Oil and the Great Moderation

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Abstract

We assess the extent to which the great US macroeconomic stability since the mid-1980s can be accounted for by changes in oil shocks and the elastiticy of oil in output. 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 oil played an important role in the stabilization, especially of inflation. In particular, the lower elasticity of oil in output explains around a third of the reduced volatility of inflation, and 18% of the reduced volatility of GDP growth. In turn, smaller oil shocks explain around 17% of the lower inflation volatility, and 11% of the reduced volatility of GDP growth. This notwithstanding, around half of the reduced volatility of inflation is explained by better monetary policy alone, while 57% of the reduced volatility of GDP growth is attributed to smaller TFP shocks.

1 Introduction

For more than a decade since Hamilton's (1983) seminal article the relevance of oil as a source of macroeconomic fluctuations was viewed as conventional wisdom. Yet 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, both around 1981.[1] 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

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[1] 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.

volatility (and sometimes the persistence) of key macroeconomic variables in a number of industrialized economies, including the US (see Table 1 and Figure 1).[2]

Since oil shocks[3] 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 major oil shocks have become less frequent in the period after 1984; another is that diversification towards less oil-intensive sectors and increased energy efficiency may have diminished the importance of oil shocks, by reducing the "share of oil in GDP".[4]

We asses the extent to which the macroeconomic moderation in the US can be explained by changes in oil shocks and the oil elasticity in production, by simulating the model of Nakov and Pescatori (2007) estimated *via* Bayesian techniques 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 by Clarida, Gali and Gertler (2000) and Boivin and Giannoni (2006). We do not control for other possible explanations, such as better inventory management (McConnell and Perez-Quiros, 2000), or financial innovation (Dynan, Elmendorf and Sichel, 2005).

We find that oil played an important role in the stabilization, especially of inflation. In particular, the diminished reliance on oil can explain around a third of the reduced volatility of inflation, and 18% of the lower volatility of GDP growth. In turn, smaller oil shocks alone can explain around 17% of the lower inflation volatility, and 11% of the reduced volatility of GDP growth. This notwithstanding, around half of the reduced volatility of inflation is explained by better monetary policy alone, while 57% of the reduced volatility of GDP growth is attributed to smaller TFP shocks.

Related to this, we find evidence that, due to the smaller elasticity of oil in production, the inflation-output gap tradeoff has become more benign after 1984, making it easier for the central bank to stabilize better both variables. More generally, oil sector shocks have become less important for US macroeco-

[2] The "Great Moderation" was noticed by Kim and Nelson (1999) and McConnel and Perez-Quiros (2000) and its beginning is usually dated around 1984. Cecchetti et. al. (2006) find evidence of volatility moderation in 16 out of 25 industrialized countries and Stock and Watson (2002) report similar evidence for 6 of the G-7 countries; on the other hand, see Canova et. al. (2007) for evidence that the Great Moderation has been more of an Anglo-Saxon phenomenon.

[3] By "oil shocks" we mean structural disturbances to productivity in the oil-producing sector, or to the capacity of non-OPEC suppliers. We do not call them "oil price", "oil supply", or "oil demand" shocks because in our model the latter are endogenous variables, responding simultaneously to any shock.

[4] The structural change of interest is of the elasticity of oil in production. Under standard assumptions about firms' objectives and technology, this parameter is related to the cost share of oil in GDP (see Section 5.1).

nomic fluctuations relative to US-originating shocks to TFP, preferences and monetary 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 lead to reduced volatility; 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 Hamilton (1983), who argued that most US recessions were (Granger) caused by increases in the price of crude oil. Bernanke, Gertler and Watson (1997) challenged this claim, documenting that essentially all U.S. recessions in the postwar period were preceded by both oil price increases *and* a tightening of monetary policy. Using a modified VAR methodology they argued that the systematic monetary policy response to inflation (presumably caused by the oil price increases) accounted for the bulk of the depressing effects of oil price shocks on the real economy. What is more, Barsky and Kilian (2001) and Kilian (2008) 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 elasticity of oil in production.

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 make the assumption that either 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 argued by Kilian (2008), and inconsistent with the evidence presented in Kilian (2008), Mabro (1998), and Hamilton (1983).[5] The issue is that with an exogenous (or, for that matter, a perfectly competitive) oil sector, and absent

[5] 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.

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.

Different from the existing contributions, in our model both the oil price *and* oil supply are endogenous general equilibrium variables, responding to *any* of the exogenous shocks. The model features a dominant oil exporter (OPEC) that charges an optimally varying oil price markup, which enters the Phillips curve as a "cost-push" term and induces a trade-off between the output gap and inflation (Nakov and Pescatori, 2007). The shocks in our model include structural disturbances to productivity of the oil-importing region, technology in the oil sector, and the capacity of the competitive fringe of (non-OPEC) oil producers.

Finally, our paper is related to the literature on the Great Moderation, starting with Kim and Nelson (1999) and McConnell and Perez-Quiros (2000). With some simplification, most of the explanations for the increased 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 (Dynan, 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).[6]

Our framework allows us to separate oil from non-oil factors, while nesting the "better policy" and "smaller non-oil shocks" explanations. In this respect, 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 modelling the oil sector from optimizing first principles rather than assuming an exogenous process for 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 better the volatility reduction facts compared to Leduc and Sill who calibrate their model. In addition, compared to their paper, we put a special focus on the role played by the reduced elasticity of oil in production and not only on oil shocks.

[6] 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.

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 and inflation declined by about 57% each, and of the nominal interest rate by around 35%. For comparison, the last row of the table shows the standard deviation of the quarterly percentage change in the real price of oil. While the reduction in its volatility by 31% is somewhat less pronounced than that of GDP growth or inflation, the difference in volatility between the two samples is statistically very significant (at the 1% level using three standard tests for equality of the variance).

