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Abstract.
In this paper we investigate crude oil and products price dynamics. We present a comparison among ten prices series of crude oils and fourteen price series of petroleum products, considering four distinct market areas (Mediterranean, North Western Europe, Latin America and North America) over the period 1994-2002. We provide first a complete analysis of crude oil and product price dynamics using cointegration and error correction models. Subsequently we use the error correction specification to predict crude oil prices over the horizon January 2002-June 2002.The main findings of the paper can be summarized as follows: a) differences in quality are crucial to understand the behaviour of crudes; b) prices of crude oils whose physical characteristics are more similar to the marker show the following regularities: b1) they converge more rapidly to the long-run equilibrium; b2) there is an almost monotonic relation between Mean Absolute Percentage Error values and crude quality, measured by API° gravity and sulphur concentration; c) the price of the marker is the driving variable of the crude price also in the short-run, irrespective of the specific geographical area and the quality of the crude under analysis.

Keywords. Oil prices; Product prices; Error correction models; Forecasting.
JEL classifications. C22; D40; E32.

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Introduction

Over the last 30 years, oil prices have been closely scrutinized by applied economic literature. Literally hundreds of applied research and policy studies have examined the role played by oil prices in determining economic growth or inflation rates, both in developed and developing countries.

Recently, several studies have contributed to this literature by examining the relation between the price of crude oil and refinery products. If we exclude the specialized literature, however, much less attention has been given to understanding the price dynamics for different crudes, even if the quality of crude oils available to refiners (and consequently their prices) is a critical factor in the strategies employed by refiners around the world.

Oil is not a homogenous commodity: as a number of experts have pointed out (see, The International Crude Oil Market Handbook, 2001) there are over 160 different internationally traded crude oils, all of which vary in terms of characteristics, quality, and market penetration.

Crude oils are classified by density and sulphur content. Lighter crudes generally have a higher share of light hydrocarbons – i.e. higher value products - that can be produced by simple distillation. Heavier crude oils give a greater share of lower-valued products through simple distillation and require additional processing to produce the desired range of products. Some crude oils also have a higher sulphur content, an undesirable characteristic in terms of both processing and product quality.

The quality of the crude oil determines the level of processing and re-processing necessary to achieve the optimal mix of product output. As a result, price and price differentials between crude oils also reflect the relative ease of refining. For example, a premium crude oil like West Texas Intermediate (WTI), the U.S. benchmark, or Brent, the European benchmark, have a relatively high natural yield of desirable Gasoline. In contrast, almost half of the simple distillation yield from Urals is a heavy residue that must be reprocessed or sold at a discount as crude oil.

Refiners are in competition for an optimal mix of crudes for their refineries, in line with the technology of the particular refinery, the desired output mix and, more important, the relative price of available crudes. In recent years, refiners have been faced with two opposing forces: a combination of consumers' desires for lower prices and government regulations specifying increasingly lighter products of higher quality (the most difficult to produce) and supplies of crude oil that are increasingly heavier, i.e. with higher sulphur content (the most difficult to refine).

The importance of identifying the way in which a given crude is linked to a specific crude benchmark comes directly from market considerations: the pressure of falling margins in the oil products market, combined with some degree of flexibility in supply decisions, obliges refiners to seek opportunities in the free market to improve their profits. Crudes are expected to continue to become heavier with higher sulphur content, while environmental restrictions are expected to significantly reduce the demand for high-sulphur content fuels. As a consequence, light sweet crudes will continue to be available and in even greater demand than today. This is why an understanding of the price dynamics, and the role played by different crudes, is crucial for the modern oil industry.

Because there are so many different varieties and grades of crude oil, buyers and sellers have found it easier to refer to a limited number of reference, or benchmark, crude oils. Other varieties are then priced at a discount or premium, according to their quality. For any given crude oil, the price is considered to be linked to another crude oil price (usually referred to as the marker). In this very simple scheme, to understand the behaviour of a given crude oil would be sufficient to explain the behaviour of its marker. However, the price difference between these two crudes is non-constant over time. To enrich the relations it is necessary to include variables other than the price marker to explain the oil price dynamics of the given crude.

In principle, several variables could affect this relation and could be used as explanatory variables. Considering data availability, the common assumption is that imbalances in the petroleum product price could reflect most of these missed variables. For example: if, due to extraordinary seasonal factors, Gasoline demand were higher than expected, this would be reflected into the relations between crudes according to various specific characteristics.

This approach has been examined in several different papers. However the specific economic literature on this issue is not very large. Adrangi, Chatrath, Raffiee and Ripple (2001) analyze the price dynamics of a specific crude (the Alaska North Slope) and its relation with US West coast diesel fuel price using a VAR methodology and a bivariate GARCH model to show the casual relationship between the two prices. Asche, Gjolberg and Volker (2003) make use of multivariate framework to test whether there is a long-term relationship between crude oil and refined product prices in the North Western Europe market.

Gjølberg and Johnsen (1999) analyze co-movements between the prices of crude oil and major refined products during the period 1992-98. Specifically, they explore the existence of long-run equilibrium price relationships, and whether deviations from the estimated equilibrium can be utilized for predictions of short-term price changes and for risk management.

In this paper we present a comparison among crudes considering four distinct market areas (Mediterranean, North Western Europe, Latin America and North America) on ten prices series of crude oils and on fourteen price series of petroleum products.

We provide first a complete analysis of crude oil and product price dynamics using co-integration and error correction models over the period 1994-2002. Subsequently we use the error correction specification to predict crude oil prices over the horizon January 2002-June 2002.

The main findings of the paper can be summarized as follows.

Differences in quality are crucial to understand the behaviour of crudes.

Prices of crude oils whose physical characteristics are more similar to the marker show the following regularities:

a) they converge more rapidly to the long-run equilibrium.
b) there is an almost monotonic relation between Mean Absolute Percentage Error values and crude quality, measured by API° gravity and sulphur concentration. This evidence can be motivated by considering the presence of the marker as an explanatory variable: the closer the crude to the marker, the higher the contribution of the latter in explaining and predicting the former.

