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Abstract

We estimate a New Keynesian general-equilibrium open economy model to examine how changes in oil prices affect the macroeconomy. Our model allows oil price changes to be transmitted through temporary demand and supply channels (affecting the output gap), as well as through persistent supply side effects (affecting trend growth). We estimate this model for Canada, the United Kingdom, and the United States over the period 1971-2008, and find that it matches the data very well in terms of first and second moments. We conclude that (i) energy prices affect the economy primarily through the supply side, whereas we do not find substantial demand-side effects; (ii) higher oil prices have temporary negative effects on both the output gap and on trend growth, which translates into a permanent reduction in the level of potential and actual output. Also, results for the United States indicate that oil supply shocks have more persistent negative effects on trend growth than oil demand shocks. These effects are statistically significant; however, our simulations also indicate that the effects are economically small.

JEL classification: F41, Q43
Bank classification: Economic models; Interest rates; Transmission of monetary policy; Productivity; Potential output

Résumé

Les auteurs analysent l’incidence macroéconomique des mouvements de prix du pétrole au moyen d’un modèle d’équilibre général en économie ouverte inspiré de la nouvelle économie keynésienne. Dans le modèle, l’évolution du prix de l’or noir peut avoir aussi bien des effets temporaires sur l’écart de production (par le canal de la demande ou de l’offre) que des effets persistants sur la croissance tendancielle (par le truchement de l’offre). Le modèle, qui est estimé pour le Canada, les États-Unis et le Royaume-Uni sur la période 1971-2008, reproduit très bien les données étudiées, en particulier les moments de premier et de second ordre. Deux conclusions se dégagent du travail des auteurs : 1) les prix de l’énergie se répercutent sur l’économie essentiellement par le canal de l’offre; 2) la hausse des cours pétroliers a des retombées négatives transitoires tant sur l’écart de production que sur la croissance tendancielle, lesquelles se traduisent par une baisse permanente du niveau de production (potentielle comme effective). Aux États-Unis, il semble que les variations de l’offre de pétrole exercent sur la croissance tendancielle des effets négatifs plus persistants que celles de la demande d’or noir. Ces effets sont statistiquement significatifs, mais les simulations réalisées indiquent qu’ils sont de faible ampleur du point de vue économique.

Classification JEL : F41, Q43
Classification de la Banque : Modèles économiques; Taux d’intérêt; Transmission de la politique monétaire; Productivité; Production potentielle

1 Introduction

The rapid increase in oil prices between 2002 and 2008 and their sharp decline in the second half of 2008 has renewed the interest in the effects of energy prices on the macroeconomy. The analysis of the macroeconomic effects of oil prices has evolved along two distinct dimensions. On the one hand, the oil price shocks of the 1970s and 1980s sparked a wave of empirical studies, aimed at quantifying the effects of higher energy prices on macroeconomic variables such as GDP, inflation, or productivity. Most studies were purely empirical, lacked a solid theoretical basis, and the results seem to depend crucially on the empirical approach. Depending on estimation technique, the identification of oil price 'shocks', or the sample period, very different conclusions can be drawn. On the other hand, theoretical studies have investigated different channels through which energy prices might affect macroeconomic outcomes. While these studies provide important insights regarding the transmission of energy price changes, the practical relevance of the different theoretical channels is not always clear, given the lack of empirical evidence.

Building on this work, we combine theory and empirics. We develop and estimate a semi-structural New-Keynesian model of an open-economy in the spirit of Lubik and Schorfheide (2007), in which oil price changes can be transmitted through multiple channels. Our model allows oil prices to have temporary and persistent effects on output through the supply and the demand sides of the economy. More specifically, we allow oil to shift the IS curve to proxy for temporary demand-side effects, to affect the Phillips curve to capture inflationary effects through the supply side, and to affect the growth rate of potential output, which generates persistent effect on the growth rate. The combination of all three channels will determine the endogenous monetary policy response in the model. Using a state space approach, the estimated version of the model for the United States, Canada and the United Kingdom matches key features of the data very well. We then use the model to investigate the importance of energy price changes on GDP, inflation, and trend growth. This analysis is done from the perspective of a central bank, aiming to fully understand how interest rates should respond to a change in energy prices. We also investigate the consequences of setting interest rates 'incorrectly', that is, by not taking into account all channels through which energy prices affect economic outcomes.

Our findings differ from the existing literature in several important ways. First, in contrast to Hamilton (1988), our approach indicates that higher oil prices affect the macroeconomy primarily through the supply side, not the demand side. This supports the notion that higher oil prices have effects similar to negative technology shocks, in that higher oil prices lower firm output in terms of value-added for a given input of capital and labor (in line with Rasche and Tatom, 1977; Bruno, 1984). Second, we find that higher oil prices have short-term effects on the output gap, but also longer-term effects by temporarily lowering trend growth, which reduces the level of GDP permanently. While these effects are *statistically* significant, the impact is small, so their *economic* importance is limited, even for substantial oil price movements. Our analysis also shows that even if central banks do not correctly identify the relationship between oil prices and growth, the resulting policy error is likely to be relatively minor. Lastly, robustness check indicate that observed changes in energy intensity over time do not affect our conclusions, and we also do not find evidence that oil prices have asymmetric effects on the economy.

Before we outline our model, we briefly review the effects of oil prices on key macroeconomic variables in models employed by central banks and policymakers, and contrasts these predictions with the academic literature. Our empirical results are presented in section 3, before we summarize our key insights in section 4.

2 The relationship between oil prices and the macroeconomy

2.1 Related literature

The relationship between energy prices and macroeconomy has been investigated using several approaches. We can distinguish between empirical studies with limited economic theory, and theoretical studies, with limited empirical applications. Also, the implications from both types of studies have changed substantially over time.

The oil price shocks of the 1970s and 1980s, and the subsequent global recession, sparked a wave of empirical studies. Focusing on oil price shocks in the 1970s and 1980s, early empirical studies tended to find a negative relationship between oil prices and real activity (e.g. Hamilton, 1983; Hulten, 1989).[1] However, this relationship was

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[1] As Barsky and Kilian (2004) note, there is a widespread belief that exogenous political events in the Middle East causes recessions in industrialized economies through the effect on oil prices, even though the empirical evidence on this link is weak. Huntington (2005) provides a recent survey.

increasingly questioned in the mid-1980s, when energy prices dropped sharply, without subsequent increase in economic activity. In response, several empirical studies suggested that the impact of energy prices on the macroeconomy was not symmetric, and measured oil price shocks, based on the notion that oil price increases should have negative effects on growth, while falling oil prices may only yield small boosts to GDP (see Mork, 1989; Hooker, 1983; Hamilton, 1996).[2] Still, by the late 1990s, a consensus began emerging in the literature that there might be a negative relationship between oil prices and real activity, but its magnitude is likely to be small (Jones et al., 2004).[3] Lastly, several empirical studies have focused on the role of monetary policy in responding to oil price shocks (Bernanke et al., 1997; Barsky and Kilian, 2004; Cologni and Manera, 2008), examining whether central banks tighten monetary policy to avoid inflationary effects, or support economic growth by lowering interest rates.

The second strand of the literature is been based on economic theory. Like the empirical literature, the findings from the theoretical contributions changed over time, and theoretical studies do not provide a clear picture whether oil prices should or should not have substantial effects on the macroeconomy. For instance, Kliesen (2008) shows that the price elasticity of the demand for oil is low in the short-term, because firms and consumers cannot change their production or consumption patterns immediately, so the effects of higher oil prices on GDP might be small (at least initially). In that case, the negative demand shock for energy-intensive goods may cause substantial reallocation of labour, which – if costly – can have a large impact on the overall economy even if oil as share of GDP is low. In Rotemberg and Woodford (1996), monopolistic producers can increase their mark-ups during oil price shocks, depressing output, and Finn (2000) models variations in utilization rates for productive capital as a function of energy use, finding that oil price shocks causes sharp, simultaneous declines in energy use and capital utilization with large effects on output.[4] Lastly, the explanation of why the fall in energy prices in the 1980s failed to spur economic growth points to asymmetric effects, arising through (at least) two important channels (Jimenez-Rodriguez

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[2] Hamilton (1996) and Guo and Kliesen (2008) proxy oil price shocks by the difference between the current oil price and the maximum price in the past 4 or 12 months (see also our robustness check in the appendix); Kilian (2008a, 2008b) uses a production-based measure to capture the difference between actual oil production and a 'counterfactual' path in the absence of exogenous production shortfalls (triggered by wars, for instance).

