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Guglielmo Maria Caporale, Davide Ciferri and Alessandro Girardi

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Time-varying spot and futures oil prices dynamics

Guglielmo Maria Caporale[a], Davide Ciferri[b] and Alessandro Girardi[c]

[a] Brunel University (London), CESifo and DIW Berlin
[b] University of Perugia
[c] ISAE, Rome

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Abstract

We investigate the role of crude oil spot and futures prices in the process of price discovery by using a cost-of-carry model with an endogenous convenience yield and daily data over the period from January 1990 to December 2008. We provide evidence that futures markets play a more important role than spot markets in the case of contracts with shorter maturities, but the relative contribution of the two types of market turns out to be highly unstable, especially for the most deferred contracts. The implications of these results for hedging and forecasting crude oil spot prices are also discussed.

*Keywords***:** Cointegration, Oil market, Futures prices, Price Discovery.

*JEL Classification***:** C32, C51, G13, G14.

Corresponding author: Professor Guglielmo Maria Caporale, Centre for Empirical Finance, Brunel University, West London, UB8 3PH, UK. Tel.: +44 (0)1895 266713. Fax: +44 (0)1895 269770. E-mail: Guglielmo-Maria.Caporale@brunel.ac.uk

1 Introduction

Despite the increasing efforts aimed at redirecting both public and private investment towards businesses and infrastructure less dependent on natural resources, developments in the oil market still represent a key issue for policy makers and investors. The recent sharp rise in oil prices fuelled by buoyant markets (Brazil, China and India) as well as by simultaneous supply disruptions in a number of oil exporting countries (Iraq, Nigeria, Venezuela) and terrorist attacks has increased demand for hedging and price risk management operations. In response to soaring oil price levels and volatility, the financial industry has devised a growing variety of (highly non-standardised) derivative contracts, albeit futures contracts remain one of the most popular tools for risk management in oil markets.

Spot and futures prices are expected to be linked to each other in the long-run on the basis of a number of theoretical models. Among the various theories explaining the spot-futures relationship, the theory of storage (Kaldor, 1939) has received substantial empirical validation (Lautier, 2005). In this theoretical set-up, futures price should be equal to the spot price plus the cost of carry (the sum of the cost of storage and the interest rate) and the convenience yield (that is, the benefit from holding spot oil which accrues to the owner of the spot commodity). Since the study of Garbade and Silver (1983), a widely recognised benefit of futures markets has been the process of competitive price discovery, that is the use of futures prices for pricing spot market transactions through the timely incorporation into market prices of heterogeneous private information or heterogeneous interpretation of public information by way of trading activity (Lehmann, 2002).

Even though spot and futures prices are likely to be driven by the same fundamentals in the long run, the stochastic properties of oil prices may differ in quiet compared to turmoil periods (Bessembinder et al. 1995). Moreover, owing to the cost-of-carry relationship, shifts

in price dynamics are translated into changes in the dynamic adjustment towards the long-run relationship between spot and futures prices (Brenner and Kroner, 1995). Therefore, their dynamic interaction is expected to vary over time.

In the present study, we allow for possible parameter instability in the adjustment process towards the long-run equilibrium, thereby making a novel contribution to the empirical literature on the relationship between spot and futures prices in the oil market (Silvapulle and Moosa, 1999; McAleer and Sequiera, 2004) and on the key role of futures markets in the process of price discovery for both consumption and investment commodities (Yang et al. 2001; Figuerola-Ferretti and Gilbert, 2005, among others). Specifically, we employ an augmented cost-of-carry model with an endogenous convenience yield (Figuerola-Ferretti and Gonzalo, 2008) and the Kalman filter based approach of Barassi et al. (2005) in order to investigate whether the spot and future markets' contribution to price discovery varies over time.

Using daily data on oil spot prices as well as the prices of 1-, 2-, 3-, 4-month futures contracts over the period from January 2, 1990 to December 31, 2008, we investigate to what extent spot and futures markets contribute to price discovery and whether their relative contributions vary over time. We find that spot and futures prices are linked to each other by a long-run relationship characterised by symmetry and proportionality between the two prices. Based on the metrics proposed by Harris et al. (1995, 2002), we also show that both markets are important for the disclosure of the full information price. On average, futures markets tend to dominate the spot market in terms of price discovery for the shortest maturities, but the relative contribution of the two markets turns out to be highly unstable, especially for the most deferred contracts.