The price of the marker is the driving variable of the crude price also in the short-run, irrespective of the specific geographical area and the quality of the crude under analysis.

This paper is organized as follows. Section 2 provides a description of the analyzed data. Section 3 discusses the econometric methods and models. In Section 4 the empirical results are reported and commented. The forecasting performance of the estimated models is illustrated in Section 5. Concluding remarks close the paper.

Data description

Our analysis is based on ten prices series of crude oils and on fourteen price series of petroleum products. These data cover four distinct market areas: Mediterranean (MED), North Western Europe (NWE), Latin America (LA) and North America (NA). In the first two areas the reference price for crude oil (marker) is represented by Brent, while for the remaining two areas the benchmark crude is WTI. The petroleum products we are considering belong to three different quality categories: unleaded Gasoline, Gasoil and Fuel oil. Within the last class we distinguish between high sulphur Fuel oil (HSFO) and low sulphur Fuel Oil (LSFO). The data frequency is weekly with the exception of the LA market, where only monthly data are available, while the sample covers the period 1994-2002. All crude oil prices are expressed in US$ per barrel, whilst product prices are in US$ per metric ton. More details on the dataset are provided in Table 1.

Table 2 and Table 3 report, for both crude oils and petroleum products, the coefficients of variation of price levels and the annualized standard deviation of price changes. On average, the coefficients of variation for crude prices are the double of the coefficients of variation of product prices, suggesting that the behaviour of crude prices is very close to that of financial assets. Moreover, if we look at the two groups separately, we find an inverse relation between quality (measured by API° gravity) and the coefficient of variation. A possible interpretation is the subsidiary role played by heavy crudes when light crudes become too expensive, while the lower-quality products are more volatile since their price is intimately linked to the price of some specific substitutes (e.g. natural gas).

Table 4 shows the percentage price correlations within crudes and between crudes and products. Higher correlations occur when crudes and products similar in terms of API° gravity are analyzed. The evidence from Tables 3 and 4 should suggest that prices characterized by more similar coefficients of variation (i.e. light crudes and heavy products) are more correlated. However, the coefficient of variation is a measure of long-run volatility, whereas price change correlation captures short-run movements in price variations. Moreover, an increase in the demand of light products has the effect of increasing the supply of both high-quality and low-quality products (see Gjolberg and Johnsen, 1999). Such considerations justify the presence of higher correlation between light (heavy) crudes and the top (bottom) of the barrel.

Model specification

Crude oil and product prices dynamics can be modelled with an Autoregressive-Distributed Lag (ADL) specification:

$$\alpha(L)\, p_t^c = \mu + \gamma(L)\, p_t^m + \vartheta(L)\, p_t^{y_1} + \xi(L)\, p_t^{y_2} + u_t \quad (1)$$

where L is the lag operator,
$\alpha(L)=1-\alpha_1 L-\ldots-\alpha_P L^P$, $\gamma(L)=\gamma_0+\gamma_1 L+\ldots+\gamma_Q L^Q$,
$\vartheta(L)=\vartheta_0+\vartheta_1 L+\ldots+\vartheta_R L^R$ and $\xi(L)=\xi_0+\xi_1 L+\ldots+\xi_S L^S$.
Capital letters P, Q, R and S represent the optimal number of lags of the polynomials $\alpha(L)$, $\gamma(L)$, $\theta(L)$ and $\xi(L)$, respectively. With p_t^c we indicate the price of the selected crude, whereas p_t^m is the price of the marker associated with p_t^c, and $p_t^{y_i}$, i=1,2, are the prices of two products; u_t is a white noise process. All variables are log-transformed.

Recent developments in time series econometrics suggest that the first step towards the estimation of model (1) is to check whether or not the different price series are stationary. Augmented Dickey-Fuller (ADF) tests for unit roots have been used and all variables have been found to be integrated of order one, or I(1), with intercept but no trend.[1]

Though non-stationary, the oil and product price series may form a linear combination which is stationary, or I(0). If this is the case, the relevant price series are said to be cointegrated. The basic model used to test for the presence of cointegration is given by the static regression

$$p_t^c=\beta_0+\beta_1 p_t^m+\beta_2 p_t^{y_1}+\beta_3 p_t^{y_2}+\varepsilon_t \qquad (2)$$

If the residuals $\hat{\varepsilon}_t$ are I(0), then equation (2) provides the long-run or equilibrium relationship between the relevant price series. When two or more variables are cointegrated, we know from the Engle-Granger representation theorem that they admit an error correction (ECM) formulation of the type:

[1] The complete set of results is reported in Tables A1-A3 of the Appendix.

$$\Delta p_t^c = \sum_{p=1}^{P-1} \delta_{0p} \Delta p_{t-p}^c + \sum_{q=0}^{Q-1} \delta_{1q} \Delta p_{t-q}^m + \sum_{r=0}^{R-1} \delta_{2r} \Delta p_{t-r}^{y_1} + \sum_{s=0}^{S-1} \delta_{3s} \Delta p_{t-s}^{y_2} + \lambda \hat{\varepsilon}_{t-1} + \eta_t \quad (3)$$

where $\hat{\varepsilon}_t = p_t^c - \left(\hat{\beta}_0 + \hat{\beta}_1 p_t^m + \hat{\beta}_2 p_t^{y_1} + \hat{\beta}_3 p_t^{y_2} \right)$, $\hat{\beta}_0 = \hat{\mu} \Big/ \left(1 - \sum_{p=1}^{P} \hat{\alpha}_p \right)$, $\hat{\beta}_1 = \sum_{q=0}^{Q} \hat{\gamma}_q \Big/ \left(1 - \sum_{p=1}^{P} \hat{\alpha}_p \right)$, $\hat{\beta}_2 = \sum_{r=0}^{R} \hat{\vartheta}_r \Big/ \left(1 - \sum_{p=1}^{P} \hat{\alpha}_p \right)$, and $\hat{\beta}_3 = \sum_{s=0}^{S} \hat{\xi}_s \Big/ \left(1 - \sum_{p=1}^{P} \hat{\alpha}_p \right)$.