[3] Blanchard and Gali (2007) claim that the mild effects on inflation and economic activity of the oil price increase in the early 2000s are due to good luck – lack of concurrent adverse shocks – smaller shares of oil in production, more flexible labor markets, and better monetary policies.

[4] In this regard a puzzle is that sharp increases in oil prices should render (part of) the existing, energy-intensive capital stock obsolete. One would expect lower prices for used equipment after an oil price shock, but earlier empirical studies have failed to confirm this hypothesis (Hulten et al. 1989; Bohi, 1991).

and Sanchez, 2005): first by rending parts of the existing capital stock obsolete, *any* change in energy prices requires costly adjustment.[5] The second channel is a negative demand shock when energy price increase, or a positive demand shock when energy prices fall.[6] Also, both shocks interact, as the impact of the positive demand shock from falling energy prices is reduced by the need to adjust the capital shock.

Two other features of the literature are noteworthy. First, narrative studies such as Olson (1988) claim that the cost of oil as a part of GDP is too small to have large macroeconomic effects. Lastly, a remarkable disconnect is observable between recent empirical studies that suggest that oil price changes have very limited effects, and the effects predicted in important macroeconomic models, such as those employed by the IMF, the European Commission, the Bank of Canada or the European Central Bank, which all suggest that oil price fluctuationss have substantial macroeconomic effects. For instance, comparing different models, Roeger (2005) reports that over a 3-year horizon, the effects of a 50 percent increase in oil prices on GDP growth range between -0.5 percentage points (OECD's Interlink model) to -2.3 percentage points (NIGEM).[7]

While we are not aware of studies that estimate a general equilibrium model to investigate the impact of energy price changes over history, three studies are relatively close to ours. First, Bodenstein et al. (2008) develop a general equilibrium model that includes oil prices. However, while we estimate our model, their model is calibrated, to investigate optimal monetary policy in response to an energy price increase for two different inflation measures (core and headline inflation). Second, Elekdag et al. (2008) build a five-country DSGE model with production and trade of crude oil. Rather than estimating the effect of oil prices over history, however, these authors study the factors driving oil prices. Third, Lubik and Schorfheide (2007) estimate a structural model to test whether central banks respond to exchange rate movements. While our study differs in terms of topic, the methodology we employ is very similar, in that we estimate a general equilibrium model and simulate the model for different ways to conduct monetary policy.

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[5] Jones et al. (2004) review studies using highly disaggregated data. The combined impression conveyed by these studies suggest extensive reallocation of labour after an oil price shocks, which occurs at the 4-digit SIC level (and consequently is hard to detect in more aggregated data). This suggests that the effect of high energy prices extends beyond the small share of oil in the economy.

[6] Even if the importance of oil as a share of GDP is small, higher oil prices can still act as an important negative demand shock, if it depresses purchases of energy-intensive goods with large dollar values, such as cars (Hamilton 1988).

[7] Similarly, a recent survey of the effect of oil in macroeconomic models employed by institutions like the IMF by Huntington (2005) suggest that an increase of $10 per barrel in the price of oil is expected to reduce U.S. output by about 0.25 percentage points in the first year.

2.2 Oil and trend growth

We propose a simple macroeconomic model to evaluate the effects of oil prices on the economy with a monetary policy response in the spirit of the current DSGE literature (see for instance Gali, 2008). We employ a very general treatment with regard to how oil prices affect the economy, allowing effects on trend growth (supply side), the output gap (demand side), and inflation.

Consider how oil prices affect a firm's production first. Assume a representative firm that produces Y units of a single final good using capital (K), labor (L), and oil (O) as inputs. In the short term, technology is fixed, represented by the following (aggregate) linearly homogeneous, twice continuously differentiable production function:[8]

$$Y = F(K, L, O). \tag{1}$$

Taking the price of inputs as given, a profit-maximizing firm will hire inputs up to the point in which their marginal product is equal to their real price (i.e., relative to the aggregate price of Y). In particular, for the case of oil, this optimal condition is $\partial F/\partial O = p$. It implies a demand function of the following form:

$$O = \Psi(K, L, p), \tag{2}$$

where p is the real price of oil and $\partial \Psi/\partial p < 0$. Let $y = Y - p \times O$ represent the firm's output in terms of value added. Substituting (1) and (2) into the expression for y gives:

$$\begin{aligned} y &= F(K, L, \Psi(K, L, p)) - p\Psi(K, L, p) = \\ &= f(K, L; p). \end{aligned} \tag{3}$$

It is easy to show that $\partial y/\partial p < 0$.[9] In other words, the production function in terms

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[8] If sustained, firms are likely to respond to changes in oil prices by adopting different technologies. We abstract from these longer-term effects.

[9] To derive this function form for the demand for oil, note the following:

$$\frac{\partial f}{\partial p} = \frac{\partial F}{\partial \Psi} \times \frac{\partial \Psi}{\partial p} - \left[p \times \frac{\partial \Psi}{\partial p} + \Psi(K, L, p) \right] \tag{4}$$

$$= \underbrace{\left[\frac{\partial F}{\partial \Psi} - p \right]}_{=0,\text{ from } \partial F/\partial O = p} \frac{\partial \Psi}{\partial p} - \Psi(K, L, p) = -\Psi(K, L, p) < 0 \tag{5}$$

of value added, $f(K, L, p)$, suggests that changes in oil prices have macroeconomic effects similar to negative shifts in total factor productivity ('technological regress'). In a factor-price frontier framework, this analogy is developed in more detail in Rasche and Tatom (1977) and Bruno (1984).[10] Consider, for example, the possibility that oil prices affect transportation costs. Cheap transportation enables geographical dispersion of production, which is arguably one of the elements underlying globalization. Sharp increases in energy prices could drive up transportation costs, slowing down or partly reversing the incentives to specialize, and thus putting downward pressure on productivity growth. In a similar vein, for given inputs of capital and labour, higher oil prices reduces the value added of production. This is similar to a fall in total factor productivity.

2.3 Building a semi-structural, New Keynesian model

In what follows, we incorporate this notion into a New Keynesian macroeconomic model to assess the effect of oil prices on potential (or trend) output growth. We do not develop a fully-fledged DSGE model, but use a structure similar to Gali (2008) as a basis for our empirical model.

We start by incorporating the notion that higher oil prices can have effects comparable to technological regress. Let y_t, and y_t^T represent value-added measures of actual and potential (or trend) output, and denote their growth rates by g_t and g_t^T, respectively. We interpret y_t^T as the level of output that would take place in a balanced growth path of a frictionless economy (that is, without nominal rigidities, see Woodford, 2003). In addition, assume that the output gap, $\hat{y}_t$, is defined as the log-difference between actual and potential output:

$$\hat{y}_t = \log y_t - \log y_t^T, \tag{6}$$

where

$$y_t = (1 + g_t) y_{t-1} \tag{7}$$

and

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[10] Kim and Loungani (1992) have an an alternative modelling approach to generate qualitatively similar insights.

$$y_t^T = (1 + g_t^T) y_{t-1}^T \tag{8}$$

Combining equations (6)-(8), g_t is a function of g_t^T and the change in $\hat{y}_t$:

$$(1 + g_t) = (1 + g_t^T) \exp(\hat{y}_t - \hat{y}_{t-1}) \tag{9}$$

To capture the effect of oil prices on y_t, y_t^T, and $\hat{y}_t$, let the law of motion for the growth rate of potential output be represented by the following stochastic process:

$$g_t^T = (1 - \rho_g) g + \rho_g g_{t-1}^T + \sum_{k=-1}^{1} \lambda_{g+k} E_t p_{t+k} + e_t^g, \tag{10}$$

where $\rho_g \in (0,1)$ is an auto-regressive coefficient, g is a constant that maps into the stationary value of g_t^T, p_t denotes the real price of oil, and $e_t^g \sim N(0, \sigma_g)$ is an i.i.d. shock that will have temporary effects on the growth rate, but permanent effects on the level of potential output.[11] Estimates of λ then provide the impact of oil prices on potential at different leads and lags.

We interpret the auto-regressive part of g_t^T as (exogenously) capturing the time-path of standard determinants of growth, such as technological progress, increase in labour productivity, population growth, physical and human capital accumulation etc. (Aghion and Hewitt, 2009). At the same time, we explicitly allow oil prices to affect trend growth through parameter λ_g. In line with section 2.2, we expect $\lambda_g < 0$, reflecting the analogy between increases in oil prices and technological regress on potential output. In the model, this is the first possible channel through which oil prices affect the economy.