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 from 1982 to 1986. Redoing the calculations with 1982:I as the break date, we obtain volatility reductions of 51%, 48%, 27%, and 37%, respectively. And doing the same with 1986:I, we obtained 60%, 56%, 38%, and 24%. While the differences are non-trivial, 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 its propagation, 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 ($\times 100$)		Volatility
	1970:I–1983:IV	1984:I–2007:IV	reduction
Inflation	0.57	0.25	57%
GDP growth	1.20	0.52	57%
Interest rate	0.88	0.57	35%
Real oil price	19.0	13.0	31%

Table 1. US volatility reduction since 1984

4 The Log-Linearized Model

We base our empirical analysis on the model of Nakov and Pescatori (2007), outlined for convenience in the Appendix. In this model the oil industry is represented by a dominant producer (OPEC), and a fringe of competitive oil suppliers (non-OPEC), who are small individually but collectively can restrain the market power of the cartel.

Our choice of modelling of the oil market in this way is motivated by the simple observation that OPEC today produces about the same amount of oil that it produced back in 1973 (slightly over 30 million barrels per day), even though it sits on the largest and lowest-cost known oil fields on the planet. At the same time, since the 1970's, the higher-cost and less oil-rich non-OPEC countries have almost doubled their output (see Figure 2), as can be expected from competitive suppliers facing secular growth in demand. While throughout the years non-OPEC output was growing (except between 1988 and 1992), on a number of peace-time occasions, OPEC's output actually *declined*. As Adelman (2002) aptly puts it, "for lower-cost output to fall or stagnate, while higher-cost output rises, is like water flowing uphill. Some special explanation is needed". Unlike any previous general equilibrium model that we are aware of, our setup is able to generate such a negative (conditional) correlation between OPEC and non-OPEC supply, as the profit-maximizing reaction of OPEC to a sudden increase in non-OPEC productive capacity.

Our view of the oil market is consistent with the empirical evidence in Griffin (1985), Jones (1990), and Dahl and Yucel (1991) who find that OPEC's behavior is closer to that of a cartel than a confederation of competitive suppliers. At the same time we acknowledge that there are alternative views of the oil market, such as those held by Kilian (2008) or Almoguera and Herrera (2007), who are more sceptical of OPEC's role as a cartel.

In this section we sketch a compact representation of the more important equations of our model, expressed in terms of log-deviations from the efficient equilibrium. In order to treat the household sector equally with the other four types of agents (final goods firms, monetary authority, OPEC and non-OPEC producers), we include a shock to the time discount factor as an additional source of aggregate fluctuation.

4.1 Dynamic IS curve

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

$$\hat{y}_t = E_t \hat{y}_{t+1} - \left(\hat{\imath}_t - E_t \pi_{t+1} - \hat{rr}_t^e\right) \tag{1}$$

where $\hat{y}_t = y_t - y_t^e$ is the (log) distance between actual value added and its efficient level (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 $\hat{\imath}_t - E_t \pi_{t+1}$ and the efficient real interest rate $\hat{rr}_t^e$. The latter is defined as the expected growth rate of efficient GDP, and in equilibrium is given by the expression

$$\hat{rr}_t^e = (1 - \rho_b)\,\hat{b}_t - \left(\frac{1 - \rho_a}{1 - s_o}\right)\hat{a}_t - \left[\frac{s_o\,(1 - \rho_z)}{1 - s_o}\right]\hat{z}_t, \tag{2}$$

which depends negatively on shocks to TFP, $\hat{a}_t$, and productivity in the oil sector, $\hat{z}_t$, and positively on the shock to the discount factor $\hat{b}_t$, where s_o is the elasticity of oil in production. The shocks $\hat{a}_t$, $\hat{z}_t$, and $\hat{b}_t$ are assumed to follow independent stationary AR(1) processes

$$\hat{a}_t = \rho_a \hat{a}_{t-1} + \epsilon_t^a, \tag{3}$$
$$\hat{z}_t = \rho_z \hat{z}_{t-1} + \epsilon_t^z, \tag{4}$$
$$\hat{b}_t = \rho_b \hat{b}_{t-1} + \epsilon_t^b, \tag{5}$$

where $\hat{a}_t \equiv \log(A_t)$, $\hat{z}_t \equiv \log(Z_t)$, $\hat{b}_t \equiv \log(\beta_t/\beta)$; ρ_a, ρ_z, and ρ_b are persistence parameters, and ϵ_t^a, ϵ_t^z, and ϵ_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 σ_a, σ_z, and σ_b respectively. Notice that the observable GDP growth rate is given by $\Delta y_t = \Delta \hat{y}_t + \Delta y_t^e$.

As a robustness check, we will also estimate our model with a hybrid backward- and forward-looking IS curve of the form

$$\hat{y}_t = \frac{1}{1+h} E_t \hat{y}_{t+1} + \frac{h}{1+h} \hat{y}_{t-1} - \frac{1-h}{1+h} \left(\hat{\imath}_t - E_t \pi_{t+1} - \hat{rr}_t^e \right) \tag{6}$$

The latter equation is obtained by assuming that households form habits in consumption, where $h \in [0,1]$ is an "external habit" parameter. When $h = 0$, the above equation reduces to the more standard forward-looking IS curve (1).

4.2 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

$$\pi_t = \beta E_t \pi_{t+1} + (1 - s_o) \lambda \hat{y}_t + s_o \lambda \hat{\nu}_t, \tag{7}$$

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

$$\lambda = \frac{(1+\psi)(\mu - s_o)(1-\theta)(1-\beta\theta)}{\left[\mu s_l + (\mu - 1)(1+\psi) s_o\right] \theta}, \tag{8}$$

where ψ is the inverse of the Frisch labor supply elasticity, μ is the average markup in the final goods sector, $1 - \theta$ is the frequency of price adjustment, and s_l is the labor elasticity 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 fall of the output gap, implying a trade-off between the two policy objectives. This is in contrast with the case of perfect competition in the oil sector (or 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

$$\pi_t = \lambda \sum_{k=0}^{\infty} \beta^k E_t \left[(1 - s_o) \hat{y}_{t+k} + s_o \hat{\nu}_{t+k} \right] \tag{9}$$

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

$$\hat{\imath}_t = \phi_i \hat{\imath}_{t-1} + (1 - \phi_i) \left(\phi_\pi \pi_t + \phi_y \hat{y}_t \right) + \hat{r}_t, \tag{10}$$

where π_t is inflation, $\hat{y}_t$ is the output gap, $\hat{r}_t$ is a zero mean *i.i.d.* monetary policy shock, and ϕ_i, ϕ_π and ϕ_y are policy reaction coefficients. Note that we allow for monetary policy to react to the output gap besides inflation, which in our model is an appropriate objective for a central bank concerned with the welfare of the representative household.

