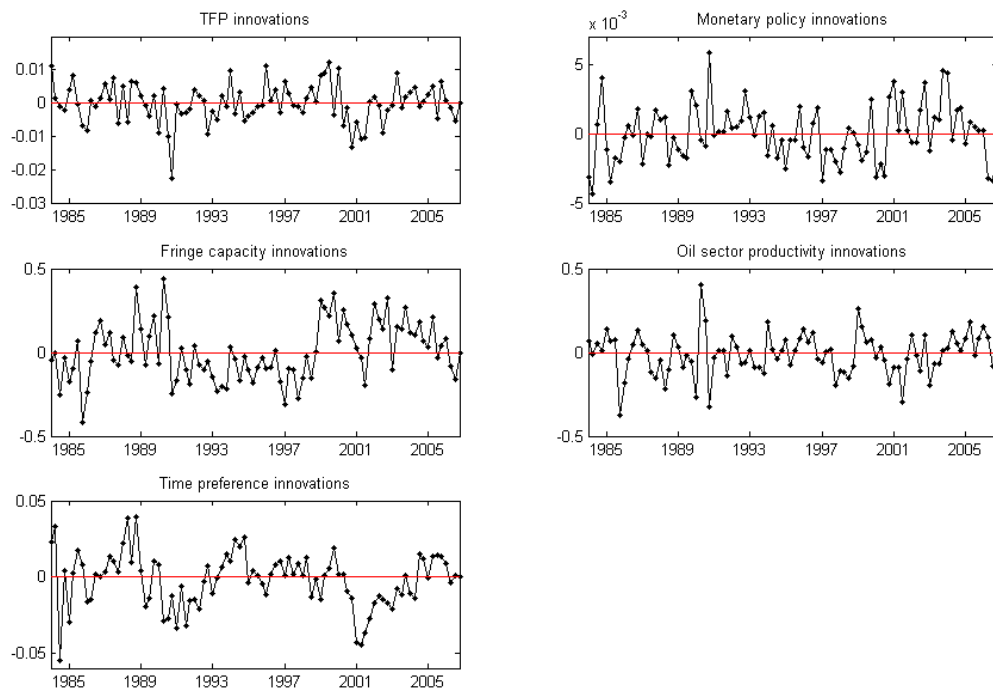


Figure 5: Imputed structural innovations, 1984-2006