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Modelling the world oil market: Assessment of a quarterly econometric model

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Abstract

This paper describes a structural econometric model of the world oil market that can be used to analyse oil market developments and risks. Oil demand depends on domestic economic activity and the real price of oil. Oil supply for non-OPEC producers, based on competitive behaviours, is constrained by geological and institutional conditions. Oil prices are determined by a "price rule" that includes market conditions and OPEC behaviour. Policy simulations indicate that oil demand and non-OPEC supply are rather inelastic to changes in price, while OPEC decisions about quota and capacity utilisation have a significant, immediate impact on oil prices.

Keywords: Oil market; Econometric modelling; Forecasting

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1. Introduction

The oil shocks of the 1970s and 1980s prompted theoretical advances in energy economics (Griffin, 1993), many of which were used to model the world oil market. Standard structural energy models that simulated energy flows in physical terms remained important for international organisations (see e.g. Cozzi, 2004; European Commission, 1995), but the bulk of oil price-related studies conducted in the 1990s analyzed the links between oil prices and macroeconomic activity by applying new econometric techniques (e.g. VAR and VECM models).

Recent price increases for oil combined with—and partly due to—geopolitical pressures and high demand have re-ignited interest in structural explanations of oil price formation based on market equilibrium (Krichene, 2002). Standard practice models the world oil market in terms of a supply–demand equilibrium schedule (e.g. Bacon, 1991; Al Faris, 1991). This approach has proved difficult due to characteristics specific to the oil market. Although a demand curve that relates quantities to prices can accurately represent oil demand, modelling supply is more difficult because oil is supplied by both a set of independent producers (non-OPEC nations) that act as price takers and an organization (OPEC) that uses a myriad of factors to determine levels of production and installed capacity. These aspects of OPEC production, along with changes in market conditions and OPEC behaviour, affect real oil prices (Kaufmann et al., 2004).

Here, we address these particularities with a quarterly model for the world oil market that includes a pricing rule and demand and supply schedules for different regions of the world. To model supply, we distinguish between non-OPEC and OPEC production behaviours. Non-OPEC behaviour is assumed to be competitive (but subject to geological and institutional constraints), while OPEC production is modelled using various behaviours that are described in an extensive literature (see Smith, 2005 for a brief review). Among the behaviours described, two can be identified as corner solutions: a cartel model, in which OPEC is the price maker, and a competitive model, in which OPEC is a price taker. Efforts to choose among these behaviours focus in part on identifying the slope of OPEC's supply curve. A negative relationship between price and production has been interpreted as a backward bending supply curve, which indicates that OPEC sets

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production based on some type of non-competitive behaviour. Econometric analyses of these relationships indicates that production by individual OPEC nations and OPEC as a whole "Granger causes" oil prices but prices generally do not "Granger cause" production (Kaufmann et al., 2004). More recent research indicates that individual OPEC nations do increase production in response to higher prices, but this response can be overwhelmed by changes in OPEC quotas and production sharing behaviours (Kaufmann et al., in review). In other words, OPEC functions somewhere between the two corner solutions. To simulate this intermediate degree of "real-world" control over the world oil market, the effect of both market conditions and OPEC behaviour on oil prices often is modelled with a "price rule." Such a rule gives the price at which OPEC is ready to act as a swing producer, given new demand conditions and market indicators that reflect the effect of behaviour by the dominant producer.

The rest of this paper is organised as follows. Section 2 describes the general structure of the model. Section 3 discusses the econometric methodology and reports estimation results for the demand, supply and price equations. Section 4 assesses the model in terms of forecast performance and simulation properties. The final section summarises the major findings.

2. General structure of the model

The present model for world crude oil consists of three blocks given by equations for demand, supply, and prices (Fig. 1). In this section, we present the general structure of the model, details of the econometric estimates are described in the next section. Specifically, this section does not describe the stochastic structure of the model.

2.1. Oil demand

Oil demand equations are estimated for ten main trading partners of the euro area; the US, Japan, UK, Euro area, Switzerland, other developed economies, non-Japan Asia, Transition economies, Latin America, and rest of the world. For each region, oil demand is a log-linear function of real *GDP*, real oil prices, and a time trend that represents technical changes, which affect energy efficiency.

The general specification for the econometric equations of oil demand is given by

$$DEM_i = \Phi\left(Y_i, \frac{POIL}{P_i^D} E_i, time\right) \tag{1}$$

in which DEM_i is oil demand in physical units for each country/region i, Y_i is real *GDP*, *POIL* is the oil price in USD, E_i the exchange rate vis-à-vis the US dollar and P_i^D is an index for domestic prices. All variables are in logarithms. As described in the estimation section, specification (1) represents the long-term determinants of demand. The regression errors from Eq. (1) are used to estimate error-correction models, in which lagged effects and short-term dynamics determine quarterly changes in demand.

2.2. Oil supply

We distinguish between the supply behaviour of OPEC and non-OPEC nations. The former can be modelled using either a cooperative behaviour, in which OPEC matches production to demand or a competitive behaviour, in which OPEC produces oil commensurate with its operable capacity. Non-OPEC production has a significant effect on OPEC's share of the world oil supply and, as a consequence, on OPEC's ability to influence prices. Production by non-OPEC countries is modelled using a technique that assumes competitive behaviour is constrained by geological and institutional factors.

2.1. OPEC supply

The model is set up to simulate two forms of OPEC production behaviour: cooperative and competitive production. Cooperative behaviour can be used to describe OPEC production since the third quarter of 1986 (Kaufmann, 1995). During that period, OPEC generally set production to match the difference between world oil demand and non-OPEC production. This behaviour can be simulated with the following equation:

$$\begin{aligned} PROD^{\text{opec}} = {} & \sum_i DEM_i + \Delta S\text{tocks}^{\text{oecd}} - \text{NGLS} \\ & - \sum_j PROD^{\text{non-opec}} - \text{PG} \end{aligned} \tag{2}$$

in which $\text{Stocks}^{\text{oecd}}$ is the level of stocks reported by OECD, NGLS the natural gas liquids, and PG the processing gains.

Alternatively, the model can simulate competitive behaviour by OPEC nations. Following this behaviour, OPEC nations compete among themselves and with non-OPEC producers for market share. To compete for market share, OPEC increases production to rates that are consistent with operable capacity. To account for competitive production behaviours, OPEC production is simulated using the following equation:

$$PROD^{\text{opec}} = 0.95 * Capacity^{\text{opec}} \tag{2′}$$

in which *Capacity* is operable capacity (million barrels per day) of OPEC.[1] As described in the next section, OPEC capacity is exogenous. Competitive behaviour described by Eq. (2′) implies that production does not match demand. Oil produced in excess of demand is put into stocks, which depresses oil prices via the price rule that is described in the next section. When the model is simulated assuming competitive behaviour by OPEC, the price rule does not use the 95 percent rate of capacity utilisation that is dictated by Eq. (2′). Instead, the rate of capacity utilisation used by the price rule is calculated based on the call for OPEC oil that is given by Eq. (2).

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[1] Data from Erik Kreil from the US Department of Energy.