4.4 Oil sector

Nakov and Pescatori (2007) model OPEC as a 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 US), 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

$$\hat{\nu}_t = \hat{p}_{ot} + \hat{z}_t = \boldsymbol{\gamma} \left(\hat{y}_{t-1}, \hat{\imath}_{t-1}, \hat{\boldsymbol{\lambda}}_{t-1}, \hat{\boldsymbol{\xi}}_t \right)' \tag{11}$$

where $\hat{\boldsymbol{\xi}}_t = \left(\hat{a}_t, \hat{b}_t, \hat{r}_t, \hat{z}_t, \hat{\omega}_t \right)$ is a vector of exogenous shocks and $\boldsymbol{\gamma}$ is a row vector of non-linear 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 nominal interest rate, $\hat{\imath}_{t-1}$, both of which are state variables; in addition, it depends on past promises about future oil supply, captured by the vector $\hat{\boldsymbol{\lambda}}_{t-1}$ 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 $\hat{\omega}_t$

$$\hat{x}_t = \hat{p}_{ot} + \hat{z}_t + \hat{\omega}_t. \tag{12}$$

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

$$\hat{\omega}_t = \rho_\omega \hat{\omega}_{t-1} + \epsilon_t^\omega, \tag{13}$$

where $\hat{\omega}_t \equiv \log\left(\Omega_t/\bar{\Omega}\right)$ and ϵ_t^ω is *i.i.d.* with mean zero and standard deviation σ_ω.

4.5 What factors could lead to reduced volatility?

We illustrate how different factors may contribute to the volatility 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 on average. Notice that smaller real shocks would reduce the volatility of $\hat{rr}_t^e$, 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 main driving variables in our model, for any given monetary policy and elasticity of oil in production, 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.[7]

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 output compared to the past. The latter can be due to increased energy efficiency and diversification away from oil-intensive sectors. The elasticity of oil in production affects the volatility of $\hat{rr}_t^e$ as well as the coefficient on the cost-push term in the Phillips curve. Other things equal, a smaller elasticity of oil in production is likely to reduce the volatility of output and the pass-through from the oil price to inflation.

To see how the elasticity of oil in production affects the inflation–output gap tradeoff, notice that a policy of strict price stability ($\pi_t = 0$) implies

$$\hat{y}_t = -\frac{s_o}{1-s_o}\hat{\nu}_t, \tag{14}$$

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

$$\pi_t = s_o \lambda \sum_{k=0}^{\infty} \beta^k E_t \hat{\nu}_{t+k}. \tag{15}$$

[7] 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.

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

5 Data and Methodology

We asses the extent to which the macroeconomic moderation in the US can be explained by changes in oil shocks and the elasticity of oil in production, by simulating counterfactually the model of Nakov and Pescatori (2007) estimated *via* Bayesian techniques for the periods pre- and post-1984. Our estimation methodology is similar to Rabanal and Rubio-Ramírez (2005), Gali and Rabanal (2005), An and Schorfheide (2007), and Smets and Wouters (2007). The observable variables (whose volatility change 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 1970:I to 2007:IV are taken from FRED II.[8] GDP growth and inflation are computed as quarterly percentage changes of real GDP and the GDP deflator[9]; the nominal interest rate is converted to quarterly frequency to render it consistent with the model; and the oil price is deflated by the GDP deflator and cast in quarterly percentage changes. The resulting series are demeaned by their sub-sample means prior to estimation.

Since our model is meant to describe the behavior of OPEC we start our sample in 1970 which is when the cartel started gaining more power. Note, however, that the market power of OPEC is endogenous in the model, that is, OPEC's market share and price markup fluctuate in response to fundamental shocks. The model is therefore particularly well suited to account for shifts between periods with more competitive and periods with more monopolistic oil markets.

The sample is split in 1984:I. This corresponds to the estimated break in US output volatility 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 (Clarida, 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.

[8] The original series names are GDPC96, GDPDEF, FEDFUNDS and OILPRICE.

[9] Our model makes no difference between GDP deflator and CPI inflation.

5.1 Calibration of the elasticity of oil in production

One of the parameters which we calibrate is the elasticity of oil in the production function. In our model, this elasticity need not be equal (or even proportional) to the cost share of oil in production. Cobb-Douglas technology together with cost minimization by monopolistic firms imply that the constant elasticity of oil in production times the current marginal cost of firms must equal the cost share of oil in gross output,

$$s_o mc_t = \frac{P_{ot}O_t}{P_t Q_t}, \tag{16}$$

where $P_{ot}O_t$ is the nominal value of oil inputs, P_tQ_t is nominal gross output, and mc_t is the *time-varying* marginal cost of final goods firms.[10] Note that the formula is consistent with a constant elasticity of oil in production s_o, as long as movements in marginal cost shadow the fluctuations in the oil cost share observed in the data. Since this relationship holds in every period, it holds also on average, that is

$$s_o mc = E\left[\frac{P_{ot}O_t}{P_t Q_t}\right], \tag{17}$$

where average marginal cost equals the inverse of the steady-state markup, $mc \equiv E(mc_t) = \mu^{-1} = \frac{\epsilon-1}{\epsilon}$ and ϵ is the constant elasticity of substitution among product varieties (which we fix at 7.66 in both samples). Note also that nominal gross output in our model is equal to value added plus the dollar value of oil inputs: $PQ = PY + P_oO$. Thus, given data on nominal GDP (PY), the oil price (P_o), and the quantity of oil used in the US (O),[11] we can infer the constant elasticity of oil in production in each sub-sample based on the *sub-sample average* of the cost share of oil in nominal gross output,

$$s_o = \frac{\mu}{T}\sum_t^T \frac{(\text{barrels of oil consumed in the US})_t \times (\$\text{ per barrel})_t}{(\text{nominal gross output})_t}, \tag{18}$$

where t runs from 1970 to 1983 in the first sample and from 1984 to 2007 in the second. In this way we obtain an elasticity of 0.0472 in the first period and 0.0264 in the second, which we fix prior to estimation.