The paper is organised as follows. Section 2 presents the theoretical framework we use to derive time-varying measures of the various markets' contribution to price discovery. Section 3 discusses the dataset and some preliminary results. Section 4 reports the main empirical findings. Section 5 offers some concluding remarks.

2. Theoretical framework

2.1 The cost-of-carry model with an endogenous convenience yield

A popular explanation for the long-run relationship between spot and futures prices in commodity markets relies on the storage theory (Kaldor, 1939). When expressed in logarithmic terms, the spot price should equal the futures price plus an additional term, i.e. the cost-of-carry term. In such a framework, the occurrence of backwardation or contango (that is, observing higher spot prices than futures prices, or *viceversa*) depends on a number of factors such as storage and warehousing costs, interest rates and the convenience yield.

The latter can be defined as the implicit gain that accrues to an owner of the physical commodity but not to the owner of a contract for future delivery of the commodity (Brennan and Schwartz, 1985). In the specific case of the crude oil market, the convenience yield turns out to be particularly relevant, not only because of the strategic benefit from the possession of the commodity, but also because of the relative scarcity of that non-renewable resource (Coppola, 2008). Consequently, in order to model adequately the link between spot and futures oil prices, we extend the standard cost-of-carry model to incorporate endogenous convenience yields along the lines of Figuerola-Ferretti and Gonzalo (2008).

Let s_t and $f_t(T)$ be respectively the oil spot price at time t and the futures price at time t for delivery of the commodity at time T, where $\Delta s_t = s_t - s_{t-1}$ and $\Delta f_t(T) = f_t(T) - f_{t-1}(T)$ are $I(0)$ processes. Further assume that the continuously

[3]

compounded interest rate prevailing in the interval from t to T, r_t, follows the process $\bar{r} + I(0)$, where the bar stands for the mean value, and that the convenience yield, y_t, is a process given by a weighted average of spot and futures prices plus a $I(0)$ term:

$$y_t(T) \equiv \varphi_1 s_t - \varphi_2 f_t(T) + I(0),\qquad(1)$$

In the absence of taxes, borrowing constraints or transaction costs, the relationship between spot and futures oil prices can by described by a cost-of-carry model of the type:

$$f_t(T) = s_t + \bar{r}(T - t) - y_t(T)\qquad(2)$$

From conditions (1) and (2), we obtain the following long-run equilibrium condition:

$$s_t = \beta_1 f_t(T) + \beta_2 + I(0)\qquad(3)$$

where $\beta_1 \equiv (1-\varphi_2)/(1-\varphi_1)$ and $\beta_2 \equiv -\bar{r}(T-t)/(1-\varphi_1)$. Notice that the stationarity of the log-basis, $s_t - f_t(T)$, and, in turn, of the convenience yield turns out to be a special case embedded into condition (3). When β_1 is greater (lower) than unity, instead, the market is under long-run backwardation (contango) and the convenience yield is a $I(1)$ process.

Since both spot and futures prices are assumed to be non-stationary, the stationarity of their relationship (3) implies cointegration between them with a cointegrating relationship given by:

$$\xi_t = s_t - \beta_1 f_t(T) - \beta_2\qquad(4)$$

where the cointegrating vector ξ_t can be seen as the stationary deviation from the cost-of-carry model. The Granger Representation Theorem (Engle and Granger, 1987) implies that futures and spot prices can be represented by a Vector Error Correction (VEC) model (Johansen, 1988; 1991), where ξ_t is the error correction term (Low et al., 2002). We use this framework and adopt a VEC representation of the following form:

[4]

$$\Delta y_t = \Pi y_{t-1} + \sum_{j=1}^{k-1} \Gamma_j \Delta y_{t-1} + u_t \qquad (5)$$

where $y_t' = [s_t \ f_t(T)]'$ includes the spot and futures oil prices; Δ is the first difference operator; Γ's are matrices of autoregressive coefficients up to the order $k-1$; $\Pi = \alpha\beta'$ is the long-run impact matrix, where $\beta' y_t = \xi_{t-1}$, that is the deviations from the long-run equilibrium condition as defined in equation (4), and $\alpha = [\alpha_S \ \alpha_F]'$ is the vector of feedback adjustments, such that $\alpha_S < 0$ and $\alpha_F > 0$, where the subscript S (F) stands for the spot (futures) market, and u_t is a vector of Gaussian white noise processes with covariance matrix Σ, $u_t \sim NIID(0,\Sigma)$.