Demand side

$$DEM_i = \Phi\left(Y_i, \frac{POIL}{\overline{P_i^D}}.\overline{E_i}, time\right) \tag{1}$$

for i = US, euro area, UK, Switzerland, Other Dev. Eco. NJA, Transition, Latin America, Rest of the world

DEM : Oil demand in mbd

Y : Real GDP

POIL : Oil price in USD

$\overline{P^D}$: Domestic price index

$\overline{E}$: Exchange rate vis - a - vis USD

time : time trend

Supply side

$$PROD^{opec} = \sum_i DEM_i + \Delta\overline{Stocks}^{oecd} - \overline{NGLS} - \sum_j PROD^{non-opec} - \overline{PG} \tag{2}$$

$$PROD^{opec} = 0.95 * \overline{Capacity}^{opec} \tag{2'}$$

$$PROD_j^{non-opec} = \Theta\left(\overline{Cost}_j, \frac{POIL}{\overline{P_i^D}}\right) \tag{3}$$

for j = US (lower 48 + Alaska), Canada, Asia, Africa, Europe, Latin America (Brazil, Mexico and others)

PROD : Oil supply in mbd

$\overline{Cost}$: Measure of production costs

$\overline{Stocks}^{oecd}$: Oil stocks reported OECD

$\overline{NGLS}$: Non Gas Liquid in mbd

$\overline{PG}$:Processing Gains in mbd (net)

Oil Price

$$POIL = \Psi\left(\frac{\overline{Stocks}^{oecd}}{\sum_{i \in oecd} DEM_i}, \overline{Quota}^{opec}, \left(PROD^{opec} - \overline{Quota}^{opec}\right), \frac{PROD^{opec}}{\overline{Capacity}^{opec}}\right) \tag{4}$$

$\overline{Quota}$: OPEC quota in mbd

$\overline{Capacity}$: OPEC capacity in mbd

Closure of the model

The model is closed by OPEC behaviour :

cooperation [equation (2)] or *non - cooperation* [equation (2') + stocks used as residuals]

Fig. 1. The model structure. *Note*: a bar over a variable means it is determined exogenously.

2.2. Non-OPEC supply

Although most producers outside OPEC can be considered as price takers and profit maximisers, economic models of non-OPEC production generally have proved unreliable because there is no simple relation between real oil prices and production (Kaufmann and Cleveland, 2001). For example, US oil production increased significantly between the end of World War II and 1970, despite a general decline in price. Conversely, prices increased greatly between 1970 and 1985, but production declined.

Similar contradictions between price and production are observed in the North Sea. These ‘‘contradictions’’ can be explained by resource depletion, technical change, economic incentives, and political considerations; therefore, these factors must be included to simulate oil production by non-OPEC nations. We describe the econometric methodology used to simulate the effect of geology, economics, and institutional factors on non-OPEC production in Section 3.

2.3. *Oil price*

Due to the presence of a dominant producer and a high degree of volatility, the real price of oil is difficult to model. Starting with Frankel (1946), several studies have tried to assess the factors that determine oil prices. In addition to market factors such as oil inventories, the behaviour of the dominant producer is an important determinant of oil prices. Between the late 1930s and the late 1960s, the Texas Railroad Commission (TRC) acted as the dominant producer by prorationing Texas production to match demand. This reduced the volatility of real oil prices. Starting in the early 1970s, OPEC became the dominant oil producer. OPEC has a different political agenda than the TRC and price volatility increased tremendously. Although the effect of behaviour by a dominant producer on the volatility of oil prices is relatively easy to see (Fig. 4 from Kaufmann, 1995), modellers find it difficult to simulate its effect for two reasons: (i) the inability to forecast behaviour of the dominant producer; and (ii) the inability to translate a particular behaviour into a change in real oil prices (Kaufmann, 1995).

As described in Section 1, the ability of OPEC to affect oil prices lies between that of a cartel and that of a price-taker. Because no theory can explain such ‘‘intermediate behaviour,’’ empirical analyses simulate this intermediate degree of control with a ‘‘price rule,’’ which relates price to measures of OPEC behaviour and market indicators of the supply/demand balance (Gately, 1995). Using a price rule to ‘‘solve’’ for oil prices can be explained as follows. At any given price, demand determines the quantity of oil supplied. Non-OPEC countries adapt their production to this new price and OPEC may act as the swing producer to equilibrate supply and demand. The price rule measures the degree to which OPEC must strain to satisfy the call for its oil, as measured by capacity utilisation and production relative to quotas. The price rule also measures the effect of other market conditions, such the levels of stocks held by OECD nations. Together, these variables proxy the supply/demand conditions that account for the stochastic trends in the historical record for real oil prices.

3. Estimation of the oil model

Prior to estimation, we use Dickey–Fuller statistics to test whether variables (other than the dummies) are non-stationary (for a complete presentation of the dataset used, see Appendix A). Because the results indicate that the variables generally are non-stationary, we generally use the dynamic ordinary least squares (DOLS) estimator developed by Stock and Watson (1993) to estimate the cointegrating relationships. We use this technique because it generates asymptotically efficient estimates of the regression coefficients for variables that cointegrate, it is computationally simple, and it performs well relative to other asymptotically efficient estimators. The coefficients estimated by DOLS represent the long-run relationship among variables. To examine the short-run dynamics in a second step, we use OLS to estimate an error correction model (ECM).

3.1. *Demand*

The estimation results of demand Eqs. (1) are reported in Tables 1 and 6a in Appendix B for detailed results.[2] The general specification for oil demand functions is given by an error-correction model. This model is estimated in a log-linear fashion. The dynamics generate by the econometric specification and estimation technique identify both short-run and long-run elasticities of oil demand with respect to real oil prices and real income. We report the preferred models in terms of statistical significance and signs as predicted by the theory among all relevant lag specifications. The real price of oil does not enter any long-run relationship. We include this variable only among the dynamic terms in the ECMs. This is in line with unit root tests, which indicate that the real price of oil—which displays a high level of volatility—appears to be stationary.

Except for Latin America, the coefficient associated with the error correction term is significantly different from zero for all countries/regions. The significance of this term indicates that a rise in the spread between oil demand and income signals higher actual future oil demand, which moves demand towards the long-run equilibrium that is implied by the DOLS estimate for the cointegrating relationship. In all regions, the income elasticity is less than one, which allows oil demand to adjust smoothly to income changes.

Table 6b reports, for some countries, alternative estimates using data for oil prices that include taxes. These data are analysed because taxes constitute a significant portion of the end-user price in many nations; therefore, percentage changes in oil prices seen by consumers are much smaller than changes in crude oil prices. To evaluate this effect on the econometric estimates for Eq. (1), we use a measure of oil prices calculated by the *International Energy Agency* that includes taxes for the US, Japan, the UK and Switzerland. Although this specification neglects any substitution effects among energy products, it captures the main factors that influence the demand for oil.[3]

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[2] The results using the tax-including end-use price variable (for the cases of US, Japan, UK, Euro area, and Switzerland) are reported in Table 6b in Appendix B. These results are roughly the same as those obtained using the real price of oil excluding taxes.