Our calibrated elasticity in the second sample is close to the value of 0.02 obtained by Rotemberg and Woodford (1996) using a related but somewhat different approach. These authors add up the average nominal value added in oil extraction and the average value of petroleum imports as a share of GDP, obtaining a share of 0.034.[12] They then round up this number to 0.04 to account for other energy inputs that might be close substitutes to oil. Assuming that

[10] A similar formula obtains with a more general CES production function.

[11] Annual data on US petroleum consumption (in barrels per day) from 1960 to 2007 is available from the Energy Information Administration, U.S. Dept. of Energy. http://www.eia.doe.gov/aer/txt/ptb1110.html

[12] It is not clear what historical period Rotemberg and Woodford (1996) have used for the calculation of these average shares.

materials account for 50% of total cost, they infer an elasticity of oil in gross output of 0.02.

Evidence of a declining cost share of oil in GDP and in consumption is found in a number of studies (e.g. Blanchard and Galí, 2007; Edelstein and Kilian, 2007a,b). In particular, Edelstein and Kilian (2007b) show the evolution of the energy share in GDP, which declined from around 5% in 1981, to 1% in 1998, before rising to 3.3% in 2005. These movements in the energy cost share are not inconsistent with a constant elasticity of oil in production over the sub-samples, as shown by equations (16) and (17) above. While the cost share in our model, as in the data, fluctuates over time (being affected among other things by the price of oil), it does so around different sub-sample means. Under our assumptions, the latter is enough to infer the elasticity of oil in production, which is the structural parameter of interest.

Parameter			Based on
Quarterly discount factor	β	0.9926	Aver. annual real rate 3%
Elast. of subst. among varieties	ϵ	7.66	Aver. markup 15%
Mean of non-OPEC capacity	$\bar{\Omega}$	4.93e-3	Aver. OPEC share 40%
Production function parameters			
Elasticity of capital	s_k	1/3	Aver. cost share of capital
Elasticity of oil, 1970-1983	s_o	0.0472	Aver. cost share of oil
Elasticity of oil, 1984-2007	s_o	0.0264	Aver. cost share of oil

Table 2. Calibrated parameters

5.2 Estimation procedure

The above procedure leaves us with fourteen parameters to estimate: the frequency of price adjustment (θ), the Frisch labor supply elasticity (ψ), the parameters of the monetary policy rule (ϕ_i, ϕ_π, ϕ_y), the shocks' autoregressive parameters (ρ_a, ρ_b, ρ_z, ρ_ω) and standard deviations of the innovations (σ_a, σ_b, σ_z, σ_ω, σ_r). In the case with a hybrid IS curve, there is an additional parameter h, measuring the degree of external habit formation by households.

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' 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 1,000,000 draws from the posterior distribution. We follow Benati's (2008) approach to obtain a scale for the jumping distribution which yields an acceptance rate of around 0.23. The posterior distributions are obtained by discarding the first two-thirds of the draws and then keeping one draw for every 100 of the remaining draws to break the serial correlation.

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 elasticity of oil in production) on the volatility moderation.

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.[13]

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 ϕ_π below 1. The reason is that, different from 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 past output gaps. This explains why we can solve and estimate our model for values of ϕ_π 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 0.6 and standard deviation of 0.1.[14] For the inverse Frisch labor supply elasticity we assume a gamma prior with mean 1 and standard deviation of 0.25.[15] The autocorrelation coefficients of the shocks are assumed to be distributed 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 non-negativity) fixing the means around the calibrated values in Nakov and Pescatori (2007).

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

[13] 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.

[14] This is consistent with the 13.9% median *monthly* frequency of regular price changes that Klenow and Kryvtsov (2008) find in U.S. micro data. The *mean* frequency of regular price changes found by these authors is 29.9% per month.

[15] 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 three equation New Keynesian model.

monetary policy was reacting more strongly to inflation compared to 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.

Secondly, the mode of the Calvo (1983) parameter governing the frequency of price adjustment is smaller in the post-1984 period suggesting that prices have become more flexible. At first sight this may seem counterintuitive given that inflation was higher in the first period, which - other things equal - should call for more frequent price changes. However, the real cost of price adjustment itself may well have decreased in the second sample, owing to improvements in the technology of calculating and posting new prices, making prices more flexible. An alternative explanation is that the fall of the Calvo parameter is a way for the model to capture the reduced inflation persistence in the second period, given that the model lacks price indexation.[16]

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 became smaller in the latter period.