2.2 Measuring each market's contribution to price discovery

Unlike the vast majority of commodities for which only forward prices are available, in the case of crude oil futures prices are publicly available and represent potentially informative and costless signals, since the actions of profit-maximising futures traders leads to the price quoted today fully reflecting the available information about the future value of the asset. A popular method to assess the informational content of the prices observed in a given trading venue (for instance, the futures market) for the process of price discovery is to use the metrics proposed by Harris et al. (1995, 2002).[1] In general, price discovery is the process of uncovering an asset's full information (or fundamental) value, which differs from the observable price, because the latter is affected by transitory noises due to fluctuations in bid-

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[1] An alternative measure for each market's contribution to price discovery is the one proposed by Hasbrouck (1995). Based on the Cholesky factorisation of the matrix Σ, Hasbrouck's model assumes that the degree of price discovery occurring in a trading venue is (positively) related to its contribution to the variance of the innovations to the common factor (market's information share, IS).

ask spreads, temporary order imbalances or inventory adjustments (Figuerola-Ferretti and Gonzalo, 2008).

Carrying out the permanent-transitory decomposition developed by Gonzalo and Granger (1995), Harris et al. (1995, 2002) attribute superior price discovery to the market that adjusts the least to price movements in the other market. Using the orthogonal component of the feedback matrix $\alpha_\perp = [\alpha_\perp^S \; \alpha_\perp^F]'$ under the condition $\alpha_\perp^S + \alpha_\perp^F = 1$, we can express markets' contribution to price discovery as:[2]

$$\alpha_\perp^S = \alpha^F /(\alpha^F - \alpha^S) \; , \; \alpha_\perp^F = \alpha^S /(\alpha^S - \alpha^F) \qquad (6)$$

so that the spot (futures) market's contribution to price discovery, $\alpha_\perp^S$ ($\alpha_\perp^F$), depends on both α's. High (low) values of the statistics indicate a sizeable (small) contribution to price discovery. [3]

However, as pointed out by Bessembinder et al. (1995), the stochastic properties of oil prices may be different in quiet or turmoil periods respectively. Because of the long-run relationship between spot and futures prices, switches in the process governing prices are expected to induce shifts in the adjustment process to restore the cost-of-carry relationship (Brenner and Kroner, 1995). In contrast to previous studies, our modelling approach takes into account possible parameter instability in this process. In order to detect structural changes

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[2] Matrix $\alpha_\perp$ is such that $\alpha_\perp'\alpha = 0$, which implies $\alpha_\perp^S\alpha^S + \alpha_\perp^F\alpha^F = 0$. Using the condition $\alpha_\perp^S + \alpha_\perp^F = 1$, we end up with a system of two equation in two unknowns ($\alpha_\perp^S$ and $\alpha_\perp^F$). Solving that system yields the coefficients given by (6).

[3] With daily data, price innovations are generally correlated across markets, and thus the matrix Σ is likely to be non-diagonal. In such a case, Hasbrouck's approach can only provide upper and lower bounds on the information shares of each trading venue. For this reason, the IS approach is more suitable for high frequency data, where correlation tends to be smaller. Furthermore, the IS methodology encounters testing difficulties.

in the adjustment coefficients, we follow Barassi et al. (2005) and allow for time-variation in the parameters using a version of the Kalman filter. This class of models consists of two equations: the state equation, describing the evolution over time of the non-observable state variables, and the measurement equation, showing to what extent the observable variables are driven by the state variables. In our framework the VEC model (5) represents the measurement equations, with the autoregressive matrices Γ's as well as the covariance matrix Σ being non-time-varying. The adjustment parameters in the matrix α are instead the state equations:

$$\alpha_t = T\alpha_{t-1} + v_t \ , \ v_t \sim N(0, Q) \tag{6}$$

with initial conditions $\alpha_0 \sim N(\alpha_0, \sigma^2 P)$. In particular, we assume that the elements of the matrix α follow a random walk process, such that $T = I$, hence possibly varying considerably over time. With the cointegrating relationship (4) kept fixed, such an assumption allows us to detect any structural changes that may occur in the causal link between two variables, as pointed out by Barassi et al. (2005). We apply this procedure to the bivariate systems linking spot/futures oil prices in order to investigate the occurrence of breaks in the causal structure of these linkages by computing as time-varying price discovery measures $\alpha_{\perp,t}^{S} \equiv \alpha_t^{F} / (\alpha_t^{F} - \alpha_t^{S})$ and $\alpha_{\perp,t}^{F} \equiv \alpha_t^{S} / (\alpha_t^{S} - \alpha_t^{F})$.