The second channel through which oil prices can affect the economy is through the supply side, that is through the traditional Phillips curve, which maps (log) deviations of actual inflation (π_t) from trend (or targeted) inflation π_t^T to the current level of the output gap ($y_t / y_t^T = \exp(\hat{y}_t)$), past and expected deviations of inflation from trend inflation, and oil prices:

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[11] The steady-state level of g_t^T is:

$$g_{SS}^T = g + \frac{\lambda_g}{(1 - \rho_g)} p_{SS}.$$

$$\frac{\pi_t}{\pi_t^T} = \beta_0 + \beta_y \exp(\hat{y}_t) + \beta_{\pi_{t-1}} \left(\frac{\pi_{t-1}}{\pi_{t-1}^T}\right) + \beta_{\pi_{t+1}} \mathrm{E}_t \left(\frac{\pi_{t+1}}{\pi_{t+1}^T}\right) + \sum_{k=-1}^{1} \beta_{p+k} E_t p_{t+k} + v_t, \tag{11}$$

where $v_t \sim N(0, \sigma_v)$ is an i.i.d. supply shock. We expect $\beta_p > 0$, as higher oil prices should contribute to increase marginal costs and inflation, for a given level of slackness in the economy.

Lastly, oil prices can affect the demand-side. We allow for the possibility that all else equal, higher oil prices shift the IS curve to the left. In our open economy model, the output gap curve is a function of its lagged value, the real interest rate (r_t), the real exchange rate (s_t), the detrended foreign output gap ($\hat{y}_t^*$), and oil prices:

$$\hat{y}_t = \gamma_y \hat{y}_{t-1} + \gamma_r r_t + \gamma_s s_t + \gamma_{y^*} \hat{y}_t^* + \sum_{k=-1}^{1} \gamma_{p+k} E_t p_{t+k} + \varepsilon_t, \tag{12}$$

where $\varepsilon_t \sim N(0, \sigma_\varepsilon)$ is an i.i.d. demand shock, $r_t = R_t / \mathrm{E}_t \pi_{t+1}$ is defined as the ratio of the nominal interest rate(R_t) to inflation expectations for $t+1$ (conditional on information up to time t); and the real exchange rate is represented by s_t, determined according to a standard uncovered interest parity (UIP) condition:

$$\frac{s_{t+1}}{s_t} = \frac{r_t}{r_t^*} + u_t,$$

where $r_t^* = R_t^* / \mathrm{E}_t \pi_{t+1}^*$ is the foreign real interest rate, and u_t is a UIP-shock following a first-order autoregressive process; R_t^* and π_{t+1}^* are the foreign nominal interest rate and inflation rate, respectively.

The monetary policy rule ‘closes’ the model. We assume that the central bank sets the nominal interest rate in reaction to (log) deviations of inflation and output from their respective trend-values, as well as the lagged interest rate:

$$\frac{R_t}{R_t^T} = \left(\frac{R_{t-1}}{R_{t-1}^T}\right)^{\rho_R} \left(\frac{\pi_t}{\pi_t^T}\right)^{\rho_\pi} [\exp(\hat{y}_t)]^{\rho_y} \exp\left(e_t^R\right), \tag{13}$$

where the trend for the interest rate ($R_t^T \equiv r_{SS} \pi_t^T$), or the ‘natural’ interest rate, is defined as the product of the steady-state level of the real interest rate (r_{SS}) and trend inflation. $e_t^R \sim N(0, \sigma_R)$ is an i.i.d. monetary policy shock.

The baseline model endogenously determines dynamic paths for y_t, y_t^T, g_t, g_t^T, $\hat{y}_t$, R_t, s_t, and r_t. For the three foreign variables, trend inflation, and the UIP shock we assume exogenous AR(1) processes, such that:

$$z_t = (1 - \rho_z) z_{SS} + \rho_z z_{t-1} + e_t^z, \tag{14}$$

where subscript SS denotes steady-state values and $e_t^z \sim N(0, \sigma_z)$, for $z = \log y^*$, $\log R^*$, $\log \pi^*$, $\log \pi^T$, u_t.

As regards the determination of oil prices, we make a distinction between the United States on the one hand, and Canada and the United Kingdom on the other. For the latter two countries, it is reasonable to assume that oil prices are exogenous. This is equivalent to saying that their oil consumption and oil supply are too small to affect the world price of oil. Hence, we assume that oil prices follow an AR(1) process:

$$\log p_t = (1 - \rho_p) \log p_{SS} + \rho_p \log p_{t-1} + e_t^p. \tag{15}$$

However, the United States is an exception, in that domestic output, relative to global output, is large enough to influence oil prices. To allow for an endogenous response of oil prices to U.S. growth, we replace eq. (15) by the following two equations for world oil supply and U.S. (net) oil demand when estimating the model for the U.S. economy:[12]

$$\begin{aligned} \text{World net oil supply: } \log Q_t &= (1 - \rho_{Q_S}) \log Q + \rho_{QS} \log Q_{t-1} + \lambda_p p_{t-1} + e_t^{QS} && (16) \\ \text{U.S. net oil demand: } \log Q_t &= \phi_0 + \phi_g g_t^T + \phi_y \exp(\hat{y}_t) + \phi_p p_t + e_t^{Q_D} && (17) \end{aligned}$$

The shocks e_t^{QS} and e_t^{QD} allow us to simulate world net oil supply and U.S. oil demand shocks separately. To allow for correlations between world supply shocks and U.S. oil demand shocks, we also add the shocks e_t^{QS} and e_t^{QD} to the remaining AR(1) processes

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[12] We also estimated the model under the assumption that the United States is a price taker on the global oil market. This modification does not change our results materially.

for the United States, such that eq. (14) becomes:

$$z_t = (1-\rho_z)z_{SS} + \rho_z z_{t-1} + \alpha^{z_{ss}^D} e_t^{QD} + \alpha^{z_{ss}^S} e_t^{QS} + e_t^z, \tag{18}$$

To illustrate how a central bank sets interest rates in our model, consider how an increase in oil prices affects the economy (figure 1). We allow for oil prices to affect trend growth, as well as the output gap. The inflationary impact of higher oil prices occurs directly through trend growth (eq. 10) and through the supply side (the Phillips curve, eq. 11). In addition, higher oil prices also affect inflation indirectly through the demand side (the IS curve, eq. 12).[13] The combination of all three channels will determine the monetary policy response (eq. 13). While these three channels exists for all countries, note that an additional feedback is present for the United States, as we allow for an endogenous response from the macroeconomy to changes in oil prices.

3 Empirical results

3.1 Estimation and model validation

The model has 13 equations, 11 shocks, and 33 parameters (14 equations, 12 shocks and 34 parameters for the United States with endogenous oil prices).[14] To estimate the model, we write it in state-space form and use the Kalman filter to estimate by maximum likelihood. We use quarterly data from 1971Q1 to 2008Q1 for the United States and Canada (1975Q1 to 2008Q1 for the United Kingdom) for the following observable variables: g_t, R, R^*, y^*, s, π, π^*, p, plus – for the United States – U.S. oil imports Q. All variables have been detrended using an Hodrick-Prescott filter.[15] Lastly, preliminary tests showed that leads and lags of oil prices are not statistically significant in the equations for potential growth, the Phillips curve or the IS curve. Therefore, in our final specification, oil prices enter in eq. (10), (11) and (12), only contemporaneously.

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[13] Additional effects occur through the exchange rate, which in turn feed back onto the IS curve and the Phillips curve.

[14] Note that our model is estimated for a ‘home country’, which may be a small-open economy (Canada and the United Kingdom) or a large economy (United States), not a multi-country model.

[15] Note that for all economies, oil prices enter in U.S. dollar terms. We could use oil prices in local currency, but then the model finds it more complicated to identify energy prices increases and exchange rate movements separately.