The coefficients β_i in equation (2) can be interpreted as long-run elasticities of the crude price to the marker price and petroleum products prices. In other terms, each β_i measures the percentage variation of crude oil price due to a unit percentage variation of each explanatory variable.

The choice of explaining oil prices in terms of petroleum product prices relies on the theory of derived demand, which states that the price of an input should be determined by its contribution to the market value of the output reflected in its market price (see Adrangi, Chatrath, Raffiee and Ripple, 2001, for a test of the causal relationship flowing from product prices to crude oil price).

Equation (3) incorporates short-run and long-run effects, captured by coefficients δ_{ij} and λ, respectively. In particular, λ is the so-called long-run adjustment coefficient which measures how fast p_t^c converges towards the long-run equilibrium represented by equation (2).

Empirical results

For each of the eight selected crudes we should estimate, at least in principle, as many specifications for equation (3) as the number of combinations of products (i.e. six models for MED and NWE, three models for LA and NA).

Given the large number of resulting models, we use a simple criterion to select the best specification for each crude. Following Stock and Watson (1993), we estimate an augmented version of equation (2), formed by adding one lead and one lag to all the independent variables (DOLS estimation). In this way we obtain corrected *t*-statistics for each estimated coefficient, which allow us to select the specifications of the long-run equation with the largest number of statistically significant parameters. If two or more long-run specifications have the same number of significant coefficients, we select the one whose associated ECM yields the largest number of statistically significant parameters. The final product selection for each crude is reported in the third column of Table 5.

As it is shown in Table 5, the sum of the estimated coefficients β in equation (2) (ignoring the intercept term) is approximately equal to one. Moreover, the null hypothesis that this sum is equal to one is not rejected by the data in 5 cases out of 8.[2] These coefficients can be interpreted as the contribution (weight) given by each independent variable to the determination of crude oil price. The price of the marker dominates relation (2), while product prices play a sort of compensation role, in order to preserve the one-to-one relation between the crude and the marker. If we exclude Maya in the LA area, the β coefficients of the corresponding selected pair of product prices have opposite signs. The contribution of each product to the market value of a particular crude oil is such that a constant balance between price of the crude and price of the marker is maintained in the long-run.

Specifically, $\hat{\beta}_1$ is always larger than one, and its magnitude increases as heavier crudes are considered. These features show that when the price of the marker increases the demand of heavy

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[2]A corrected Wald test, based on the DOLS coefficient estimates, rejects the null hypothesis at 1% significance level for Kern River and Thums, and at 5% for Iranian.

crude oils increases, which, in turn, forces their price to rise more than proportionally.

Furthermore, when the MED and NWE areas are considered, the long-run coefficients $\hat{\beta}_2$ and $\hat{\beta}_3$ have positive and negative signs, respectively. The converse is true when we concentrate on NA. A possible interpretation of this empirical evidence is that, while Europe is characterized by two highly demanded light products (i.e. Gasoline and Gasoil), only Gasoline has a primary role in North America. As a consequence, an increase in the demand for Gasoline in Europe is met using very light crudes in the production process of Gasoline, while medium-quality crudes are employed to produce Gasoil. On the contrary, the North American refinery system is mainly oriented towards the production of Gasoline, which explains the positive long-run correlation between crude and Gasoline prices.

In all areas each crude price is cointegrated with the price of the marker and the prices of the selected pair of products, according to the ADF tests on the residuals of the long-run equation (2) reported in Table 6.

The best ECM specification is attained with the product pair LSFO-Gasoline for seven crudes out of eight (the only exception is HSFO-Gasoline for Urals NWE). The short-run coefficient of Gasoline in the ECM equation (3) is significant, in all markets and for all crudes, with the exception of Forcados. The more volatile product in the short-run (Gasoline) is responsible of the short-run dynamics of the crude oil price. It is well known that the refined barrel can be ideally divided in two classes of products: high-quality (light) and low-quality (heavy) products. Hence, the best explanation of both short-run and long-run behaviour of a crude oil price is obtained when we include in the ECM specification the pair formed by the most representative products in each class, that is LSFO-Gasoline (Table 7).

If we combine the information included in Table 1 with Table 7, it is easy to see that the magnitude of the estimated long-run adjustment coefficients is sensitive to the gravity of the specific crude, that is, with the exception of Forcados, a sort of monotonic relation between speed of adjustment and API° emerges. Prices of crude oils whose physical characteristics are more similar to the marker are likely to converge more rapidly to the long-run equilibrium.

Furthermore, the price of the marker is the driving variable of the crude price also in the short-run, irrespective of the specific geographical area and the quality of the crude under analysis (see Table 5)[3].

Forecasting crude oil prices

We assess the ability of the ECM specification to predict crude oil prices over the horizon January 2002-June 2002 by computing three different sets of forecasts: static, dynamic and simulated. With the exception of LA area, where only monthly data are available, we split the forecasting horizon (24 weeks) into six windows of four weeks, with the purpose of partially neutralizing potential contingent factors that could affect the forecasting evaluation (e.g. changes in OPEC policy). Moreover, in order to make the calculated forecasts comparable, instead of estimating the ECM just once and using the same estimated parameters to calculate forecast values of the dependent variable for each of the six windows, we re-estimate the ECM six times with a rolling-sample technique: in this way, the forecast values in each window depend on updated coefficients estimates from samples of the same size.