3. Data description and preliminary analyses

3.1 The dataset

The dataset includes daily observations of spot prices, S, of West Texas Intermediate (WTI) Crude as well as four daily time series of prices of NYMEX futures contracts (with a maturity of 1 month, $F(1)$, 2 months, $F(2)$, 3 months, $F(3)$, and 4 months, $F(4)$) written on WTI Crude with delivery in Cushing, Oklahoma over the period from January, 2 1990 to

December, 31 2008. The dataset is obtained from the US Energy Information Administration (EIA). According to the definitions provided by EIA (2008), both spot and futures prices are the official daily closing prices at 2.30pm from the trading floor of the NYMEX for a specific delivery month for each product listed. Each futures contract expires on the third business day prior to the 25th calendar day of the month preceeding the delivery month.[4]

As pointed out by Büyükşahin et al. (2008), crude oil represents the world's largest futures market for a physical commodity. We focus our attention on shorter maturities for three main reasons. First, when the analysis is expanded with the inclusion of contracts with an expiration date exceeding one or two production cycles (that is, from 6 to 10 years), the explanatory factors of the storage theory are likely to be of little use (Lautier, 2005). Second, Büyükşahin et al. (2008) document that contracts dated one year and beyond tend to move closely with nearby prices only in the last five years, suggesting the occurrence of market segmentation or the lack of market integration for deferred contracts for most of our sample span. Third, even though contracts for crude oil are traded with maturities for each of the following eighteen months, the number of contracts traded with maturities in 'far' months (dates far into the future) is much smaller than in the case of maturities in 'near' months, with the consequence that the market for deferred contracts is thin and prices for those contracts are likely to be rather unreliable (Kaufmann and Ullman, 2009).

As a background to the discussion, Figure 1 presents daily spot prices versus futures prices for different maturities. Close overlapping of the series can be noted, although there are some divergencies, especially in the case of the most deferred contract. The evolution over time of the series indicates that small shocks affected the mean value of prices over the

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[4] If the 25th calendar day is not a business day, trading ceases on the third business day prior to the last business day before the 25th calendar day.

nineties. After reaching their minimum level (13 US$ per barrel) in 1998, oil prices increased dramatically and became more volatile over the subsequent decade. In mid-2008 they reached their maximum (more than 145 US$ per barrel), and then a sharp fall followed, down to a level of 44 US$ per barrel at the end of 2008.

[Figure 1]

3.2 Summary statistics and unit root tests

Table 1 reports some descriptive statistics, namely first and second moments for the log-series both in levels and in first differences. Spot and futures prices appear to move closely. The following is also noteworthy: *i*) the first moment of the log of oil prices indicates that the market is in backwardation, as previously documented by Edwards and Canters (1995) and Litzenberg and Rabinowitz (1995), among others; *ii*) price movements in the spot market are larger and more erratic than those for futures prices, suggesting that positive shocks to demand for spot commodities tend to increase convenience yields (Fama and French, 1988); *iii*) the second moment of futures prices declines with maturity, consistently with the Samuelson effect (Samuelson, 1965), according to which a shock affecting the nearby contract price has an impact on following prices that decreases as the maturity increases; *iv*) the correlation between spot and futures prices decreases monotonically with the maturity of contracts. A similar conclusion holds when the variables in first differences are considered. The only exception concerns the average growth rates of futures prices which turn out to be greater than the average rate of change for spot prices, suggesting some degree of convergence between prices over the sample.

[TABLE 1]

In order to assess the stochastic properties of the variables, we check for the presence of a unit root in each series by means of the DF-GLS test (Elliott et al., 1996), allowing for an

intercept as the deterministic component. As reported in Table 2, the null of a unit root can be rejected at conventional levels of significance in all cases. On the other hand, first-differencing the series appears to induce stationarity. The KPSS (Kwiatkowski et al., 1992) stationarity test corroborates these conclusions. Given the evidence of I (1)-ness for all individual series, testing for cointegration between spot prices and (each of the) futures price series is the logical next step in the empirical analysis.[5]

[TABLE 2]

4. Empirical evidence

4.1 VEC models estimates

Estimating (5) requires testing the rank of the Π matrix at the outset. Trace and maximum eigenvalue tests suggest rank 1 in all cases (Table 3). Finding a common trend for both spot and futures prices is consistent with the idea that they are driven by the same fundamentals (such as interest rates, macroeconomic variables and oil reserves), futures prices representing expectations of the future spot price of the physical commodity (Bernanke, 2004) or effective long-term supply prices (Greenspan, 2004).