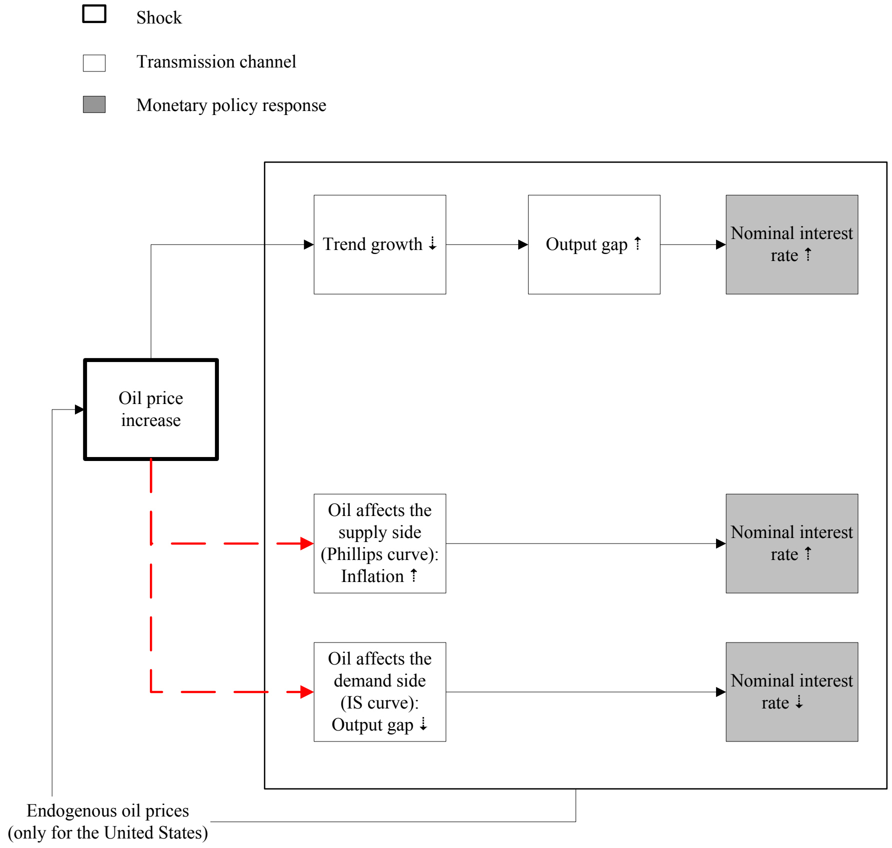

Figure 1: Transmission channels

The estimated model matches the data remarkably well. Table 1 shows for each country the relative volatility of key economic variables (x) over the volatility of output growth, $\sigma(x)/\sigma(g_t)$, and the covariance of variables x with output growth, $\sigma(x, g_t)$). Differences between the model and the actual data are very small. Formal tests indicate that the observed and model data are not statistically different along these dimensions (see appendix A.2).

Table 2 tests the difference between observed and model data reported in table 1 statistically. For each country, the first column tests whether the correlation coefficient between our estimated series and output growth is statistically different from the actual data, and the second column tests for differences in variance between estimated series

	$\sigma(x)/\sigma(g_t)$		$\sigma(x,g_t)$	
Series (x)	Model	Data	Model	Data
United States				
Exchange Rate	4.48	4.57	-0.10	-0.05
Inflation	0.63	0.67	-0.15	-0.12
Interest Rates	0.50	0.53	-0.25	-0.21
Oil Prices	22.32	23.95	-0.27	-0.26
Oil Imports	9.85	11.67	0.09	0.11
United Kingdom				
Exchange Rate	7.84	9.41	0.23	0.20
Inflation	1.00	1.10	-0.38	-0.37
Interest Rates	0.49	0.53	-0.31	-0.26
Oil Prices	21.87	26.36	-0.27	-0.30
Canada				
Exchange Rate	3.93	4.39	0.02	0.00
Inflation	0.62	0.69	-0.23	-0.22
Interest Rates	0.44	0.49	-0.33	-0.30
Oil Prices	22.50	24.87	-0.15	-0.10

Table 1: Relative variances and covariances in the data and the model

and the data.[16] None of the estimated moments are significantly different from the empirical moments in the data. Table 2 reports autocorrelation coefficients in the data, and compares them to our model-generated coefficients. Again, they are very similar. Taken together, these findings provide an indication that our model captures underlying macroeconomic relationships very well.

3.2 Results

Table 3 shows the parameter estimates and table 4 shows the estimated parameters for the shock processes for the United States, the United Kingdom and Canada. Parameters for which we do not report p-values – such as the effect of foreign output on demand for the United States – were calibrated at zero, because they were not statistically significant. Let us first discuss how the model replicates standard macroeconomic relationships, before we examine the impact of oil prices in more detail.

Table 3 shows that in all three countries, monetary policy reacts to higher inflation

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[16] For test of mean, the F-test is consistent with t-test, Satterthwaite-Welch t-test and Welch F-test (reported statistic is Anova F-test); for the test of variance, the reported F-test is consistent with Siegel-Turkey, Bartlett, Levene and Brown-Forsythe tests.

	1 lag AR(1)		2 lags AR(2)	
	Model	**Data**	**Model**	**Data**
United States				
Growth	0.29	0.21	0.18	0.09
Exchange Rate	0.81	0.79	0.59	0.55
Inflation	0.39	0.40	0.01	0.02
Interest Rates	0.81	0.81	0.55	0.54
Oil supply	0.74	0.77	0.44	0.46
Oil demand	0.41	0.42	0.09	0.04
United Kingdom				
Growth	0.03	-0.14	0.20	0.08
Exchange Rate	0.77	0.77	0.53	0.52
Inflation	0.34	0.34	0.17	0.17
Interest Rates	0.83	0.83	0.58	0.58
Oil Prices	0.76	0.78	0.44	0.49
Canada				
Growth	0.36	0.21	0.15	-0.01
Exchange Rate	0.79	0.78	0.53	0.52
Inflation	0.24	0.24	-0.05	-0.04
Interest Rates	0.82	0.82	0.56	0.56
Oil Prices	0.74	0.77	0.44	0.46

Table 2: Autocorrelation coefficients

and higher output by raising interest rates (positive values for ρ_π and ρ_y). The Phillips curve indicates that higher oil prices or a positive output gap lead to higher inflation in the short term (positive values for β_p and β_y). Domestic output – the IS curve – reacts negatively to higher real interest rates (γ_r) and positively to a depreciation of the real exchange rate (γ_s) for all three countries; for Canada and the United Kingdom, higher foreign output also boosts demand (γ_{y^*}).

As regards the effect of oil prices, oil prices do not enter the IS curve in any of the three countries, which is why we dropped the parameter γ_p in table 3. In contrast, we find significant, positive effects of oil prices on the Phillips curve (β_p). This suggests that most of the short-term macroeconomic effects occur through the supply side. Lastly, higher oil prices have small, yet significant effects on trend growth (λ_g). In the model for the United States with endogenous oil prices, U.S. oil demand reacts positively to higher U.S. growth (ϕ_y) and negatively to higher oil prices (ϕ_p).[17] Lastly, a past increase to the price of oil leads to an increase of world oil supply (λ_p). To check the model performance without oil at all, we also conduct likelihood ratio tests, whereby we restrict oil price-related coefficients to zero and then compare the restricted and unrestricted model. The results in table 5 suggest that despite oil prices having a statistically significant effect on the macroeconomy through the supply side, these effects are likely to be small (even in the short run), since the restricted model is not rejected by the data.

Comparing the estimates between countries, we find that the Canadian IS curve reacts more strongly to changes in foreign output than the United Kingdom (γ_{y^*}), and the shock to foreign output is most persistent for Canada (reflected by the highest value of ρ_{y^*}). This likely reflects that Canada is the most open economy of all G7 countries. In contrast, shocks to foreign inflation and the foreign interest rate (parameters ρ_{π^*}, ρ_{R^*}) have relatively similar effects in all three economies. Also, our findings indicate that the effect of higher oil prices on trend growth (λ_g) is the highest for the United Kingdom, followed by the United States and Canada.[18]

To examine the effects of oil prices on the different economies in more detail, table 6 shows the variance decomposition to oil-related shocks. We would like to highlight

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[17] This does not contradict Kilian and Vega (2008), who fail to find evidence that oil prices respond to macroeconomic news, as we do not distinguish between anticipated developments and macroeconomic 'news'.

[18] We also tested for a possible structural break in the relationship between oil and macroeconomy for Canada in the early 1990s, when Canada moved from being a net energy importer to a net energy exporter. Our tests rejected presence of a structural break.