Para-meter	Prior distribution				Posterior distribution		
	Density and domain		Mean	Std	Mean	Std	Mode
θ	Beta	$[0,1)$	0.60	0.10	0.614	0.068	0.622
ψ	Gamma	$\mathbb{R}^+$	1.00	0.25	0.961	0.224	0.897
ϕ_i	Normal	$\mathbb{R}$	0.60	0.10	0.542	0.079	0.537
ϕ_π	Gamma	$\mathbb{R}^+$	1.10	0.50	2.438	0.359	2.224
ϕ_y	Normal	$\mathbb{R}$	0.50	0.125	0.545	0.108	0.531
ρ_a	Beta	$[0,1)$	0.90	0.05	0.958	0.017	0.969
ρ_b	Beta	$[0,1)$	0.90	0.05	0.890	0.035	0.896
ρ_z	Beta	$[0,1)$	0.90	0.05	0.917	0.032	0.927
ρ_ω	Beta	$[0,1)$	0.90	0.05	0.926	0.031	0.937
$100\sigma_a$	Inv. Gamma	$\mathbb{R}^+$	0.70	∞	1.359	0.127	1.331
$100\sigma_b$	Inv. Gamma	$\mathbb{R}^+$	0.70	∞	2.762	0.599	2.207
$100\sigma_z$	Inv. Gamma	$\mathbb{R}^+$	10.0	∞	21.27	2.436	21.33
$100\sigma_\omega$	Inv. Gamma	$\mathbb{R}^+$	10.0	∞	34.95	6.763	30.73
$100\sigma_r$	Inv. Gamma	$\mathbb{R}^+$	0.10	∞	0.530	0.068	0.494

Table 3a. Prior and posterior distributions, 1970–1983

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 more precise, although it slightly overestimates the volatility of GDP growth and underestimates the volatility of the oil price in both periods, the model matches quite well the post-1984 reduction in the volatility of both variables. And while the volatility moderation of the nominal interest rate is

[16] We are grateful to one of the referees for making this point.

somewhat overestimated, the volatility of inflation in both periods (and hence its reduction) is matched pretty well.

Parameter	Prior distribution				Posterior distribution		
	Density and domain		Mean	Std	Mean	Std	Mode
θ	Beta	$[0,1)$	0.60	0.10	0.473	0.063	0.477
ψ	Gamma	$\mathbb{R}^+$	1.00	0.25	1.070	0.238	1.009
ϕ_i	Normal	$\mathbb{R}$	0.60	0.10	0.676	0.059	0.691
ϕ_π	Normal	$\mathbb{R}$	1.50	0.50	3.191	0.295	3.100
ϕ_y	Normal	$\mathbb{R}$	0.50	0.125	0.535	0.098	0.539
ρ_a	Beta	$[0,1)$	0.90	0.05	0.978	0.010	0.983
ρ_b	Beta	$[0,1)$	0.90	0.05	0.951	0.015	0.951
ρ_z	Beta	$[0,1)$	0.90	0.05	0.881	0.033	0.882
ρ_ω	Beta	$[0,1)$	0.90	0.05	0.954	0.018	0.960
$100\sigma_a$	Inv. Gamma	$\mathbb{R}^+$	0.70	∞	0.630	0.045	0.620
$100\sigma_b$	Inv. Gamma	$\mathbb{R}^+$	0.70	∞	2.133	0.516	1.862
$100\sigma_z$	Inv. Gamma	$\mathbb{R}^+$	10.0	∞	14.92	1.596	15.18
$100\sigma_\omega$	Inv. Gamma	$\mathbb{R}^+$	10.0	∞	25.43	4.721	23.40
$100\sigma_r$	Inv. Gamma	$\mathbb{R}^+$	0.10	∞	0.231	0.034	0.212

Table 3b. Prior and posterior distributions, 1984–2007

	1970-1983		1984-2007		Volat. reduction	
	Data	Model	Data	Model	Data	Model
Inflation	0.57	0.61	0.25	0.25	57%	58%
GDP growth	1.20	1.64	0.52	0.72	57%	56%
Interest rate	0.88	0.89	0.57	0.43	35%	51%
Real oil price	19.0	16.6	13.0	12.0	31%	28%

Table 4. Second moments of model and data

7 Macroeconomic Implications

7.1 What factors explain the Great 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 elasticity of oil in production; (2) oil shocks; (3) the monetary policy rule; (4) monetary policy shocks; (5) total factor productivity shocks; and (6) other factors (including shifts in the frequency of price adjustment, and in the Frisch labor supply elasticity, as well as a residual due to the interaction of all factors).

Table 5a reports the percent contribution to the total volatility reduction achieved by a change in a single factor keeping the rest of the parameters at their pre-1984 values.[17] For instance, had the elasticity of oil in production

[17] We do not model transition dynamics here; Canova and Gambetti (2007) propose an

in the period 1970-1983 been at its post-1984 value (that is, 0.0264 instead of 0.0472), inflation would have been 18% less volatile, while GDP growth would have been 10% less volatile. Expressed as a percentage of the predicted volatility reduction for these variables (the last column of Table 4), the diminished reliance on oil alone can explain around 32% of the reduced volatility of inflation, and 18% of the smaller volatility of GDP growth. By the same token, the diminished incidence of major oil shocks is responsible for 17% of the inflation volatility moderation, and 11% of the reduced volatility of GDP growth. This suggests that oil-related factors have played an important role in the stabilization, especially of inflation.

Nevertheless, we find that better monetary policy played the biggest role in reducing the volatility of inflation. In particular, the more aggressive policy reaction to inflation after 1984 accounts for 40% of its volatility decrease. In addition, smaller monetary shocks have contributed another 11% to reducing the volatility of inflation. However, we find that monetary policy played only a minor role in the reduced volatility of GDP growth (4%).

Our calculations lead us to conclude that the main factor for the reduced volatility of GDP growth (contributing around 57%) has been a favorable shift in the distribution of productivity shocks in the U.S. By contrast, we find only a trivial role of productivity shocks in reducing the volatility of inflation (by 2%).

The bottom line of this analysis is that the smaller "oil share" and oil shocks have played an important role in the reduced volatility, especially of inflation, even if the other two factors – better monetary policy and smaller TFP shocks – have played the dominant role in the stabilization of inflation and GDP growth respectively.

	Oil		Monet. policy		TFP	Other
	share	shocks	rule	shock	shock	factors
Inflation	32	17	40	11	2	-2
GDP growth	18	11	0	4	57	10
Interest rate	12	3	37	4	8	36
Real oil price	-3	101	0	0	0	2

Table 5. Contributions to the reduced volatility (%)

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 little or no pass-through since that

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 (2002) treating our parameters as behavioral.