While static and dynamic forecasts are self-explanatory, the procedure we use to generate the simulated forecasts needs some explanation. The aim of this exercise is to produce "true" out-of-sample, multistep-ahead forecasts for the crude oil price, given the presence of marker and product prices as exogenous variables in

[3] The estimated short-run coefficients of the ECM are reported in Table A4 of the Appendix.

model (3). Let's indicate with T the last in-sample observation for each window. Then:

i) For each variable $\Delta p_t^m, \Delta p_t^{y_1}, \Delta p_t^{y_2}$ and $\hat{\varepsilon}_t$, we estimated an ARMA(1,1) model of the type $x_t = \phi_1 x_{t-1} + u_t + \vartheta_1 u_{t-1}$, t=2,..,T. Since all estimated ARMA(1,1) models are found to be statistically adequate to capture the behaviour of these series, for each model we calculated the residuals $\hat{u}_t$.

ii) Each ARMA residual vector $\hat{u}_t$, t=2,..,T, is bootstrapped R=1000 times, to obtain bootstrapped residuals $\hat{u}_t^{b(r)}$, where r=1,..,R=1000 indicates the r-th replication and superscript b denotes a bootstrapped series.

iii) Each series $\Delta p_t^m, \Delta p_t^{y_1}, \Delta p_t^{y_2}$ and $\hat{\varepsilon}_t$ is simulated R times out-of-sample (t=T+1,…,T+h) using the estimated ARMA models of stage (i) and the bootstrapped residuals of stage (2). That is: $\hat{x}_t^{*(r)} = \hat{\phi}_1 \hat{x}_{t-1}^{*(r)} + \hat{u}_t^{b(r)} + \hat{\vartheta}_1 \hat{u}_{t-1}^{b(r)}$, t=T+1,..,T+h, where the superscript * denotes a simulated series, and h=4 (h=6 for the crudes of the LA area, since only monthly data are available).

iv) for each series $\Delta p_t^m, \Delta p_t^{y_1}, \Delta p_t^{y_2}$ and $\hat{\varepsilon}_t$, we select, among the R simulated series, that series whose standard deviation is closest to the standard deviation of the actual series (this last calculated using in-sample observations).

Formally: $\tilde{x}_t = \min_r \left(\left| Std.Dev.\left(\hat{x}_t^{*(r)}\right) - Std.Dev.\left(x_t\right) \right| \right)$, where $\tilde{x}_t$ denotes the selected simulated series.

v) we re-estimate the ECM specification (3) over the sample $t=k,..,T$, where $k = \max\left(P,Q,R,S\right)$, and we calculate the residuals $\hat{\eta}_t$.

vi) Residuals $\hat{\eta}_t$ are bootstrapped R times, thus obtaining $\hat{\eta}_t^{b(r)}$.

vii) The dependent variable p_t^c is simulated R times, using the bootstrapped residuals of the ECM model (stage vi) and the simulated exogenous series (stage iv):

$$\hat{p}_t^{*c(r)} = \hat{p}_{t-1}^{*c(r)} + \sum_{p=1}^{P-1} \hat{\delta}_{0p} \Delta\tilde{p}_{t-p}^{c} + \sum_{q=0}^{Q-1} \hat{\delta}_{1q} \Delta\tilde{p}_{t-q}^{m} + \sum_{r=0}^{R-1} \hat{\delta}_{2r} \Delta\tilde{p}_{t-r}^{y_1} + \sum_{s=0}^{S-1} \hat{\delta}_{3s} \Delta\tilde{p}_{t-s}^{y_2} + \hat{\lambda}\tilde{\varepsilon}_{t-1} + \hat{\eta}_{i,t+j}^{b(r)}$$

$t=T+1,..,T+h$.

For crudes belonging to the MED, NWE and NA markets, we repeat this procedure for all the 6 windows using the rolling-sample technique illustrated above.

After completion of the three forecasting exercises, we obtain, for the MED, NWE, and NA areas, 24 one-step-ahead (static) forecasts, 24 (dynamic) *h*-steps-ahead forecasts (h=1,..,4) and 24 (simulated) forecast distributions, each formed by R=1000 simulated forecasts. All forecasts are collected in six windows of size 4. For the LA area we produce 6 (static) one-step-ahead forecasts, 6 (dynamic) *h*-steps-ahead forecasts (h=1,..,4) and 6 (simulated) forecast distributions.

In order to evaluate the predictive ability of each ECM specifications, we calculate the mean absolute percentage error (MAPE), the Theil's inequality coefficient (decomposed in bias, variance and covariance proportions) and the SR (success ratio), which indicates the percentage number of times the forecasted series has the same sign of the corresponding actual series.

Moreover, for the simulated forecasts only, we calculate a range of dispersion measures associated to each forecast distribution, as follows. First, we compute the standard deviations of the distribution of forecasts in each window and in each forecasting period (24 standard deviations). Second, we calculate the mean of the 24 standard deviations. Third, for each window, we calculate the mean of the standard deviations relative to the h-th forecasting point, h=1,…,4 (mean of 6 standard deviations).

Results from static and dynamic forecast are reported in Table 9. The following comments apply.

First, due to the different data frequencies, a direct comparison between the LA market and the remaining areas is not possible, although comments that hold for the weekly series can be directly extended to the monthly data.

Second, if we rank the different crudes according to the forecasting performance of the corresponding ECM specifications using the MAPE, the same ranking holds irrespective of whether the forecasts are static or dynamic. The only exception is Iranian heavy, whose dynamic forecasts seem to be relatively better than the static predictions.

Third, there is an almost monotonic relation between MAPE values and crude quality, measured by API° gravity and sulphur concentration. Actually, among the crudes with similar gravity, crudes with less sulphur are characterized by lower MAPE. This evidence can be motivated by considering the presence of the marker as an explanatory variable: the closer the crude to the marker, the higher the contribution of the latter in explaining and predicting the former.

Fourth, from inspection of the Theil's statistic, we experience an increase of the bias proportion and a correspondent reduction of variance and covariance proportions when moving from static to dynamic forecasts. Nonetheless, the values of the Theil's coefficient are generally quite small, indicating a good predictive fit.