	United States		United Kingdom		Canada	
Parameter	Estimate	p-value	Estimate	p-value	Estimate	p-value
Potential Output Growth						
g	0.0202	0.0006	0.0171	0.0000	0.0166	0.0000
ρ_g	0.2526	0.0019	0.0000		0.3539	0.0000
λ_g	-0.0094	0.0083	-0.0115	0.0000	-0.0058	0.0909
Monetary Policy Rule						
ρ_R	0.6663	0.0000	0.9079	0.0000	0.9025	0.0000
ρ_p	0.7772	0.0938	0.1342	0.0000	0.3871	0.0027
ρ_y	0.0981	0.0646	0.0140	0.0036	0.0466	0.0278
Supply (Phillips Curve)						
β_0	0.7275	0.0000	0.6775	0.0000	0.8495	0.0000
β_y	0.6323	0.0069	0.7479	0.1016	1.4549	0.0147
$\beta_{\pi_{t-1}}$	0.2651	0.0001	0.3158	0.0003	0.1408	0.0534
$\beta_{\pi_{t+1}}$	0.0000		0.0000		0.0000	
β_p	0.0074	0.0010	0.0067	0.0807	0.0097	0.0000
Demand (IS Curve)						
γ_y	0.0419	0.1247	0.4233	0.0001	0.0000	
γ_r	-0.0563	0.0002	-0.0221	0.0007	-0.0576	0.0091
γ_s	0.0566	0.0002	0.0163	0.0000	0.0360	0.0066
γ_{y^*}	0.0000		0.0059	0.0680	0.0220	0.0460
Oil Prices (treated as exogenous)						
ρ_p			0.7369	0.0000	0.6887	0.0000
U.S. Oil Demand						
ϕ_0	-3.3766	0.0804				
ϕ_y	6.6811	0.0005				
ϕ_p	-3.3045	0.0804				
World Net Oil Supply						
ρ_{Q_S}	0.3767	0.0000				
λ_p	0.0225	0.0033				
Likelihood	-4,276.6		-3,697.2		-4,241.3	
Obs.	149		133		149	
d.f.	121		108		125	

Note: Parameters for which we do not report t-statistics are calibrated by conducting a grid search: we estimates all parameters, conditional on the calibrated parameter value, and picked the calibration that yielded the highest maximum likelihood.

Table 3: Maximum likelihood estimates of the structural parameters

	United States		United Kingdom		Canada	
Parameter	Estimate	p-value	Estimate	p-value	Estimate	p-value
AR(1) components						
ρ_{y^*}	0.5211	0.0000	0.5337	0.0000	0.8519	0.0000
ρ_{p^*}	0.1535	0.0084	0.2431	0.0069	0.1219	0.0667
ρ_{R^*}	0.8695	0.0000	0.7921	0.0000	0.8660	0.0000
ρ_{μ}	0.7580	0.0000	0.5819	0.0000	0.6679	0.0000
$\alpha_{\pi^*}S$	-0.0073	0.0636				
$\alpha_{\pi^*}D$	0.0026	0.0856				
α_{π^*}			0.0062	0.0039	0.0171	0.0000
α_{y^*}			0.0129	0.0497	-0.0098	0.0522
α_{R^*}	0.0013	0.0657	0.0034	0.0009	0.0014	0.1223
Standard deviations						
e_t^p	0.0077	0.0000	0.0074	0.0000	0.0075	0.0000
v	0.0044	0.0000	0.0071	0.0000	0.0047	0.0000
e_t^R	0.0171	0.1126	0.0024	0.0000	0.0056	0.0087
$e_t^{y^*}$	0.0105	0.0000	0.0081	0.0000	0.0072	0.0000
$e_t^{\pi^*}$	0.0037	0.0000	0.0023	0.0000	0.0037	0.0000
$e_t^{R^*}$	0.0013	0.0000	0.0013	0.0000	0.0013	0.0000
e_t^{μ}	0.0017	0.0000	0.0138	0.0000	0.0039	0.0000
e_t^p			0.1101	0.0000	0.1207	0.0000
e_t^{QS}	0.0865	0.0000				
e_t^{QD}	0.5878	0.0833				
Obs	149		133		149	
d.f.	121		108		125	

Table 4: Maximum likelihood estimates of AR(1) coefficients and standard deviation of shocks

	Likelihood ratio	p-value
United States	0.084	0.99
UK	0.001	0.99
Canada	0.007	0.99

Table 5: Likelihood ratio tests, comparing the model with and without oil

	Shock	$\hat{y}$	g_t	g_t^T	π_t	R_t	p_t
United States	e_t^{QS}	0.19	2.26	2.20	2.47	2.09	51.86
	e_t^{QD}	0.10	1.74	1.68	1.91	0.72	47.84
UK	e_t^p	1.93	6.05	6.02	3.34	3.00	100.00
Canada	e_t^p	4.09	2.24	2.05	5.98	1.77	100.00

Table 6: Variance decomposition of oil price shocks

two results. First, comparing the results for Canada and the United Kingdom, oil shocks have a relatively large effect on trend growth in the United Kingdom, whereas the Canadian effect occurs primarily through the output gap (and is thus temporary). Consistent with this, the inflationary impact of oil price changes is also bigger in Canada, and a larger share of the variation in interest rates in the UK can be explained by oil shocks (this is consistent with oil shocks having a bigger inflationary impact in Canada.) Second, our U.S. model also allows examining the differences in effects of oil supply and oil demand shocks. We find that variation in the price of oil are almost equally attributable to fluctuations in oil supply and oil demand (e_t^{QS} and e_t^{QD}, respectively), and, as a rule of thumb, a larger portion of the variation in the output gap and trend growth is attributable to oil supply shocks than to oil demand shocks. This is not surprising, given that oil supply shocks are more persistent and therefore have a bigger impact on U.S. inflation.

3.3 The effect of a shock to oil prices

As a graphical way to gauge the model's performance, let us look at impulse-response functions for a 10 per cent increase in oil prices. Consider Canada and the United Kingdom, the two countries for which oil prices are exogenous. In figure 2, shocks have been calibrated so that in both cases the price of oil increases by 10 per cent to facilitate comparison (all graphs are in percentage points deviations from the steady state). As indicated before, the effect on the output gap are substantially larger for Canada than for the United Kingdom, whereas the effect on trend growth is larger for the United Kingdom. This implies that in response to an oil price shock, the effects on the Canadian economy occur relatively more through a temporary opening up of a negative output gap, whereas the effects on the United Kingdom are relatively more long-lasting, as they occur through lower potential growth. Second, Canadian inflation increases by more than UK inflation, which is consistent with Canadian monetary policy reacting less to energy price increases (for both countries, real interest rates are

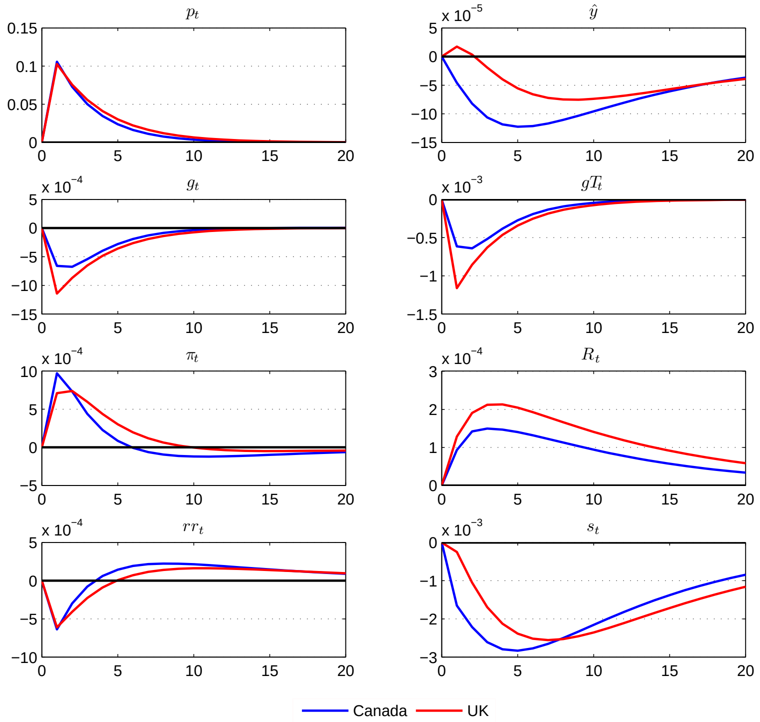

Figure 2: The effect of a 10 per cent increase in oil prices for Canada and the United Kingdom (effects shows in percentage point deviations from the steady state)

initially negative, which indicates that the monetary policy response is not aggressive enough to lower real interest rates). Note, however, that Canadian inflation reverts faster back to its pre-shock level. This is because the Canadian exchange rate appreciates not only by more in response to higher oil prices than the UK exchange rate, but also the appreciation is much faster, helping to bring down inflation.[19]

Given that we have endogenized oil prices for the United States, we can simulate the effects of oil demand shocks and oil supply shocks for U.S. variables separately. Figure 3 shows two impulse response function, one simulating a shock to oil demand, one to oil supply (both have been scaled such that the resulting increase in the price of oil is also 10 per cent for both shocks). Confirming the results of Kilian (2009), not all oil price shocks are alike, as the source of the shock matters and oil price increases

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[19] The exchange rate reactions are in line with Cayen et al. (2008) who have found that higher commodity prices tend to appreciate the real exchange rates of both currencies.