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 findings are in broad agreement with these claims (see Table 6). Indeed, they point to the decrease in the elasticity of oil in production as a likely cause for the improvement in the Phillips curve tradeoff 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 44% reduction of the elasticity of oil in production from 4.7% to 2.6% (and keeping all other factors unchanged), the volatility of the output gap is reduced by around 40%, and the coefficient of "pass-through" from the cost push term to inflation declines by around 45%. Thus, the decrease in the elasticity of oil in production alone explains a 18% decline in the volatility of inflation (around a third of the total reduction).

In addition, thanks mostly to smaller oil shocks, the volatility of the oil price markup itself has decreased by around 27% in the period after 1984. This, together with a stronger reaction of monetary policy to inflation since the mid-1980s, has made it possible for monetary policy to stabilize better both the output gap and inflation.

		1970–83	1984–07	Counter-factual s_o
Elast. of oil in production	s_o	0.047	0.026	0.026
Common slope coefficient	λ	0.668	1.748	0.664
Oil markup pass-through	$s_o\lambda$	0.032	0.046	0.018
Oil markup volatility	$\text{std}(\hat{\nu}_t)$	0.238	0.175	0.233
Oil markup persistence	$\rho(\hat{\nu}_t)$	0.934	0.939	0.933
Output gap coefficient	$(1-s_o)\lambda$	0.637	1.702	0.647
Output gap volatility	$\text{std}(\hat{y}_t)$	0.012	0.005	0.007
Output gap persistence	$\rho(\hat{y}_t)$	0.886	0.913	0.779

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 the second sample.[18]

Notably, the last two columns of both tables reveal that the contribution of oil sector shocks to US inflation and GDP growth variability was stronger in the first sample and weaker in the second. In particular, oil productivity and fringe capacity shocks ($\hat{z}$ and $\hat{\omega}$) together contributed to as much as 48% of

[18] This is obtained by solving the equation $\Sigma_y = A\Sigma_y A' + B\Sigma_u B'$ in Σ_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.

inflation volatility and 25% of growth volatility in the period 1970–1983. By contrast, in the period 1984–2007 oil shocks contributed less: around 20% of inflation volatility, and 20% of growth volatility. Interestingly, the shock to oil sector productivity ($\hat{z}$) turns out to be more important for the volatility of GDP growth (and the oil price), while the fringe capacity shock ($\hat{\omega}$) is more relevant for the volatility of inflation (and the nominal interest rate).

	US shocks			Oil shocks	
	Real		Nom.		
	$\hat{a}$	$\hat{b}$	$\hat{r}$	$\hat{z}$	$\hat{\omega}$
Inflation	2.74	33.3	15.7	12.2	36.0
GDP growth	69.1	1.10	4.99	22.7	2.13
Interest rate	8.70	69.3	4.44	0.27	17.3
Real oil price	0.05	0.00	0.04	87.1	12.8

Table 7a. Variance decomposition, 1970–1983

	US shocks			Oil shocks	
	Real		Nom.		
	$\hat{a}$	$\hat{b}$	$\hat{r}$	$\hat{z}$	$\hat{\omega}$
Inflation	0.80	37.4	41.5	1.18	19.0
GDP growth	77.8	0.42	2.13	17.5	2.14
Interest rate	3.30	87.4	1.10	1.08	7.11
Real oil price	0.02	0.00	0.01	87.7	12.3

Table 7b. Variance decomposition, 1984–2007

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 after that year (but has decreased its impact on inflation and the interest rate). The preference shock ($\hat{b}$) was important for inflation and the nominal interest rate before 1984 and has become even more relevant for both variables since then; and the interest rate shock ($\hat{r}$) has increased its relative importance for inflation (but has become less relevant for GDP growth and the interest rate).

Finally, figures 3 and 4 shows the imputed structural innovations. The shocks are signed so that a positive value is associated with an increase in the oil price. Interestingly, Figure 4 suggests that the recent persistent climb of the oil price (starting after the Asian crisis in 1997 and interrupted temporarily around the recession of 2001), reflects to a greater extent fringe capacity shocks (that is, a strengthening of OPEC due to reduced availability of oil outside its control) rather than changes in the marginal cost of oil production (which for much of the past ten years seems to have decreased rather than increased).

7.4 Robustness of the results with a hybrid IS curve

Some of the empirical DSGE literature has found an important role for habit formation in matching the strong autocorrelation of the output gap, mitigating the need for persistent structural shocks (e.g. Galí and Rabanal, 2005; Smets and Wouters, 2007). In this section we test the sensitivity of our results to allowing individual household utility to depend on its consumption relative to an external habit, proportional to average consumption in the previous period. Formally, utility of consumption at time t is a function $u(C_t - H_t)$, where $H_t = hC_{t-1}$ and h is an external habit parameter. This assumption results in an log-linearized IS curve of the form

$$\hat{y}_t = \frac{1}{1+h} E_t \hat{y}_{t+1} + \frac{h}{1+h} \hat{y}_{t-1} - \frac{1-h}{1+h} \left(\hat{\imath}_t - E_t \pi_{t+1} - \hat{rr}_t^e \right) \tag{19}$$

with weight $h/(1+h)$ on the lagged output gap. Notice that with $h = 0$ the above equation reduces to the more standard forward-looking IS curve (1).

We assume a beta prior for h with mean 0.5 and standard deviation 0.2. Our posterior mode estimate is 0.21 for the first sample and 0.26 for the second. Thus, while we find a role for external habit formation in consumption, it is somewhat less important in our model than in the model of Galí and Rabanal (2005), who obtain a posterior mean for h of 0.4 assuming a uniform prior between 0 and 1.

Our main conclusions are robust to assuming a hybrid IS curve with the estimated degree of habit persistence. Namely, we find that the smaller elasticity of oil in production was responsible for 31%, and smaller oil shocks for 11%, of the reduced volatility of inflation (compared to 32% and 17% without habit formation). Likewise, we find that the smaller elasticity of oil in production contributed 16%, and smaller oil shocks 10%, to reducing the volatility of output growth (compared to 18% and 11% before). As before, smaller TFP shocks are responsible for the bulk of the reduction in GDP growth volatility (55%). And better monetary policy explains around half of the reduced volatility of inflation. Overall, we conclude that our main findings are not affected by considering a hybrid IS curve instead of the more traditional purely forward-looking IS equation.