Fifth, the low value of the variance proportion in the dynamic forecasts is perfectly consistent with the values of SR.

Results from the simulated forecasts are reported in Table 10. MAPE, Theil's coefficient and SR are calculated on the mean of each forecasted distribution. As expected, the forecasting performance for each model is slightly worse than in the static and dynamic cases. Nevertheless, taking into account the crudes from the LA area, we find that this kind of forecasts performs relatively better for heavier crudes. Actually, MAPE values are almost five times larger than those obtained from the dynamic forecasts in NWE, and almost twice than in NA. Conversely, the heaviest crude in LA (i.e. Boscan) has MAPE values which are less than twice those of the dynamic forecast, while Maya, the lightest crude in that area, has a MAPE value which is four times larger.

The SR, though lower than in both static and dynamic cases, has values which are higher than 0.50, meaning that the simulated series produce reasonable predictions of the turning points of crude prices.

The second section of Table 10 reports several dispersion measures of the forecasted distributions. The mean of all the standard deviations (SD) indicates that lower predicting variability is associated with higher quality crudes. The overall coherence of the simulation exercise is guaranteed by the values of each standard deviation, which increase as the forecasting horizon increases.

Conclusions

This paper presents two different exercises that need to be commented in a separate way even if there are some common interesting features.

The first conclusion is related to the different relation between a given crude, its area-specific market and the related petroleum products. In this paper we investigate crude oil and products price dynamics using cointegration and ECM. Empirical evidence shows that product price are statistically relevant in explaining short- and long-run adjustment in petroleum markets. The relevant product mix also depend on the specific market area and on the characteristics of the selected crude. It is also worth to underline that the long-run adjustment coefficients are sensitive to the gravity of the specific crude. Prices of crude oils whose physical characteristics are more similar to the marker are likely to converge more rapidly to the long-run equilibrium. Furthermore, the price of the marker is the driving variable of the crude price also in the short-run, irrespective of the specific geographical area and the quality of the crude under analysis.

The second conclusion is related to the part of the paper aimed at assessing the ability of the ECM specification to predict crude oil prices over the horizon January 2002-June 2002. We computed three different sets of forecasts, namely static, dynamic and simulated, and in general the lower predicting variability is associated with higher quality crudes. Also in this case there is almost monotonic relation between MAPE values and crude quality, measured by API° gravity and sulphur concentration. Actually, among the crudes with similar gravity, crudes with less sulphur are characterized by lower MAPE. This evidence can be motivated by considering the presence of the marker as an explanatory variable: the closer the crude to the marker, the higher the contribution of the latter in explaining and predicting the former.

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Table 1. Dataset

Area:	Mediterranean (MED)	North Western Europe (NWE)	Latin America (LA)	North America (NA)
Marker:	Brent (38.3°, 0.37%)	Brent	WTI (39.6°, 0.24%)	WTI
Crudes:	- Urals MED (32°, 1.3%) - Iranian heavy (30.2°, 1.77%)	- Urals NWE (32°, 1.3%) - Foracdos (31°, 0.19%)	- Maya (21.8°, 3.33%) - Boscan (10.1°, 5.4%)	- Kern River (13.4°, 1.1%) - Thums (17°, 1.50%)
Products:	- Premium Gasoline - Gasoil - Low Sulphur Fuel Oil (LSFO) - High Sulphur Fuel Oil (HSFO)	- Premium Gasoline - Gasoil - Low Sulphur Fuel Oil (LSFO) - High Sulphur Fuel Oil (HSFO)	- Super Unleaded - Gasoil N°2 - Low Sulphur Fuel Oil (LSFO)	- Super Unleaded - Gasoil N°2 - Low Sulphur Fuel Oil (LSFO)
Sample:	10/7/1994-06/28/2002	10/7/1994-06/28/2002	01/1994-06/2002	10/7/1994-06/28/2002
Frequency:	weekly	weekly	monthly	weekly

Note to Table 1. Sources Platt's and Petroleum Intelligence Weekly (2000); API° gravity and sulphur content (%) are reported in parentheses; HSFO is not traded in LA and NA.

Table 2. Descriptive statistics: crude oil prices

		Coefficient of variation (CV) Percent price level	Annualized standard deviation (ASD) Percent price variation
	Brent	9.40	33.53
MED	Urals MED	9.62	37.37
	Iranian	10.47	39.23
NWE	Urals NWE	9.52	36.50
	Forcados	9.42	34.70
	WTI	8.40	26.82
LA	Maya	11.49	38.28
	Boscan	12.67	35.48
NA	Kern River	12.96	35.67
	Thums	11.76	31.87

Note to Table 2. All prices are expressed in logs. $CV = 100\left(\hat{\sigma}_p / \hat{\mu}_p\right)$ where $\hat{\mu}_p = \sum_{t=1}^{T} p_t \Big/ T$ and $\hat{\sigma}_p^2 = \sum_{t=1}^{T}\left(p_t - \hat{\mu}_p\right)^2 \Big/ (T-1)$ and $ASD = 100\left(\sqrt{n}\hat{\sigma}_{\Delta p}\right)$, where *n* is the number of observations per year, $\hat{\sigma}_{\Delta p}^2 = \sum_{t=1}^{T}\left(\Delta p_t - \hat{\mu}_{\Delta p}\right)^2 \Big/ (T-1)$ and $\hat{\mu}_{\Delta p} = \sum_{t=1}^{T} \Delta p_t \Big/ T$.