[3] As we focus on macroeconomic aspects, we have deliberately excluded any distinction between sectors, although the sector-related behaviours

Table 1
Results of oil demand estimations

	Adjustment coefficient of the ECM	Estimation period	Long-term coefficients		Short-term dynamics	
			Real *GDP*	Time trend	Real *GDP*	Real oil price[a]
United States	0.67	1984:1–2002:2	0.98	−0.004	0.77	−0.02
Japan	0.25	1984:1–2002:1	0.89	−0.002	0.69	−0.03
Euro area	0.82	1984:1–2002:1	0.57		0.45	−0.03
United Kingdom	0.14	1985:2–2002:1	0.17		0.09	−0.06
Switzerland	0.93	1984:1–2002:1	0.54	−0.001	0.46	−0.07
Non-Japan Asia	0.34	1993:1–2002:1	0.77		0.001	−0.03
Other dev. eco.	0.83	1993:1–2002:1	0.39		0.001	−0.01
Transition eco.	0.004	1995:1–2002:1	0.51	−0.010	0.002	−0.02
Latin America	0.23	1993:1–2002:1	0.85		0.82	−0.00
Row	0.51	1991:1–2002:2	0.58		0.44	

[a] Defined as the oil price in national currency deflated by a domestic price index for each country. CPI has been used as a proxy for domestic price index. It can been shown that the results obtained with CPI are more satisfactory than the ones obtained with other domestic price proxies (*GDP* deflator in particular).

A comparison of Tables 6a and b indicate that using end-user prices, as opposed to crude oil prices, does not change the estimation results significantly.

3.2. *Supply*

Simulating the behaviours that determine OPEC production is rather straightforward (see Section 2), but simulating the complex mix of economic, institutional and geological factors that influence non-OPEC production warrants further discussion. To estimate the latter component of oil supply, we update a hybrid methodology developed by Kaufmann (1991) that combines the curve-fitting technique developed by Hubbert (1962) with econometric models pioneered by Fisher (1981). For this application, the supply equations are estimated from annual data and quarterly forecasts are generated by interpolating annual values. We realize that such interpolations ignore the intrannual maintenance patterns, but these errors have relatively little effect on the price forecast (see Section 4: forecast performance of the model).

This hybrid methodology is estimated in three steps. First, a logistic curve is estimated for cumulative oil production according to the method developed by Hubbert. The logistic curve is estimated using the following equation:

$$\ln\left(\frac{Q^{\infty}}{Q_t - 1}\right) = \ln(a) + b(t - t_0) \tag{3a}$$

in which Q^{∞} is the ultimate recoverable supply of oil, Q_t the cumulative oil production at time t, and t_0 the the start date of the analysis.

The first difference of the logistic curve gives Hubbert's bell-shaped curve for the production cycle of a non-renewable resource, which we term the production curve. Using this curve, Hubbert was able to generate a remarkably accurate forecast for the peak in US oil production. Subsequent analyses by Kaufmann and Cleveland (2001) indicate the basis for this success—Hubbert's bell-shaped curve is a proxy for the non-linear long-run cost curve for oil production.

Because physical characteristics of oil fields do not entirely determine production, the hybrid methodology also includes the effects of economic and institutional variables. These effects are included in the second step, in which the annual rate of production generated by the production curve (ΔQ_t) is used as an explanatory variable in a cointegrating relationship for the economic, geological, and institutional determinants of production that is given as follows:

$$\begin{aligned} PROD_t = {} & \alpha + \beta_1\,\Delta Q_t + \beta_2\,ROIL_t \\ & + \beta_3 Local + \beta_4\,Asym + \mu_t \end{aligned} \tag{3b}$$

in which $PROD_t$ is oil production, $ROIL$ is the real price of oil, $Local$ is a continuous or discrete variable that affects local production (e.g. prorationing by the TRC in the US (continuous), the "Peso" crisis in Mexico (discrete)), and $Asym$ is a variable designed to test the assumption of symmetry that is implicit in the production curve. $Asym$ is the product of ΔQ_t and a dummy variable, which is equal to one after the peak of the production curve. As such, the $Asym$ variable can be used only for regions where production has continued beyond the peak of the production curve.

In the third step, the short-run dynamics of the supply equations are estimated using an ECM that has the following specification:

$$\begin{aligned} \Delta PROD_t = {} & \gamma + \delta_1\mu_{t-1} + \sum_i \delta_2\,\Delta\Delta Q_{t-i} + \sum_i \delta_3\,\Delta ROIL_{t-i} \\ & + \sum_i \delta_4\,\Delta Asym + \varepsilon_t \end{aligned} \tag{3c}$$

(*footnote continued*)
might be strongly differentiated. We have also excluded any forward-looking variables (e.g. expectations about oil prices) in order to keep the model as simple as possible.

Table 2a
Results for Eq. (2)

	Start date (t_0)	Q^{∞}	a	b	R^2
Lower 48 (US)	1858	170000	161.0	−0.08	0.954
Alaska (US)	1948	15000	435.3	−0.21	0.995
Canada	1940	50000	235.8	−0.12	0.961
Western Europe	1908	90000	246.0	−0.12	0.995
Non-OPEC Asia	1877	67000	181.2	−0.09	0.887
Non-OPEC Africa	1932	27000	222.3	−0.11	0.996
Non-OPEC Latin America	1940	30000	128.8	−0.06	0.999
Mexico	1904	80000	151.4	−0.07	0.700
Brazil	1948	34000	321.3	−0.16	0.861

Table 2b
Results for Eq. (2′)

	ΔQ_t	*ROIL*	*Cost*	*Dummy*	*Asym*	0^2	ADF
Lower 48 (US)	0.62 (23.32)	1.36 (2.69)			0.17 (10.43)	0.96	−4.33
Alaska (US)	0.53 (20.26)	993.2 (2.71)		282098.5 (18.0)	−0.07 (−3.57)	0.99	−4.92
Canada	0.50 (10.32)	1.77 (2.45)	−170.77 (−7.01)			0.85	−1.13
Western Europe	0.84 (47.29)	6.03 (4.72)				0.98	−3.51
Non-OPEC Asia	0.67 (53.19)	1.30 (2.69)				0.99	−3.28
Non-OPEC Africa	1.04 (67.17)	0.84 (2.59)				0.99	−4.16
Non-OPEC Latin America	0.94 (53.93)				0.37 (14.56)	0.98	−4.30
Mexico	0.15 (9.04)	7.18 (9.71)		500.66 (14.55)		0.70	−4.36
Brazil	0.30 (24.36)	0.79 (2.25)				0.93	−4.01

in which μ is the residual from Eq. (3b). The value of δ gives the rate at which oil production adjusts towards its long-run equilibrium.

The start date for the production curve t_0 and the value for Q^{∞} are not known a priori. To identify these values, Eqs. (3a)–(3c) are estimated using a range of values and the results reported in Tables 2a and b are chosen using the following criteria. First, the combination of t_0 and Q^{∞} is chosen so that the residual in Eq. (3b) is stationary. This is done to identify the form of the production curve that cointegrates with production (and the other variables). Next, we retain combinations in which the regression coefficients have the correct sign and are statistically significant in both the long-term relationship (Eq. (3b)) and the ECM (Eq. (3c)). Of these combinations, we chose the combination that has the highest R^2. Eqs (3a)–(3c) are estimated for nine non-OPEC supply regions; Lower 48 (US), Alaska (US), Canada, Western Europe, non-OPEC Asia, non-OPEC Africa, non-OPEC South America other than Brazil, Brazil, and Mexico.