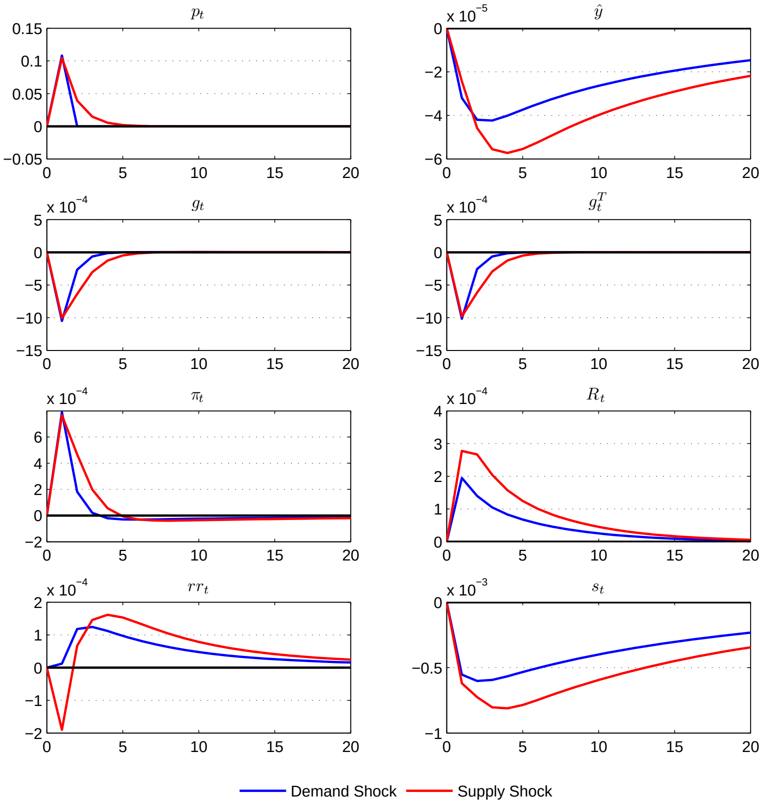

Figure 3: The macroeconomic effects of oil demand and oil supply shocks for the United States (effects shows in percentage point deviations from the steady state)

driven by negative supply shocks have different effects than higher prices driven up by higher demand for oil. In our model, a strong oil demand shock can be thought of as an increase in the energy intensity of production, that is, for a given output, more energy is required, driving up the demand for oil (and thus oil prices). Negative supply shocks have much more persistent effects on trend growth, and lead to a stronger reduction in growth. Negative oil supply shocks also lead to a much larger monetary policy reaction, but real interest rates are negative, suggesting that the monetary policy reaction is simulative – not surprising in light of the relatively larger output effects. In constrast, monetary policy increases real interest rates in response to a positive oil demand shock, as the oil price increase in this model is triggered by higher growth of the US economy.

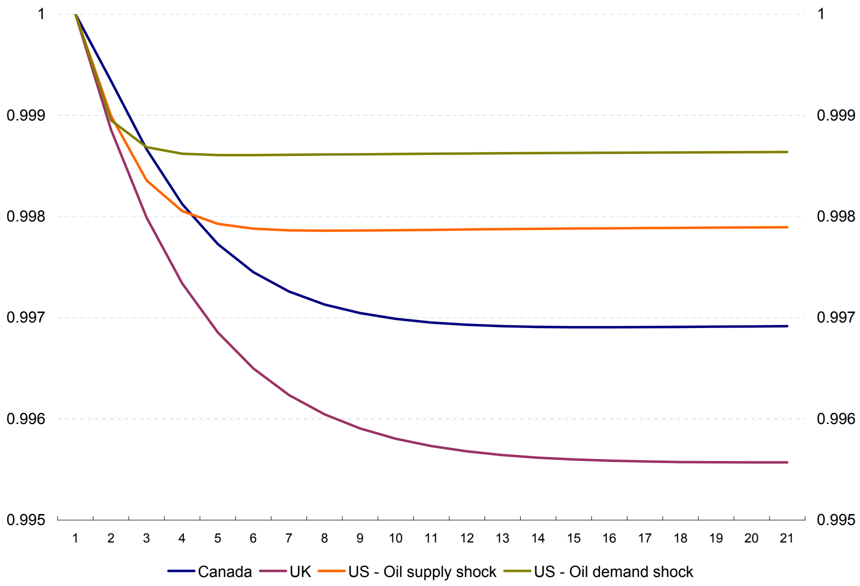

Figure 4: The effect of a 10 per cent oil price shock on the level of GDP

Lastly, note that while the estimated effects on growth rates are small, changes in oil prices may have non-negligible macroeconomic impacts, as changes in oil prices have permanent effects on the level of GDP. Consider figure 4, which shows the level of GDP and the level of trend GDP after an 10 per cent oil price increase. As can be seen, the effects are permanent, that is, lower the level of GDP permanently, ranging from from a drop of roughly 0.4 per cent in the United Kingdom to a drop of 0.1 per cent for a shock to oil prices from lower demand in the United States.

3.4 What if the central bank makes a mistake?

As shown, the impact of changes in energy prices on the level of GDP are permanent and significantly different from zero. This means that an optimal monetary policy should take into account the short-term, as well as the long-term effect on economic activity. Higher energy prices have short-term effects through the output gap, but they also lower trend growth. Not identifying these transmission channels correctly could imply that the output gap is calculated incorrectly, and interest rates could possibly be set inappropriately low, as the amount of excess supply after a positive energy price increase is overestimated. What would be the economic consequences of the central bank making this ‘policy error’?

In what follows, we take the example of Canada and simulate the central bank’s policy response to a 10 per cent increase in oil prices under three different assumptions:

- first, the central bank correctly identifies the negative effect of higher energy prices through all channels of the model (‘correct policy response’);
- second, the central bank identifies the temporary short-term effects on the output gap through shifts of the IS curve correctly, but fails to take into account the longer-term effects through trend growth (‘mild policy error’);
- third, the central bank fails to identify both the negative effects of higher oil prices through the IS curve and the negative effect on trend growth (‘severe policy error’).

Table 7 show the relative volatility of key economic variables under the different scenarios, where volatility under the ‘correct’ response has been normalized to 1. In the ‘mild policy error’ case, volatility of all economic variables increases (except the interest rate, which is set by monetary policy), as the central bank overestimates trend growth and consequently miscalculates the output gap. As potential output is overestimated, the central bank sets interest rates too low. Conversely, in the ‘severe policy error’ scenario, the central bank miscalculates both trend output and the output gap, and by not taking into account that rising oil prices have slowed the economy, the entire fall in output is attributed to the output gap. Consequently, interest rates are set too high, which results in low inflation, but amplifies the volatility in output, relative to the case in which the central bank makes no mistake.

Figure 5 shows the estimated central bank responses under the different scenarios. As can be seen, the difference between the ‘correct’ policy response and the case in which the effects on the IS curve are correctly identified, but the lower trend growth is not recognized, are small. To give a sense of the magnitude of the monetary policy response under a severe oil price shock, suppose that oil prices increase by 100 per cent in a single quarter. Under the ‘correct’ response, this would lead to an increase in Canadian interest rates of 15 bps. If the central bank makes a ‘mild policy error’, interest rates are only raised by 7 bps.[20] The difference in the interest rate response

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[20] Even more dramatic, assume that the 600 per cent increase witnessed between 2002 and early 2008 occured in one quarter. Our simulations indicate that in this case, the peak impact on monetary policy rates would be 90 bps under the correct response and 45 basis points under the ‘mild policy error’ case. These differences are fairly small.

Volatility, relative to ‘correct response’	‘Mild policy error’	‘Severe policy error’
Interest rate	89%	282%
Output gap	110%	118%
Inflation	103%	81%
Exchange rate	103%	100%

Volatility for each variable has been set to 100 per cent under the ‘correct’ response.