Table 3. Descriptive statistics: prices of products

	Coefficient of variation (CV)				Annualized standard deviation (ASD)			
	MED	NWE	LA	NA	MED	NWE	LA	NA
Gasoline	5.08	4.99	4.48	4.56	30.24	31.18	36.56	35.77
Gasoil	5.58	5.14	4.86	4.90	30.64	26.53	25.10	29.38
LSFO	5.46	5.05	5.80	5.85	29.38	25.33	33.01	31.12
HSFO	6.07	5.66	-	-	32.41	33.74	-	-

Notes to Table 3. See Table 2

Table 4. Price change correlations

	Brent	Urals MED	Iranian	Urals NWE	Forcad.	WTI	Maya	Boscan	Kern River	Thums
Brent	1.00									
Urals MED	0.96	1.00								
Iranian	0.96	0.99	1.00							
Urals NWE	0.98	-	-	1.00						
Forcados	0.99	-	-	0.97	1.00					
WTI						1.00				
Maya						0.91	1.00			
Boscan						0.76	0.84	1.00		
Kern River						0.68	-	-	1.00	
Thums						0.70	-	-	0.96	1.00
Gasoline	0.63	0.59	0.59	0.62	0.62	0.74[m] 0.57[w]	0.70	0.53	0.44	0.45
Gasoil	0.66	0.63	0.63	0.66	0.66	0.83[m] 0.65[w]	0.78	0.64	0.48	0.49
LSFO	0.45	0.41	0.42	0.40	0.44	0.71[m] 0.43[w]	0.81	0.67	0.44	0.48
HSFO	0.37	0.33	0.33	0.49	0.52	-	-	-	-	-

Notes to Table 4. m= monthly; w= weekly.

Table 5. Estimation of the long-run relationship

	Crudes	Products (y_1, y_2)	R^2	$\hat{\beta}_1$	$\hat{\beta}_2$	$\hat{\beta}_3$
MED	Urals MED	LSFO, Gasoline	0.99	1.04*** (11.69)	0.12* (1.72)	-0.16** (-2.58)
	Iranian	LSFO, Gasoline	0.99	1.13*** (11.00)	0.18** (2.34)	-0.24*** (-3.34)
NWE	Urals NWE	HSFO, Gasoline	0.99	1.01*** (11.54)	0.11* (1.83)	-0.13** (-2.14)
	Forcados	LSFO, Gasoline	0.99	1.06*** (16.23)	0.01 (0.43)	-0.08 (-1.51)
LA	Maya	LSFO, Gasoline	0.95	1.85*** (4.69)	-0.52* (-1.63)	-0.20 (-0.58)
	Boscan	LSFO, Gasoline	0.91	2.04*** (3.53)	-0.87* (-1.85)	0.03 (0.06)
NA	Kern River	LSFO, Gasoline	0.94	1.35*** (3.77)	-0.07 (-0.24)	0.04 (0.13)
	Thums	LSFO, Gasoline	0.95	1.32*** (4.70)	-0.10 (-0.42)	0.03 (0.11)

Notes to Table 5. $\hat{\beta}_i$ *i*=1,..,3, are the DOLS estimates of the augmented dynamic regression $p_t^c = \beta_0 + \beta_1 p_t^m + \beta_2 p_t^{y_1} + \beta_3 p_t^{y_2} + \sum_{i=-r}^{r} \theta_i \Delta p_{t-i}^m + \sum_{i=-r}^{r} \phi_i \Delta p_{t-i}^{y_1} + \sum_{i=-r}^{r} \gamma_i \Delta p_{t-i}^{y_2} + \varepsilon_t$, with *r*=1 (see Stock and Watson, 1993), in parentheses the rescaled *t*-statistics; * (**)[***] indicates significance at 10% (5%) [1%]

Table 6. Cointegration tests

	Crudes	Products (y_1, y_2)	*a*	*b*	*p*	ADF
MED	Urals MED	LSFO, Gasoline	no	no	2	-5.98^{***}
	Iranian	LSFO, Gasoline	no	no	2	-5.98^{***}
NWE	Urals NWE	HSFO, Gasoline	no	no	2	-5.33^{***}
	Forcados	LSFO, Gasoline	no	no	1	-4.88^{***}
LA	Maya	LSFO, Gasoline	no	no	0	-3.82 (57.96^{***})
	Boscan	LSFO, Gasoline	no	no	0	-3.79 (53.72^{***})
NA	Kern River	LSFO, Gasoline	no	no	2	-5.09^{***}
	Thums	LSFO, Gasoline	no	no	0	-5.55^{***}

Notes to Table 6. ADF is the calculated *t* test for the null hypothesis of no cointegration (i.e. $\gamma=0$) in the Augmented Dickey-Fuller regression on $\hat{\varepsilon}_t$: $\Delta\hat{\varepsilon}_t = a + bt + \gamma\hat{\varepsilon}_{t-1} + \sum_{i=1}^{p}\gamma_i\Delta\hat{\varepsilon}_{t-i} + v_t$, where $\hat{\varepsilon}_t$ are the estimated residuals of the DOLS regression; *p* is the order of the augmentation needed to eliminate any autocorrelation in the residuals of the ADF regression; * (**)[***] indicates significance at 10% (5%) [1%] on the basis of the critical values by MacKinnon, (1991); for crudes in the LA area the Johansen's (1991) trace test is reported in parentheses.

Table 7. Selected products and long-run adjustment coefficients

	MED	NWE	LA	NA
Selected products	LSFO-Gasoline (Urals, Iranian)	HSFO-Gasoline (Urals) LSFO-Gasoline (Forcados)	LSFO-Gasoline (Maya, Boscan)	LSFO-Gasoline (Kern River, Thums)
Long-run products	LSFO-Gasoline (Urals, Iranian)	HSFO-Gasoline (Urals) - (Forcados)	LSFO (Maya, Boscan)	-
Short-run products	Gasoline (Urals, Iranian)	Gasoline (Forcados)	LSFO-Gasoline (Maya, Boscan)	LSFO-Gasoline (Kern River, Thums)
Long-run adjustment coefficients ($\hat{\lambda}$)	-0.12 (Urals, Iranian)	-0.11 (Urals) -0.06 (Forcados)	-0.15 (Maya) -0.09 (Boscan)	-0.07 (Kern River, Thums)

Notes to Table 7. Selected products = pair of products corresponding to the best model specifications (1) and (2); long-run products = products whose coefficients are statistically significant in the long-run relation (1); short-run products = products whose short-run coefficients are statistically significant in model (2); crudes associated with selected products, long-run products, short-run products and long-run adjustment coefficients (see equation (2)) are reported in parentheses.