The results reported in Tables 2a and b indicate that non-OPEC production is determined by geological, economic, and institutional factors. In general, augmented Dickey–Fuller statistics indicate that geological, economic, and institutional factors are responsible for the stochastic trends in production. Furthermore, the signs on the variables are consistent with theory—prices have a positive effect on production while long-run costs, as proxied by the inverse of the bell-shaped curve, have a negative effect on production. Finally, the combination of the cointegrating relationships and ECMs are able to account for a large fraction of the historical variation in production, as indicated by the relatively large R^2.

3.3. Prices

As described in Section 2, the final equation of the model is a price rule. The specification and econometric estimation of the rule is from Kaufmann et al. (2004)

$$POIL_t = \alpha + \beta_1\, DAYS_t + \beta_2\, Quota_t + \beta_3\, Cheat_t + \beta_4\, Caputil_t + \beta_5 Q_1 + \beta_6 Q_2 + \beta_7 Q_3 + \beta_8\, War + \mu_t \tag{4}$$

in which *Days* is days of forward consumption of OECD crude oil stocks, *Quota* the OPEC production quota, *Cheat* the difference between OPEC production and OPEC quotas, *Caputil* the capacity utilisation by OPEC, Q_1, Q_2, and Q_3 the dummy variables for quarters 1, 2, and 3, respectively, and *War* a dummy variable for the Persian Gulf War (third and fourth quarters of 1990). As described in Kaufmann et al. (2004), this equation is estimated from quarterly data 1986 Q_3 through 2000 Q_3 using the DOLS estimator developed by Stock and Watson (1993) and the full information likelihood estimator of a vector ECM developed by Johansen (1988) and Johansen and Juselius

(1990). We summarize the results below—a full description for the motivation and econometric estimation of the price rule is available in Kaufmann et al. (2004).

The signs on the regression coefficients Eq. (4) (Table 3) are consistent with previous results described by Kaufmann (1995) and Balabanoff (1995). The regression coefficient associated with *Days* is negative—an increase in stocks lowers real oil prices by reducing reliance on current production and thereby lowers the risk premium that is associated with a supply disruption. Similarly, an increase in the OPEC quota tends to alleviate upward pressure on prices. An increase in the *Cheat* variable also tends to reduce price—an increase in OPEC production relative to their quota increases supply relative to the demand perceived by OPEC when setting the quota (perceived demand may not be the most important or only variable used to set the quota). The sign on the regression coefficient associated with *Caputil* is positive, which is consistent with those described by Gately and Kyle (1977) and Kaufmann (1995). The positive sign indicates that increases in capacity utilisation tend to increase prices. This effect is consistent with OPEC's role as the marginal producer during the 1986 Q_3–2000 Q_3 period. During this period, OPEC generally set production to match the expected difference between non-OPEC supply, which is determined largely by non-OPEC capacity (as price takers, non-OPEC producers generally operate at or near capacity), and demand (and to keep prices within a desired range). As demand for oil from OPEC increases production relative to capacity, utilisation rates rise, which signals some "tightness" in the market. The War variable has a positive effect on prices—prices rose after the Iraqi invasion of Kuwait in anticipation of a supply disruption, but this effect disappeared during the first quarter of 1991, when it became apparent that the war would have little effect on oil supplies from the Persian Gulf.

Results of the ECM estimate indicate that prices do not adjust immediately to the long-term relationship. The regression coefficient associated with the error correction term is negative and statistically significant (Table 3). The point estimate of the error correction coefficient is −0.56, which indicates that 56 percent of the disequilibrium among prices and the right-hand side variables in Eq. (4) is eliminated after one quarter. This result is consistent with the interpretation of Eq. (4) as a cointegrating relation in which the right-hand side variables "Granger cause" real oil prices.

Table 3
Estimates for price equation

Variables	Coefficients
Days	−1.45 (3.35)
Caputil	32.47 (2.30)
Cheat	−2.00 (2.87)
Quota	−2.05 (2.85)
Adjustment rate	−0.56 (2.85)

Values in parenthesis are *t*-statistics that are calculated using the Newey–West (1987) estimator.

4. Assessment of the model properties

4.1. Forecast performance of the model

To evaluate the model's ability to simulate the behaviour of the world oil market, we perform simple static and dynamic forecasts from 1995 Q_1 to 2000 Q_3 (Fig. 2).[4] We know of no model for oil prices in the peer review literature that have been subjected to this type of "backcasting" in which the only exogenous variables are *GDP*, global production of natural gas liquids, and crude oil production by Russia and China, and OPEC capacity. For example, the scenarios for international oil models run by the Stanford Energy Modeling Forum (1992) make prices exogenous (Huntington, 1994). The results of the simulation suggest that the model simulates real oil prices fairly accurately, as measured by standard measures. For example, the root mean square error of the fully dynamic simulation is less than 2% after one quarter, about 2.5 percent after 1 year, and slightly less than 5 percent after 3 years (Table 4). These errors are small relative to the volatility in real oil prices, which have a sample mean of $17.8 per barrel and a variance of $17.0.

Consistent with this high degree of volatility, the model performs better in some periods than others. The model does a relatively poor job of simulating the price collapse in the second half of 1998 and 1999 that is associated with the Asian Financial crisis. In the fourth quarter of 1998, the observed price of oil is about 40 percent lower than the price "backcast" by the fully dynamic simulation. On the other hand, the model is able to simulate the subsequent recovery in price and the start of the post-2000 increase in prices that is associated with increased rates of OPEC capacity utilisation and reductions in OECD stocks.

The accuracy of the price simulation does not imply that the model is able to forecast oil prices accurately. Nonetheless, the results of the backcast indicate that the model is able to capture changes in oil supply and demand that have caused real oil prices to fluctuate over the last two decades. As such, the model can be used to simulate how the market may respond to various types of "exogenous shocks" and changes in OPEC behaviour. Some of these scenarios are described below.

4.2. The effect of an oil price shock

To evaluate the effect of oil prices on supply and demand, the model is simulated with oil prices exogenous (i.e. the oil price rule is "turned off"). The first scenario assumes a 50 percent permanent increase in the price of oil. The 50 percent increase in the price of oil reduces demand by 3 percent in the long-run (Fig. 3). Higher prices increase non-OPEC production, although the response is small (non-OPEC production

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[4] Static forecasts are one-step ahead forecasts of the dependent variables. Dynamic forecasts are multi-step forecasts from the start of the forecast period and use the recursively computed forecast of the lagged value of the dependent and all other endogenous variables.