8 Comparison of the Results with the Literature

Compared to Clarida, Gali and Gertler (2000), our analysis ascribes to monetary policy only a minor role in the stabilization of GDP growth (but an important role in stabilizing inflation). This could be for several reasons. One is the proximity of our model to the RBC paradigm: apart from nominal price rigidities (with a Calvo parameter estimated around 0.6 in the first period and 0.5 in the second 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 enhance the 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, however, better monetary policy does not necessarily imply smaller output volatility, especially if real disturbances imply large fluctuations in the efficient level of output. Third, the estimated reaction to the output gap is quite similar 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 may not have stabilized output much better than the pre-1984 one.

While it may not be very appealing intellectually to attribute the stabilization of growth to unexplained changes in productivity, a similar conclusion has been reached in a number of other studies, e.g. by Stock and Watson (2002), Justiniano and Primiceri (2006), and Leduc and Sill (2007). Based on a calibrated model with exogenous oil supply, Leduc and Sill (2007) in particular 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. These findings are similar to ours. However, our results are distinct when it comes to ascribing the volatility moderation to oil-related factors. While we find that smaller oil shocks have contributed to 17% of the diminished inflation volatility and 11% of the reduced GDP growth volatility, Leduc and Sill claim that oil shocks became larger after 1984 and hence pushed in the direction of *raising* overall volatility. This discrepancy is due to the different way in which Leduc and Sill identify oil shocks by treating oil supply as constant except for four episodes of military conflict, with larger average production drops after 1984. This is in contrast to our modelling of the oil sector from first principles, and identifying oil shocks as structural disturbances to oil productivity or fringe capacity. In addition, we find that the reduced elasticity of oil in production can explain about 32% of the reduced volatility of inflation and 18% of the decrease in volatility of GDP growth, a question which is not addressed by Leduc and Sill.

Blanchard and Gali (2007) introduce real wage rigidities to generate an inflation-output gap trade-off. They demonstrate how a reduction in the oil share in 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 tradeoff 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 the Great Moderation in the US by estimating the benchmark small scale New Keynesian model with Bayesian techniques over rolling samples. He finds that even though changes in the parameters of the private sector are largest, they cannot account by themselves for the full decline in 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 the reduced volatility of GDP growth is attributed to smaller real shocks, while half of the inflation volatility moderation is due to better monetary policy. Yet we find that as much as a third of the inflation volatility moderation and 18% of the volatility reduction of output growth is attributable to the smaller elasticity of oil in production, which is not directly measurable in the 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. They show that a significant fraction of the observed changes in co-movements 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. Herrera and Pesavento (2007) estimate a VAR in the spirit of Bernanke, Gertler and Watson (2004) identifying oil shocks through exclusion restrictions. They find that better monetary policy was responsible for around half of the reduced volatility of inflation and a quarter of the lower volatility of GDP growth, while oil shocks played only a minor role. On the other hand, using a VAR with time-varying coefficients 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.

Finally, there are a number of alternative (or complementary) explanations for the reduced macroeconomic volatility. Kilian (2008) and Kilian and Park (2008), for example, argue that the reduced impact of oil price shocks on the economy in recent years reflects mostly changes in the composition of oil price shocks. Herrera and Pesavento (2005) point to changes in inventory behavior as an explanation for the reduced output volatility. Edelstein and Kilian (2007a,b), and Kilian (2007) identify declines in the employment and output share of the U.S. automobile industry since the 1980s as a key factor. This latter explanation in particular is not inconsistent with the notion of a declining elasticity of oil in output discussed in the present paper.

Compared with the above studies, our analysis based on a structural model assigns an important role to monetary policy, especially in reducing the volatility of inflation. At the same time we find a significant contribution of the reduced dependence on oil, and of smaller structural disturbances in the oil sector, to the stabilization, especially of inflation.

9 Conclusions

We asses the extent to which the increased macroeconomic stability in the US after 1984 can be accounted for by changes in oil shocks and the elasticity of oil in production 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 an important role in the volatility reduction, especially of inflation. In particular, we find that the diminished reliance on oil can explain around a third of the reduced volatility of inflation, and 18% of the lower volatility of GDP growth. In turn, oil sector shocks alone can explain around 17% of the lower inflation volatility, and 11% of the reduced volatility of GDP growth. At the same time, around half of the reduced volatility of inflation is explained by better monetary policy alone, while 57% of the reduced volatility of GDP growth is attributable to smaller TFP shocks.

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10 Appendix

10.1 Model equations

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

$$\max E_0 \sum_{t=0}^{\infty} \beta^t \log \left[p_{ot} O_t - O_t / Z_t \right] \tag{20}$$

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

$$X_t = p_{ot} \Omega_t Z_t \tag{21}$$

of households and final goods firms in the oil importing country

$$w_t = C_t L_t^{\psi} \tag{22}$$

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

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

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

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

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

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

$$L_t = s_l m c_t Q_t \Delta_t / w_t \tag{29}$$

$$Q_t = \frac{A_t}{\Delta_t} L_t^{s_l} \bar{K}^{s_k} \left(O_t + X_t \right)^{s_o} \tag{30}$$

the rule followed by the monetary authority

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

and the global resource constraint

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

We assume that OPEC can commit to the optimal 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

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

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

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

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

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

$$0 = \lambda_{8t}w_t + \lambda_{9t}s_l Q_t \Delta_t / L_t + \lambda_{10t}C_t \psi L_t^{\psi-1} \tag{38}$$

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

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

$$0 = E_t \left[\lambda_{6t+1}\beta\theta\Pi_{t+1}^{\epsilon} \right] - \lambda_{6t} + \lambda_{7t}s_o mc_t Q_t - \lambda_{8t}s_l mc_t Q_t - \lambda_{9t}Q_t \tag{41}$$

$$0 = \lambda_{4t}\mu_t \hat{b}_t + \lambda_{7t}s_o\Delta_t - \lambda_{8t}s_l\Delta_t \tag{42}$$

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

$$0 = \lambda_{8t}L_t - \lambda_{10t} \tag{44}$$

The set of equations (21) to (44), together with the laws of motion of the exogenous states (3), (4), (5) and (13), constitute a full description of the model.