Table 7: Note: Volatility of key macroeconomic variables if the central bank makes a policy mistake (Canada)

reflects that the central bank overestimates the slack in the economy by not taking into account that the growth rate of potential has fallen in response to higher oil prices, and therefore is not sufficient restrictive in its monetary policy response.

The response of the central bank to an increase in energy prices under the ‘severe policy error’ scenario differs more substantially from the ‘correct’ response. Where interest rates should be set about 15 bps higher under the correct response to a 100 per cent increase in oil prices in a quarter, the central bank raises interest rates by more than 60bps under a ‘severe policy error’.

Taken together, they key message from this exercise is that even during severe oil price shocks, central banks are not likely to amplify economic volatility dramatically, even if interest rates were set incorrectly. Admittedly, there is the risk that interest rates are not set *optimally* if the central bank estimates incorrectly the economic effects of higher oil prices. However, we would like to point out two additional considerations. First, our assumption of an increase in oil prices by 100 per cent is fairly extreme. Second, given uncertainties about the ‘correct’ level of interest rates even absent major economic shocks, it seems that changes in oil prices account for major policy mistakes, even if the central bank is somewhat over- or underestimating the effects of higher oil prices on trend growth or the output gap.

4 Conclusion

The period of high volatility in oil markets between 2002 and 2008 has renewed interest in the analysis of energy prices. Central banks are interested in the macroeconomic effects of changes to oil prices, since the appropriate monetary policy reaction to higher energy prices depends on the correct identification of its macroeconomic impact, which

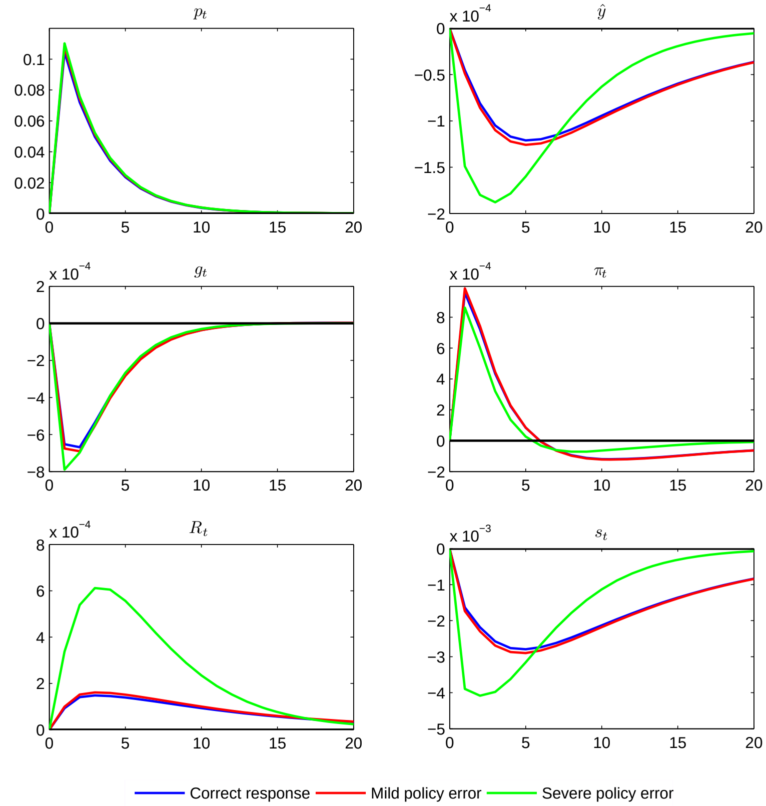

Figure 5: Correct policy responses and central bank 'policy errors' for Canada (effects shows in percentage point deviations from the steady state)

requires an understanding of the transmission channels. Unfortunately, most existing studies employ either a empirical approach with little theoretical underpinnings, or a primarily theoretical approach with limited empirical application.

Our study estimates a simple model, inspired by the New Open Macroeconomy literature. We allow for the possibility that oil prices affect the macroeconomy in the short-term through demand and supply side effects, but also through more persistent supply side effects. As our model replicates key features of the data very well, we seem to accurately capture the effects of commodity prices on the macroeconomy.

While our results are broadly in line with the literature, our model-based approach provides several interesting, additional insights. The recent literature suggests that fluctuations in oil prices have little, if any, macroeconomic impact (Jones et al., 2004), and that the transmission occurs primarily via the demand side (Hamilton 1988, 2003). Our findings qualify both statements. First, we find that higher oil prices have only small (but still statistically significant) effects on trend growth, but they lower the level of GDP permanently. Second, our results indicate that the most likely channel in the short term is not the demand side effect, but the supply side channel. This confirms the notion put forward in Rasche and Tatom (1977) and Bruno (1984) that higher energy prices act in a similar way as technological regress. Third, our findings regarding the monetary policy response to higher oil prices qualify the results of Cologni and Manera (2008). All countries respond to higher oil prices by increasing interest rates, but *real* interest rates become negative, as the rise in inflation more than offsets the increase in interest rates. Consequently, monetary policy remains stimulative – the only exception is a positive shock to oil demand, to which U.S. monetary policy responds with tighter real interest rates (confirming that the distinction between oil supply and oil demand shocks made in Kilian, 2009, is important). Lastly, when considering the possibility that central bank might not fully understand the transmission of energy prices and consequently set monetary policy incorrectly, it turns out that oil price movements have only minor effects on the economy as a whole, and consequently the effects are likely to be too small to lead to policy errors with sizable economic consequences.

Several avenues exist for extending this study. First, our model does not distinguish between demand for different consumption goods. A richer model could split out the demand for durable and non-durable goods, which would allow testing the hypothesis that higher energy prices depresses the demand for durable consumer goods (notably cars). Second, our model treats developments in the rest of the world exogenously, and arguably a more realistic model response for variables such as exchange rates could be derived in a fully-blown two-country setup. Lastly, we only provide estimates for three countries, limiting the scope to investigate what drives the differences in the impact of energy prices on trend growth between countries. Plausible hypothesis include that the impact depends on the oil intensity of production, or the degree to which oil is imported or exported. We leave these issues for future research.

A Appendix

A.1 Robustness checks

We have conducted a number of robustness checks, investigating different modelling choices for energy prices. In what follows, we discuss the sensitivity of our results, based on the the baseline model for the United States.[21]

Oil prices versus broader indices of commodity prices Our first robustness broadens the focus from oil prices to larger sets of commodity prices. One of the developments witnessed in the 1970s, as well as in the period 2007/08, is that broad indices of commodity prices increased as the same time as oil prices soared. One possible explanation for this development is that the rise in oil prices over these periods reflects strong demand (which also drives up prices for other commodities), not supply constraints specific to the oil sector (such as, for instance, the spike in oil prices in the early 1990s, which was clearly related to Iraqi invasion of Kuwait). If our model is able to distinguish between these effects, our results shold not change materially.

To test for this possibility, we replace the price of crude oil by the BIS' commodity price index in place of crude oil.[22] As can be seen in the second and third column of table 8, our estimated effect on trend growth (λ_g) is slightly higher than in our baseline model. Given that an increase in a broad range of commodities can be expected to have larger effects on the production function than isolated price increases in oil, it

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[21] In addition to the robustness checks reported below, we also estimated a version of our model for the United States with exogenous oil prices (that is, analogous to our models for the UK and Canada, we assume that eq. (15) holds for the United States, too). Again our results were robust, as oil prices still had a small, yet significant effect on trend growth.

[22] An alternative measure would be the IMF's commodity price index, but this series starts only in 1992. Over the period where data for both are available, they are highly correlated (around 0.99 both in levels and first differences).

is not surprising that λ_g is higher, but note that overall the key insights remain fairly unchanged.

Oil intensity Energy usage as input to production has declined substantially in most countries since the 1980s, and Guilloux and Kharroubi (2008) show that the impact of commodity import price inflation on CPI inflation depends on the volume of commodity imports. In our second robustness check we control for oil intensity by replacing the oil price by a constructed series, where we pre-multiply oil prices by a measure of energy consumption, relative to GDP. Essentially, this amplifies the oil price increase in the 1970s, relative to the more recent period. In terms of the model, we replace eq. (10) by the following:

$$g_t^T = (1-\rho_g)g^{ss} + \rho_g g_{t-1}^T + \bar{\lambda_g} p_t + e_t^g,$$

where $\bar{\lambda_g} = k * \lambda_g$. As weighting factor k we again use thousands of barrels of oil per day, divided by billions of GDP in constant 2000 dollars. As can be seen in the fourth and fifth column of table 8, the results do not change much, with a slight drop in significance for some parameters (the value of the likelihood function is close to, but lower than for the baseline U.S. model). The estimated coefficient for λ_g – the effect of oil prices on trend growth – is slightly lower, reflecting that we multiplied the data by $k > 1$ (consequently, λ_g is divided by the same factor k).