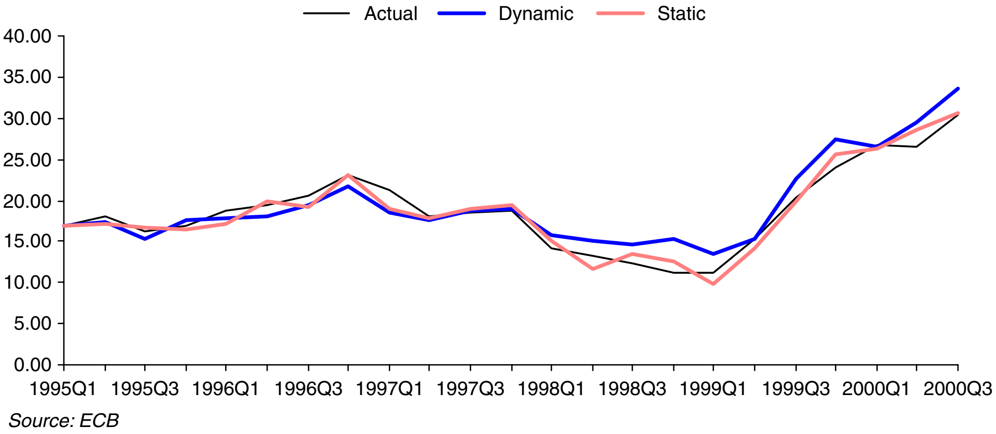

Fig. 2. Oil price \$/b: actual and model projections.

Table 4
Computations of the in-sample forecasting performance for oil price (root mean squared errors in percentage of the baseline value)

	1 quarter	1 year	2 years	3 years
Dynamic simulation	1.90	2.46	3.70	4.97
Static simulation	1.39	2.23	3.40	4.63

increases by about 1.75% relative to baseline). These relatively small responses are consistent with literature findings, which indicate that oil demand and oil supply is quite inelastic over the medium term, 3–5 years.

Although the aggregate response of non-OPEC supply is inelastic, the response differs among non-OPEC regions (Fig. 4). For most non-OPEC nations, the 50 percent increase in real oil prices generates a 1 percent increase in production. Two notable exceptions are Mexico and the lower 48 US states, where higher prices increase production by about 5.5 percent. In Mexico, the relatively elastic response is associated with its large undeveloped resource base and its significant lack of funds. Under these conditions, a large increase in oil prices would boost revenues and generate the capital that is needed to increase operable capacity (assuming that the Mexican government returns increased revenues to PEMEX at about the same rate as it did during the sample period). In the US, the relatively elastic response is associated with the presence of a large number of small independent producers who are willing and able to increase production in response to higher oil prices.

4.3. *Change in OPEC capacity*

A reduction in OPEC capacity was partially responsible for the oil price shock in 1979. At that time, the fall of the Shah plunged Iran into revolution and Iran's capacity (and production) was removed from the market for much of that year. To evaluate the effects of a change in OPEC capacity, we simulate a 5 percent increase in OPEC capacity. By definition, this increase reduces OPEC's rate of capacity utilisation, which reduces oil price. As with this previous scenario, the change in capacity has no immediate effect on OPEC production. Rather, OPEC production changes in response to the immediate effect on oil price. As indicated in Fig. 5, the magnitude of the response as well as its dynamic pattern is very similar to the previous simulation.

The reduction in oil prices indicated in Fig. 5 may explain why OPEC generally is unwilling to increase capacity (OPEC capacity in 2005 is essentially the same as it was in 1973). According to our simulation, increasing capacity depresses the real price of oil by about 12 percent immediately and by about 10 percent in the long term. The reduction in price causes the call for oil from OPEC to increase by about 2 percent. Together, these changes reduce OPEC revenues by about 8 percent. This reduction is consistent with results found by Gately (1995).

Lower revenues imply that it is not in OPEC's interest to add capacity in a timely fashion. If our simulations are accurate, OPEC should not add capacity until the call for oil from OPEC approaches capacity and prices rise. OPEC could then use a portion of the additional revenue to fund additions to capacity. These additions would then lower price back towards the level that prevailed before the capacity induced price spike. This dynamic may foreshadow the "solution" to the high price environment of 2005 that is caused in part by high rates of capacity utilisation. That is, OPEC producers may use some of their increased revenues to increase capacity and lower prices.

Conclusions about the economic attractiveness of additions to OPEC capacity generated by this simulation stand in stark contrast to the assumption used to simulate the National Energy Modeling System (NEMS), which is built and maintained by the US Department of Energy. The NEMS assumes that oil prices are exogenous and uses these prices to calculate oil demand and non-OPEC production. To balance supply and demand, the model assumes that OPEC will add capacity to balance supply and demand (as we do in Eq. (2)). But coupling this assumption with exogenous oil prices eliminates the effect of capacity utilisation on price and so the models can generate forecasts that contradict stated intentions of OPEC members. For

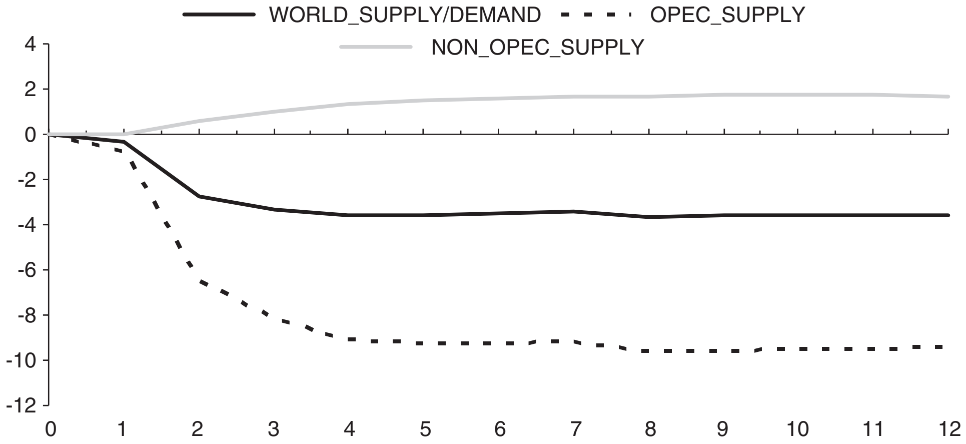

Fig. 3. Impact of a 50% increase in oil price (exogenous) (percentage deviation from baseline).

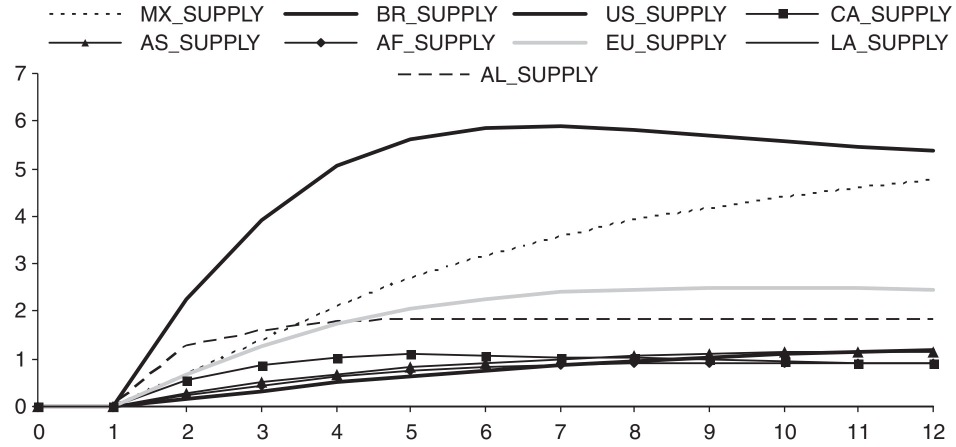

Fig. 4. Impact of a 50% increase in oil price (exogenous) (percentage deviation from baseline).