Table 8. Static and dynamic forecast evaluation of selected ECM models

		MED		NWE		LA		NA	
		Urals med	Iranian	Urals NWE	Forcad.	Maya	Boscan	Kern River	Thums
Static Forecasts	MAPE	0.26	0.37	0.24	0.08	0.96	1.95	0.74	0.86
	Theil	0.002	0.002	0.002	0.001	0.01	0.01	0.004	0.005
	BP	0.29	0.06	0.31	0.54	0.29	0.49	0.26	0.28
	VP	0.29	0.35	0.29	0.14	0.003	0.03	0.44	0.35
	CP	0.42	0.59	0.41	0.32	0.71	0.49	0.30	0.37
Dynamic Forecasts	MAPE	0.55	0.52	0.52	0.19	2.08	5.32	1.48	1.39
	Theil	0.003	0.003	0.003	0.001	0.01	0.03	0.01	0.01
	BP	0.62	0.63	0.71	0.74	0.82	0.68	0.79	0.65
	VP	0.14	0.18	0.21	0.11	0.07	0.27	0.17	0.29
	CP	0.25	0.19	0.08	0.15	0.11	0.05	0.04	0.06
	SR	0.875	0.958	1.00	0.958	1.00	1.00	0.958	0.958

Notes to Table 8. Static forecasts indicate one-step-ahead forecasts, dynamic forecasts indicate 4-step-ahead forecasts (6 steps for LA area); MAPE is the mean absolute percentage error, Theil is the Theil's Inequality Coefficient and BP, VP, CP are the bias, variance, and covariance proportions. SR is the mean of the success ratio calculated as the percentage number of times the sign of the forecasted series is the same as the sign of the actual series. All the reported values, with the exception of those referring to LA, are mean values calculated over the 6 forecast windows.

Table 9. Simulated forecast evaluation of selected ECM models

		MED		NEW		LA		NA	
		Urals med	Iranian	Urals NWE	Forcad.	Maya	Boscan	Kern River	Thums
Mean	MAPE	2.42	2.26	2.40	2.09	9.83	9.56	3.54	3.22
	Theil	0.01	0.01	0.01	0.01	0.06	0.06	0.02	0.02
	BP	0.69	0.51	0.61	0.67	0.75	0.67	0.66	0.59
	VP	0.29	0.45	0.37	0.30	0.25	0.33	0.19	0.26
	CP	0.02	0.04	0.02	0.03	0.004	0.005	0.16	0.14
	SR	0.58	0.5	0.71	0.54	0.67	0.66	0.625	0.54
Dispersion	SD	0.50	0.53	0.38	0.16	0.86	1.44	0.91	0.68
	SD1	0.25	0.27	0.19	0.09	-	-	0.55	0.47
	SD2	0.45	0.48	0.35	0.15	-	-	0.80	0.62
	SD3	0.58	0.62	0.45	0.19	-	-	1.03	0.73
	SD4	0.70	0.73	0.51	0.22	-	-	1.26	0.88

Notes to Table 9. Simulated forecast stands for 'true' out of sample 4 (6) step-ahead forecast. In order to calculate the reported measures of dispersion we proceeded as follows: i) we calculated the standard deviations of the distribution of forecasts in each window and in each forecasting period (24 standard deviations); ii) in order to obtain SD we calculated the mean of all the standard deviations of point i. (mean of 24 standard deviations); iii) in order to obtain SD*k* *k*=1,..,4 we calculated the mean by window of the standard deviations referring to *k*-th forecasting point (mean of 6 standard deviations).

Appendix

Table A1. Unit root tests: Crudes

	a	b	P	ADF
Brent	yes	no	1	-2.06
Δ Brent	no	no	0	-15.94**
Urals med	yes	no	1	-2.31
Δ Urals med	no	no	0	-15.81**
Iranian	yes	no	1	-2.24
Δ Iranian	no	no	0	-15.90**
Urals NWE	yes	no	1	-2.24
Δ Urals NWE	no	no	0	-16.07**
Forcados	yes	no	1	-2.18
Δ Forcados	no	no	0	-15.60**
WTI	yes	no	0	-1.69
Δ WTI	no	no	0	-8.70**
Maya	yes	no	0	-1.82
Δ Maya	no	no	0	-8.33**
Boscan	yes	no	1	-2.24
Δ Boscan	no	no	0	-6.95**
Kern River	yes	no	1	-2.26
Δ Kern River	no	no	0	-15.52**
Thums	yes	no	1	-2.11
Δ Thums	no	no	0	-16.00**

Notes to Table A1. ADF is the calculated t test for the null hypothesis of a unit root (i.e. $\gamma=0$) in the series x_t from the Augmented Dickey-Fuller regression: $\Delta x_t = a + bt + \gamma x_{t-1} + \sum_{i=1}^{p} \lambda_i \Delta x_{t-1} + \eta_t$; *p* is the order of the augmentation needed to eliminate any autocorrelation in the residuals of the ADF regression; * (**)[***] indicates significance at 10% (5%) [1%] on the basis of the critical values by MacKinnon, J.G. (1991) "Critical Values for Co-Integration Tests", in R.F. Engle and C.W.J. Granger (eds.), *Long-run Economic Relationships*, Oxford, Oxford University Press..