Asymmetric effects A number of previous studies have considered the case that the macroeconomic effects of energy price shocks might be asymmetric. Mork (1989), Hooker (1983) and Bernanke et al. (1997) found that higher oil price lead to declines in output, while lower oil prices do not seem to lead to increase in output. An intuitive explanation for this effect is that *any* change to the price of energy requires changes in the capital stock, which is why lower energy prices may require investment in different technology to reap the full benefit. As the initial investment takes times, output does not immediately increase in response to lower energy prices. Note, however, that Kilian and Vigfusson (2009) show in a recent study that estimates of asymmetric effects in most previous studies were obtained incorrectly, possibly invalidating these results.[23]

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[23] Griffin and Schulman (2005) use a panel of OECD countries covering 1961 to 1999 and show that symmetric price responses of energy and oil demand functions cannot be rejected, after controlling for changes in energy consumption.

To investigate this issue in our last robustness check, we replaced our simple oil price series with a series inspired by Hamilton (1996) and compare current oil prices with prices during the four quarters preceding the current quarter. If the price in a given quarter is greater than the largest price over the preceding four quarters, we set the value equal to one ('price increase'), and zero otherwise ('no increase'). Then, we take this constructed series, and include it in the model as an explicit shock process, which is multiplied into two lambda coefficients – λ_g (up) and λ_g (no chg.) – such that in each period, one of the coefficients is estimated.

The results for asymmetric effects are reported in the sixth and seventh column of table 8. As can be seen, both parameter estimates of the asymmetry parameter λ_g are significant, but the estimates values are very close. This supports the notion that possible asymmetries are probably of second order.

A.2 Detrending and model validation checks

There are multiple ways to ensure stationarity of the series used for the estimation. The analysis was done using an HP filter; other solutions could be to use first differences. Table 9 compares different detrending methods for oil prices. The HP filter is clearly the preferred method, yielding the highest likelihood ratio. Figure 6 shows the actual series, after they have been rendered stationary by applying an HP filter, and the model-generated data. As can be seen, both series are very close.

Table 2 reports the estimated autocorrelation coefficients and compares them to the empirical moments. As can be seen, the differences are usually small. Taken together, these tests provide further evidence that our model matches the data very well.

	Commodity Index		**Intensity Adjusted**		**Asymmetric Effects**	
Parameter	**Estimate**	**p-value**	**Estimate**	**p-value**	**Estimate**	**p-value**
Potential Output Growth						
g	0.0279	0.0000	0.0058	0.3070	0.0280	0.0000
ρ_g	0.2157	0.0090	0.2647	0.0016	0.2668	0.0013
λ_g	-0.0159	0.0027	-0.0043	0.2475		
λ_g (up)					-0.0103	0.0133
λ_g (no chg.)					-0.0102	0.0054
Monetary Policy Rule						
ρ_R	0.6417	0.0001	0.7391	0.0000	0.6494	0.0015
ρ_p	0.7819	0.0853	0.6408	0.0393	0.4921	0.0613
ρ_y	0.0986	0.0608	0.0848	0.0255	0.1086	0.0490
Supply (Phillips Curve)						
β_0	0.7074	0.0871	0.6425	0.0958	0.7651	0.0806
β_y	0.6159	0.0082	0.6264	0.0110	0.0215	0.3839
$\beta_{\pi_{t-1}}$	0.2875	0.0001	0.3575	0.0000	0.2349	0.0002
$\beta_{\pi_{t+1}}$	0.0000		0.0000		0.0000	
β_p	0.0051	0.1362	0.0000		0.0000	
Demand (IS Curve)						
γ_y	0.0411	0.1152	0.0453	0.1247	0.0000	1.0000
γ_r	-0.0563	0.0002	-0.0530	0.0003	-0.0584	0.0011
γ_s	0.0562	0.0002	0.0533	0.0003	0.0620	0.0010
γ_{y^*}	0.0000		0.0000		0.0000	
U.S. Oil Demand						
ϕ_0	-3.2917	0.0882	-6.8611	0.0005	-7.1496	0.0003
ϕ_y	8.9833	0.0380	6.8611	0.0007	7.1496	0.0000
ϕ_p	-5.6916	0.1866	-3.4931	0.0783	-3.7745	0.0000
World Net Oil Supply						
ρ_{Q_S}	0.3796	0.0000	0.3841	0.0000	0.3765	0.0000
λ_p	0.0965	0.0000	0.0176	0.2014	0.0175	0.0196
Likelihood	-4,328.4		-4,260.5		-4,260.3	
Obs	149		149		149	
d.f.	121		122		118	

Table 8: Robustness checks for the United States (maximum likelihood estimates of structural parameters)

Transformation	Observable	λ_g (t-stat)	Likelihood
HP Filter	Log deviations from SS	-0.0094 (3.2)	-4276.6
Linear Filter	Log deviations from SS	-0.0009 (1.1)	-4069.4
First Difference	First Difference	0.0000 (0.02)	-4084.9
First Difference	Log Difference	0.0000 (0.02)	-4084.9
Log Difference	First Difference	0.0000 (0.03)	-4089.1
Log Difference	Log Difference	0.0000 (0.01)	-4089.1
Log Difference*	Log deviations from SS	Supply: 0.0102 (1.3)	
		Demand: -0.0021 (1.2)	-4047.6

All results are from the model for the United States

* This version allows features oil supply and demand shocks in the growth equation.

Table 9: Robustness checks: different transformations to ensure stationarity of oil prices

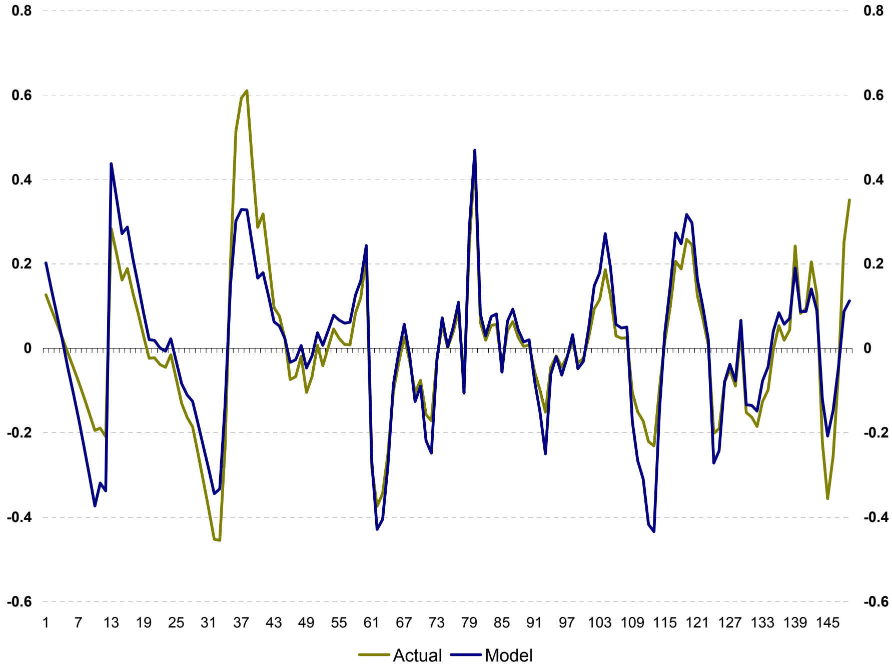

Figure 6: Model series and actual oil prices for the United States

	United States		United Kingdom		Canada	
Series	$\sigma(x,g_t)$	$\sigma(x)$	$\sigma(x,g_t)$	$\sigma(x)$	$\sigma(x,g_t)$	$\sigma(x)$
Output Growth		0.42		0.34		0.24
Exchange Rate	0.27	0.57	0.36	0.24	0.40	0.86
Inflation	0.36	0.97	0.45	0.84	0.45	0.98
Interest Rates	0.31	0.94	0.27	0.97	0.36	0.95
Oil Price	0.45	0.96	0.36	0.23	0.27	0.95
Oil Imports	0.40	0.99				

* Null: Equal Variance

Table 10: Test of equality of moments (p-values of F-tests)

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