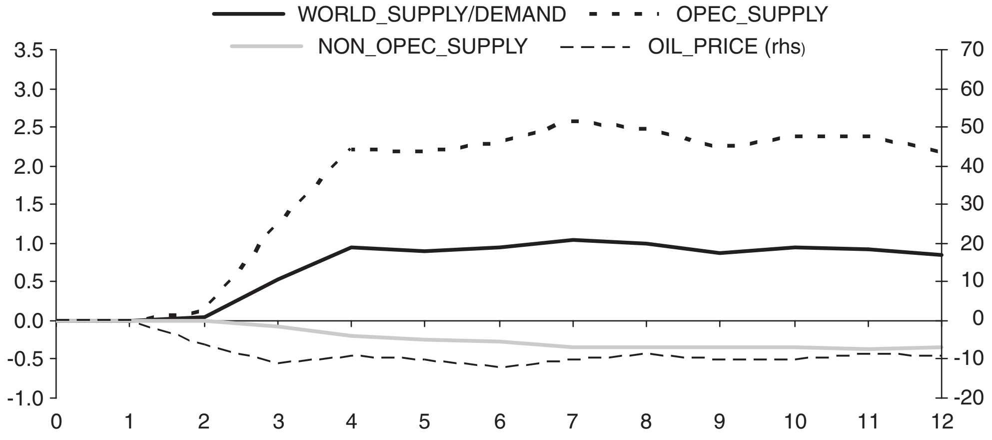

Fig. 5. Impact of a 5% increase in OPEC capacity with immediate OPEC production unaffected (percentage deviation from baseline).

example, the most recent NEMS simulation (EIA, 2005) forecasts that OPEC will double its production of crude oil by 2025. Clearly, much of this 100 percent increase would come from Saudi Arabia. But Saudi Arabia has stated repeatedly that it does not plan to increase production anywhere near the levels forecast by the NEMS.

4.4. Shock on OECD stocks

Kaufmann et al. (2004) argue that changes in inventory practices that reduced OECD stocks of crude oil are responsible for a significant portion of the general increase in real oil prices since the late 1990s. To evaluate the effect of changes in stocks, we simulate a 10 percent permanent reduction in stocks. Consistent with the sign of the regression coefficient associated with $DAYS$ in Eq. (4), the 10 percent decrease in stocks leads to a reduction in the number of days of forward consumption that increases real oil prices by about around 25 percent immediately and by 32 percent after 1 year (Fig. 6). Assuming that the decrease in stocks is permanent, these price increases reduce demand and raise non-OPEC supply, which tends to decrease the demand for oil from OPEC. Such reductions decrease price, but by a much smaller amount than the initial effect of the stock reduction. Under these conditions, a long-term decrease in stocks has a permanent, positive impact on real oil prices.

The effect of stock reductions on price confirm a preliminary discussion offered by Kaufmann et al. (2004) about an externality associated with holding stocks. Individuals that hold stocks do so to avoid the risk of a disruption. But as illustrated by this simulation, holding stocks also reduces the real price for oil. This reduction has social benefits in OECD nations that extend beyond the firms that hold stocks. As such, private decisions about the optimal level are biased by an externality that causes individuals to underinvest in stocks. This underinvestment may cause a significant loss in total social welfare, as indicated by the large permanent increase in real oil prices. This suggests that policy makers may wish to develop instruments that will increase the willingness of individuals to hold stocks of crude oil.

4.5. Alternative OPEC behaviour

Previous simulations assume that OPEC acts cooperatively to set production. This cooperation is coordinated by setting quotas, which have a significant effect on production by individual members (Kaufmann et al., in review). Without quotas, operable capacity would allow OPEC to produce more oil than required by the market. Prior to the recent run-up in oil prices, quotas limited OPEC production to about 85 percent of operable capacity.

In this last simulation, we explore the effects of a breakdown in OPEC cooperation. To do so, we assume that OPEC sets production at 95 percent of its operable capacity, regardless of the quantity demanded by the market. This implies a significant increase in OPEC production, which exceeds current levels of demand. Under these conditions, the supply demand balance is maintained by putting excess quantities of OPEC oil into OECD stocks. The increase in stocks causes oil prices to decline sharply, by about 40 percent. In the longer term, lower prices increase demand and lower non-OPEC production. These changes increase the demand for oil from OPEC towards levels that are consistent with capacity. As OPEC production increases towards capacity, prices rise. This rise depresses demand and increases non-OPEC production. This reduces the demand for oil from OPEC, which causes prices to fall.

Because of this dynamic, prices fluctuate sharply around a lower midpoint for the remainder of the simulation (Fig. 7). This volatility mirrors the high degree of volatility in prices that prevailed prior to the formation of the TRC, which was formed to damp the boom-and-bust cycle that characterised a "competitive" oil market. The boom-and-bust cycle is generated by the small price elasticities for oil supply and demand, the long life-times that are associated with energy-using capital, and the high fixed costs of oil production relative to the operating costs (Kaufmann, 1995).

The high price volatility highlights the costs and benefits to consuming nations of OPEC acting cooperatively as the marginal supplier. On average, real oil prices would be considerably lower if OPEC collapsed and individual members acted competitively. The potential for such a collapse provides an important economic incentive for cooperation among OPEC members, which have vastly

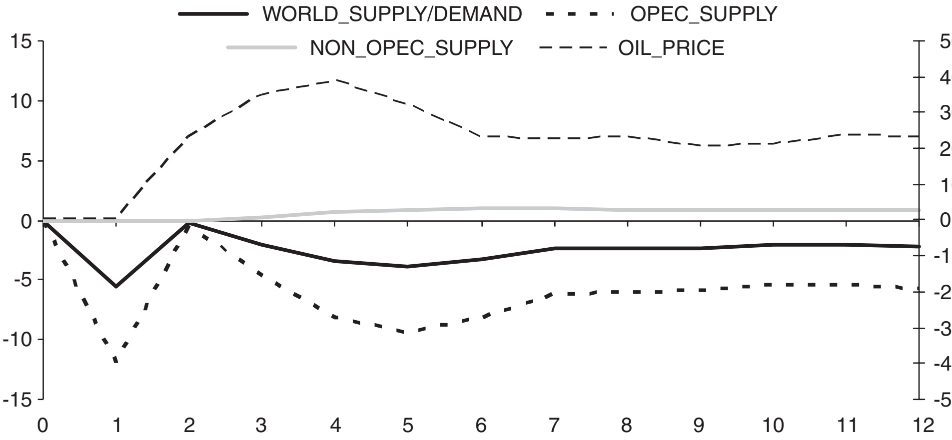

Fig. 6. Impact of a 10% decrease in oil stocks (percentage deviation from baseline).