Table A2. Unit root tests: Products, Europe

	MED				NWE			
	a	b	p	ADF	a	b	p	ADF
Gasoline	yes	no	1	-2.18	yes	no	1	-2.15
Δ Gasoline	no	no	0	-14.17**	no	no	0	-15.02**
Gasoil	yes	no	1	-2.03	yes	no	1	-1.84
Δ Gasoil	no	no	0	-14.63**	no	no	0	-15.12**
LSFO	yes	no	1	-2.50	yes	no	1	-2.16
Δ LSFO	no	no	0	-12.51**	no	no	0	-13.45**
HSFO	yes	no	2	-2.44	yes	no	1	-2.19
Δ HSFO	no	no	1	-11.26**	no	no	0	-15.59**

Notes to Table A2. see Table A1

Table A3. Unit root tests: Products, America

	LA				NA			
	a	b	p	ADF	a	b	p	ADF
Gasoline	yes	no	0	-2.27	yes	no	1	-2.73
Δ Gasoline	no	no	0	-9.51**	no	no	0	-16.34**
Gasoil	yes	no	1	-1.88	No	no	1	-1.73
Δ Gasoil	no	no	0	-7.68**	no	no	0	-19.25**
LSFO	yes	no	0	-1.73	yes	no	1	-2.37
Δ LSFO	no	no	0	-8.92**	no	no	0	-14.54**

Notes to Table A3. see Table A1

Table A4. ECM model estimates

	Urals MED	Iranian	Urals NWE	Forcados	Maya	Boscan	Kern River	Thums
Products (y_1, y_2)	LSFO, Gasoline	LSFO, Gasoline	HSFO, Gasoline	LSFO, Gasoline	LSFO, Gasoline	LSFO, Gasoline	LSFO, Gasoline	LSFO, Gasoline
$\hat{\delta}_{01}$	0.51^{***} (11.15)	0.42^{***} (8.89)	0.48^{***} (10.56)	0.30^{***} (6.04)	-	-	0.02 (0.37)	-0.05 (-1.13)
$\hat{\delta}_{02}$	-0.22^{***} (-4.46)	-0.15^{***} (-2.95)	-0.28^{***} (-5.88)	-0.001 (-0.03)	-	-	0.03 (0.57)	-0.02 (-0.54)
$\hat{\delta}_{03}$	-	-	-	-	-	-	0.13 (3.19^{***})	0.15 (3.53^{***})
$\hat{\delta}_{10}$	1.11^{***} (64.9)	1.15^{***} (59.53)	1.09^{***} (74.96)	1.04^{***} (167.06)	1.11^{***} (13.39)	0.98^{***} (6.74)	0.73^{***} (16.51)	0.66^{***} (17.67)
$\hat{\delta}_{11}$	-0.57^{***} (-10.8)	-0.49^{***} (-8.49)	-0.52^{***} (-10.2)	-0.29^{***} (-5.58)	-	-	0.33^{***} (5.84)	0.34^{***} (6.91)
$\hat{\delta}_{12}$	0.23^{***} (4.27)	0.16^{***} (2.77)	0.30^{***} (5.65)	-0.01 (-0.15)	-	-	0.10^{*} (1.76)	0.12^{**} (2.30)
$\hat{\delta}_{13}$	-	-	-	-	-	-	-0.02 (-0.29)	0.002 (0.05)
$\hat{\delta}_{20}$	-0.02 (-0.98)	0.003 (0.17)	-0.02 (-1.44)	-0.01 (-1.19)	0.34^{***} (6.19)	0.27^{***} (2.70)	0.07^{*} (1.70)	0.11^{***} (2.96)
$\hat{\delta}_{21}$	-0.01 (-0.29)	-0.02 (-0.87)	0.01 (0.96)	-0.01 (-0.77)	-	-	-0.10^{**} (-2.26)	-0.08^{**} (-2.03)

Table A4 Continuous

$\hat{\delta}_{22}$	0.01 (0.79)	0.02 (0.82)	-0.01 (-0.36)	0.01 (1.24)	-	-	0.02 (0.36)	0.03 (0.70)
$\hat{\delta}_{23}$	-	-	-	-	-	-	0.01 (0.18)	0.02 (-0.91)
$\hat{\delta}_{30}$	-0.04** (-2.01)	-0.04* (-1.84)	0.01 (0.29)	-0.02** (-2.51)	-0.08 (-1.47)	-0.17* (-1.83)	-0.01 (-0.38)	-0.03 (-0.91)
$\hat{\delta}_{31}$	0.07*** (3.26)	0.04* (1.81)	0.001 (0.05)	0.01 (1.54)	-	-	0.09** (2.29)	0.05* (1.64)
$\hat{\delta}_{32}$	-0.04** (-2.04)	-0.02 (-0.75)	-0.02 (-1.45)	0.01** (2.08)	-	-	0.01 (0.22)	0.03 (0.77)
$\hat{\delta}_{33}$	-	-	-	-	-	-	-0.05 (-1.37)	-0.04 (-1.31)
$\hat{\lambda}$	-0.12*** (-5.56)	-0.12*** (-5.55)	-0.11*** (-5.45)	-0.06*** (-4.32)	-0.15*** (-3.75)	-0.10** (-1.96)	-0.07** (-4.18)	-0.07*** (-3.71)
BG-stat	0.01	0.63	0.71	2.07	0.61	6.21*	0.36	0.94
R2	0.95	0.94	0.97	0.99	0.90	0.64	0.64	0.67

Notes to Table A4. The ECM specification is

$$\Delta p_t^c = \sum_{p=1}^{P-1} \delta_{0p} \Delta p_{t-p}^c + \sum_{q=0}^{Q-1} \delta_{1q} \Delta p_{t-q}^m + \sum_{r=0}^{R-1} \delta_{2r} \Delta p_{t-r}^{y_1} + \sum_{s=0}^{S-1} \delta_{3s} \Delta p_{t-s}^{y_2} + \lambda \hat{\varepsilon}_{t-1} + \eta_t$$

, where *P*=*Q*=R=*S*; BG-stat is the LM version of the Breusch-Godfrey test for absence of first order residual autocorrelation in the regression; * (**)[***] indicates significance at 10% (5%) [1%]