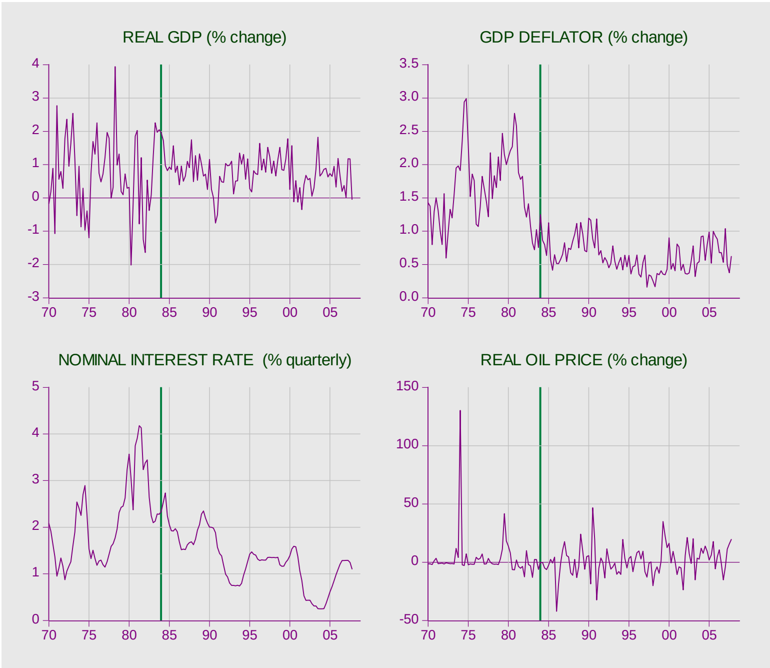

Figure 1: US volatility moderation and the price of oil

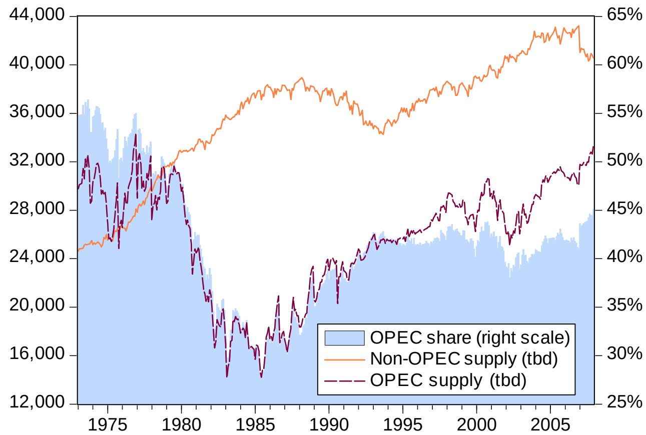

Figure 2: OPEC and non-OPEC supply (thousands of barrels per day) and OPEC market share. Source: EIA (2008)

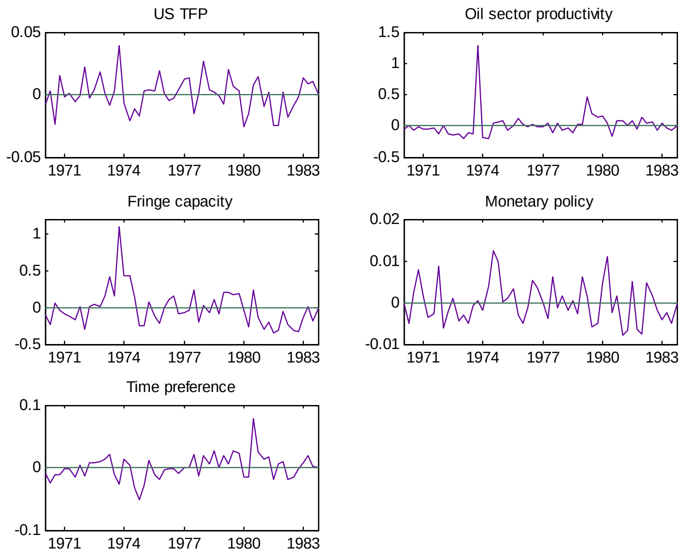

Figure 3: Imputed structural innovations, 1970-1983

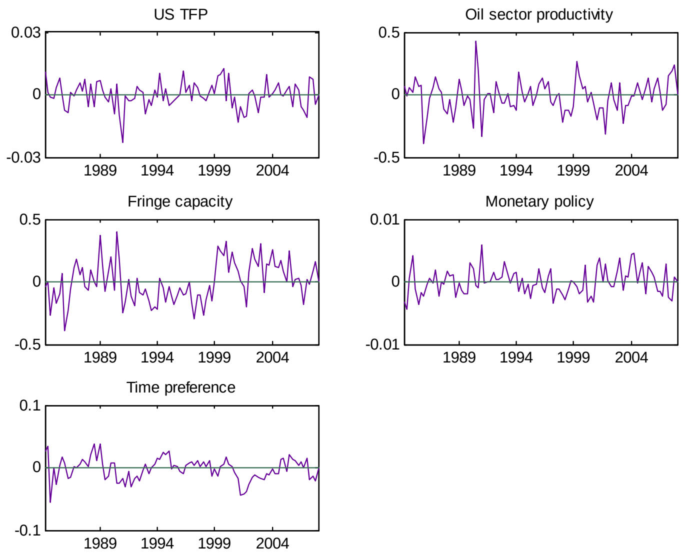

Figure 4: Imputed structural innovations, 1984-2007