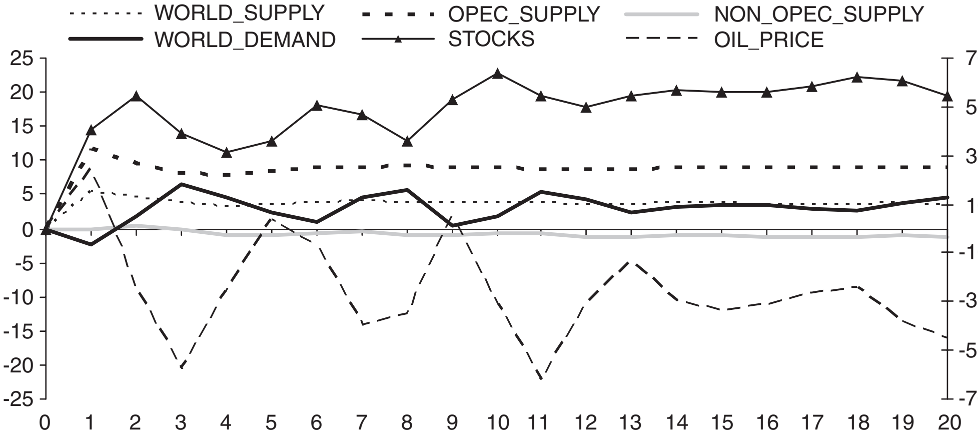

Fig. 7. Impact of a change in OPEC behaviour with production at 95% of its capacity (percentage deviation from baseline).

different geological endowments, economic structures, and political/social aspirations.

At first glance, a collapse in OPEC and real oil prices would seem to benefit oil-consuming nations. But such a change in OPEC behaviour would increase price volatility. And price volatility imposes costs to consuming nations. Specifically, it makes planning very difficult, which is especially important for energy markets where energy-using capital devices have relatively long life-times. Hence, these fluctuations make it difficult to choose the energy-using technology that will maximise the net present value of profits or utility. In addition, the trough of the boom-and-bust cycle increases bankruptcies by high cost producers, like many non-OPEC nations, such as the US. Because of these consequences, a collapse in OPEC cooperation may not be in the best interest of oil consuming nations.

5. Concluding remarks

This paper describes a model of the world oil market that can be used to forecast oil supply, demand, and real prices and to analyse risks with each. The model simulates oil demand with behavioural equations that relate demand to domestic economic activity and the real price of oil. Oil supply for non-OPEC producers is simulated assuming a competitive behaviour that is constrained by geological and institutional factors. Real oil prices are simulated using a "price rule" that represents the effects of market conditions and OPEC behaviour. OPEC behaviour can be simulated using two modes, a cooperative behaviour, which ensures a balance between supply and demand, and a competitive behaviour which uses a rule that mimics basic petroleum economics.

Simulations indicate that the model can be used to understand the responses of the world oil market to various types of shocks and changes in OPEC behaviours. For instance, the scenario that describes the effect of changes in OPEC capacity points out the economic reasons that OPEC members are reluctant to add capacity. The scenario that simulates a shock in OECD stocks demonstrates the significance of an externality associated with private decisions regarding optimal stock levels. The scenario that simulates alternative OPEC behaviours describes how the collapse of OPEC cooperation may have negative consequences for oil consuming nations, despite the reduction in average price.

Finally, the model is able to generate a fairly accurate dynamic price "backcast", by capturing changes in oil supply and demand that have caused real oil prices to fluctuate over the last two decades.

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Appendix A. Statistical appendix

The estimation sample includes quarterly data from 1984 Q_1 to 2002 Q_1 (due to data constraints, the sample starts later for emerging economies and other developed economies). The relatively small sample period may limit the robustness of the results, especially for the transition economies, whose sample includes only 24 observations. Nonetheless, we use the same methodology for all equations to ensure similar properties across countries and regions.

The series of oil prices (*POIL*), measured in US dollars, refer to the Brent variety. Although the Brent index can be considered as reflecting a very small market, we can show that the different indices available exhibit a very high correlation, making us confident about the choice of a single index. This index corresponds to prices traded in the futures market and therefore does not include taxes. In Eqs. (1), (3b) and (3c), the price index used to deflate oil prices is the CPI (the *GDP* deflator was also used, but did not yield statistically different results).

OPEC production data is taken from Monthly Energy Review (various months). Estimation of the non-OPEC supply requires, in light of the geological and economic environments differences among these nations, separate data for: Lower 48 states (US), Alaska (US), Canada, Mexico, Brazil, Non-OPEC Latin America, Western Europe, Non-OPEC Africa, and Non-OPEC Asia. Other non-OPEC regions include the Former Soviet Union, China, and non-OPEC Middle East. Production by these regions is forecast exogenously due to the difficulties associated with market structure (Former Soviet and China) and/or geographical disparity (e.g. non-OPEC Middle East includes non-contiguous nations such as Syria, Oman, etc.).

The variables other than the oil price needed to estimate the equation for prices (4) include: *Days*, which is calculated by dividing OECD crude oil stocks by OECD oil demand (Monthly Energy Review, various months), *Quota*, measured in million barrels per day (mbd), *Cheat,* computed from OPEC production and OPEC quotas (mbd), and *Caputil,* which is calculated by dividing OPEC production (mbd) by OPEC capacity (mbd).

Appendix B. Oil demand equation results

This appendix presents detailed econometric results of the demand equations presented in the main text. Table 5 presents unit root tests of the variables and Tables 6a and b give the complete estimation results.

Table 5
Unit root tests

	ADF-constant and trend		ADF-constant		ADF-without constant	
	DEM	ΔDEM	DEM	ΔDEM	DEM	ΔDEM
US	−1.88	−3.41*	−0.37	−3.49***	2.27	−2.77***
Japan	0.42	−4.22***	−1.75	−3.25**	0.93	−3.13***
UK	−4.83***	−6.77***	−2.53	−6.87***	−0.56	−6.98***
Euro area	−2.36	−14.95***	−1.75	−14.84***	3.28	−3.92***
ODE	1.56	−2.63	−2.78*	−1.52	1.77	−1.48
Transition	−1.81	−3.05	−2.93**	−2.03	−0.90	−1.94**
NJA	−0.46	−10.42***	−3.96***	−3.26**	2.32	−1.74*
Lat. America	−0.60	−2.77	−1.64	−2.29	1.18	−1.95**
RoW	−3.71**	−9.50***	−4.32***	−3.16***	2.64	−1.51
	Y	ΔY	Y	ΔY	Y	ΔY
US	−2.18	−3.86**	−0.41	−3.89***	3.27	−1.95**
Japan	−1.24	−2.70	−2.51	−1.63	0.82	−1.51
UK	−2.76	−2.90	−1.01	−2.86*	2.35	−1.55
Euro area	−2.50	−7.69***	−0.97	−7.58***	8.82	−1.36
ODE	−3.21*	−4.98***	−2.22	−4.43***	13.41	−1.18
Transition	−0.07	−3.75**	0.65	−3.16**	1.73	−1.51
NJA	−2.52	−3.27*	−1.81	−2.89**	2.48	−1.09
Lat. America	−2.16	−4.06***	−1.79	−3.36**	1.79	−2.73***
RoW	−1.99	−2.19	−0.11	−2.26	4.21	−0.75
	ROIL	ΔROIL	ROIL	ΔROIL	ROIL	ΔROIL
US	−3.70**	−4.87***	−3.34**	−4.76***	−0.70	−4.74***
Japan	−2.63	−5.20***	−3.37**	−4.71***	−0.87	−4.66***
UK	−3.61**	−4.86***	−3.72***	−4.49***	−0.95	−4.43***
Euro area	−3.79**	−7.23***	−2.99**	−7.28***	−0.62	−7.29***
ODE	−2.59	−5.17***	−3.15**	−4.77***	−0.64	−4.76***
Transition	−3.74**	−2.93	−3.35**	−2.96**	0.43	−2.48**
NJA	−3.35*	−3.26**	−3.12**	−3.17**	−0.40	−3.23***
Lat. America	−3.36*	−5.13***	−2.51	−5.01***	−0.64	−5.00***

Note: We use data-driven lag selection procedures in the ADF tests, taking 1.645 as the critical value used for significance of lagged terms and 4 as the maximum number of lags allowed in these procedures into account. We denote with */**/***the rejection of the null hypothesis at a 10%/5%/1% critical levels.Critical levels used for ADF are the following:

- In the model with constant and trend: −4.05 (1%), −3.45 (5%) and –3.15 (10%).
- In the model with constant: −3.50 (1%), −2.89 (5%) and –2.58 (10%).
- In the model without constant: −2.59 (1%), −1.94 (5%) and –1.62 (10%).

Table 6a
Econometric results

	NJ Asia	Transition	Latin America	ODE	ROW
Long-term equation					
Constant	5.49 (11.27)	4.60 (4.53)	6.67 (28.07)	6.59 (41.1)	3.12 (2.11)
GDP	0.98 (8.61)	0.89 (3.77)	0.17 (3.36)	0.57 (16.32)	0.54 (1.65)
Time trend	−0.004 (−4.99)	−0.002 (−1.24)			−0.001 (−0.57)
Short-term equation					
Adj. coef.	−0.67 (−5.37)	−0.42 (−3.91)	−0.15 (−2.17)	−0.82 (−6.89)	−0.94 (−6.40)
Constant	−0.01 (−1.73)	0.08 (9.12)	0.0 (1.57)	0.02 (2.79)	−0.04 (−2.38)
ΔGDP	0.77 (2.29)		0.09 (0.16)	0.45 (0.85)	0.46 (0.35)
$\Delta GDP(-1)$		0.67 (2.02)			
$\Delta ROIL$			−0.06 (−2.72)	−0.03 (−1.45)	−0.07 (−1.56)
$\Delta ROIL(-1)$	−0.02 (−1.78)	−0.02 (−1.05)			
$\Delta DEM(-1)$			−0.08 (−0.78)		
Q_2	−0.01 (−2.20)	−0.25 (−21.81)	−0.05 (−5.29)	−0.06 (−7.50)	−0.004 (−0.19)
Q_3	0.01 (1.99)	−0.08 (−4.52)	−0.004 (−0.34)	−0.03 (−2.63)	0.07 (2.97)
Q_4	0.01 (2.65)	0.004 (0.25)	0.02 (1.91)	0.01 (1.06)	0.07 (4.10)
Sample	84:1–02:2	84:1–02:1	85:2–02:1	84:1–02:1	88:2–02:2
Nb of obs.	72	72	66	72	55
ADF resid.	−8.40	−9.05	−8.45	−8.24	−8.23
Adj. R^2	0.54	0.96	0.56	0.77	0.69
	NJ Asia	Transition	Latin America	ODE	RoW
Long-term equation					
Constant	5.77 (35.27)	6.67 (0.88)	4.81 (22.89)	6.41 (27.91)	6.25 (123.2)
GDP	0.77 (22.33)	0.51 (2.49)	0.85 (18.80)	0.39 (7.90)	0.55 (50.66)
Time trend		−0.01 (−5.27)			
Short-term equation					
Adj. coef.	−0.47 (−2.40)	−0.83 (−4.75)	−0.004 (−0.64)	−0.23 (−1.98)	−0.61 (−3.80)
Constant	0.02 (1.32)	0.01 (0.83)	0.10 (0.57)	−0.01 (−1.66)	0.001 (0.18)
ΔGDP	0.001 (0.11)		0.82 (3.03)	0.001 (0.49)	
$\Delta GDP(-1)$		0.002 (0.48)			0.44 (1.20)
$\Delta ROIL$		−0.01 (−1.55)	−0.01 (−0.51)		
$\Delta ROIL(-1)$	−0.03 (−0.77)				
$\Delta DEM(-1)$	0.09 (0.55)				0.23 (1.41)
Q_2	−0.02 (−1.11)	−0.04 (−5.27)	0.03 (4.14)	−0.02 (−2.41)	0.004 (0.63)
Q_3	−0.02 (−1.20)	−0.03 (−2.83)	0.03 (3.56)	0.03 (3.39)	0.01 (1.29)
Q_4	0.05 (3.07)	0.02 (1.80)	−0.01 (−0.87)	0.03 (5.10)	−0.01 (−2.00)
Sample	93:1–02:2	95:1–02:1	93:1–02:1	93:1–02:1	91:1–02:2
Nb. of obs.	37	28	36	35	44
ADF resid.	−6.52	−4.89	−7.43	−6.39	−6.01
Adj. R^2	0.66	0.90	0.56	0.75	0.48

Table 6b
Econometric results with tax-including oil prices

	United States	Japan	United Kingdom	Euro area	Switzerland
Long-term equation					
Constant	5.49 (11.27)	4.60 (4.53)	6.67 (28.07)	6.59 (41.1)	3.12 (2.11)
GDP	0.98 (8.61)	0.89 (3.77)	0.17 (3.36)	0.57 (16.32)	0.54 (1.65)
Time trend	−0.004 (−4.99)	−0.002 (−1.24)			−0.001 (−0.57)
Short-term equation					
Adj. Coef.	−0.67 (−5.79)	−0.42 (−4.14)	−0.12 (−1.58)	−0.81 (−7.01)	−0.98 (−7.30)
Constant	−0.01 (−2.01)	0.08 (9.45)	0.01 (1.59)	0.02 (2.80)	−0.03 (−2.60)
ΔGDP	0.86 (2.57)		0.24 (0.41)	0.002 (0.37)	
$\Delta GDP(-1)$		0.56 (1.74)			0.05 (0.04)
$\Delta ROIL$		−0.06 (−0.73)	−0.19 (−2.37)	−0.17 (−2.71)	−0.34 (−2.72)
$\Delta ROIL(-1)$	−0.03 (−1.03)				
$\Delta DEM(-1)$			−0.12 (−0.97)		
Q_2	−0.01 (−2.94)	−0.25 (−23.32)	−0.05 (−5.41)	−0.06 (−7.13)	0.002 (0.09)
Q_3	0.01 (2.24)	−0.08 (−4.51)	−0.01 (−0.66)	−0.03 (−2.56)	0.06 (4.21)

Table 6b (*continued*)

	United States	Japan	United Kingdom	Euro area	Switzerland
Q_4	0.01 (2.56)	0.01 (0.45)	0.02 (1.78)	0.01 (1.37)	0.07 (4.61)
Sample	84:1–02:2	84:1–02:1	85:2–02:1	84:1–02:1	88:2–02:2
Nb. of obs.	72	72	66	72	55
ADF resid.	−8.69	−8.43	−7.84	−8.41	−8.51
Adj. R^2	0.54	0.96	0.55	0.79	0.72

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