[TABLE 3]

As Panel A of Table 4 shows, the estimated long-run parameters for the futures prices are very close to unity. Furthermore, both feedback parameters have the expected sign, implying convergence towards the long-run relationship in all models. Moving from Model 1

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[5] This conclusion arising from the unit root/stationarity tests implies that the evidence from the descriptive statistics for the variables in log-levels should be taken with caution. Note, however, that the estimated long-run relationships are broadly consistent with the existence of backwardation in the oil crude market (see Section 4.1). Furthermore, the pair-wise correlations between spot and futures prices at different maturities are qualitatively similar, irrespective of whether the variables are considered in levels or in first differences.

to Model 4, however, the lower (in absolute value) adjustment coefficients suggest weaker convergence when longer-dated futures are considered: the overall speed of adjustment, $|\alpha^S|+\alpha^F$, indeed, declines from 0.43 to 0.02, which implies that the corresponding half-lives (computed as $\ln 0.5/\ln[1-(|\alpha^E|+\alpha^D)]$) soar from 1.2 days for Model 1 to 27.5 for Model 4. These figures are quite plausible since the NYMEX 1-month futures contract is the world's most actively traded futures contract on a physical commodity and its prices serve as a benchmark for the pricing of crude oils around the world (Coppola, 2008); furthermore, spot and nearby futures contracts prices are virtually identical and have the same future delivery period for all but a few days each month. As the maturity of futures contracts increases, instead, the degree of integration between spot and futures markets dwindles dramatically.

[TABLE 4]

The symmetry and proportionality assumption implied by the standard cost-of-carry model is tested through a standard χ^2-distributed LR test. In all models, the over-identifying restriction is not rejected by the data; moreover, the estimated values for the adjustment coefficients turns out to be very close to those obtained for the corresponding unrestricted VEC models. The statistical evidence of a (1, -1) cointegration vector for all models indicates that the oil market is neither in long-run backwardation nor in long-run contango using the terminology of Figuerola-Ferretti and Gonzalo (2008). Even though our estimates document the existence of stationary convenience yields, the intercept term in the cointegration relationships seems to increase (in absolute terms) with time-to-delivery, indicating that spot prices are higher than futures prices, on average; moreover, futures prices of contracts with shorter maturities are higher than those of contracts with longer ones.

The estimated values of the price discovery measures ($\alpha_\perp$'s) are presented in Panel C of Table 4. They suggest that the process of price discovery takes place mainly in the futures

[11]

market for the shortest time-to-delivery: the futures market contributes by more than 80 percent in Model 1 and Model 2. However, the relative contribution of the spot market to price discovery increases with the time-to-delivery. While for Model 3 the share of the futures market is still dominant (around 60 percent), in the case of the longest time-to-delivery the spot market accounts for more than 70 percent of price discovery. Testing the null of no contribution leads to the conclusion that the futures market provides relevant information for price discovery in all models but Model 4. The contribution of the spot market is statistically significant especially for Model 3 and Model 4.

4.2 Time-varying contributions of spot and futures markets to price discovery

Our analysis thus far has provided empirical support for the standard cost-of-carry relationship between spot and futures markets and shown that markets' contributions to price discovery vary. In order to ascertain the stability over time of these results, we analyse the process of price discovery in a time-varying framework by recasting the VEC model (5) - with $\Pi = \alpha\beta'$ and the constraint (1 -1) imposed in the cointegration space - into a state space form and estimate it with time-varying feedback coefficients using a Kalman filter approach as suggested by Barassi et al. (2005).

Figures 2-5 show the evolution over time of each market's contribution to price discovery (on the left) as well as and the associated p-value for the test of the null of no contribution of that market (on the right).

As in the time-invariant analysis, price discovery takes place mainly in the futures market for Model 1 and Model 2. On average, the contribution of the spot market to the process of price discovery is small and exhibits a downward trend, although it gains in significance at the very end of the estimation period in the case of Model 2 (see Figure 3 and Figure 4). As for the statistical significance of price discovery measures, Figures 2-5 show

that the null of no contribution is strongly rejected for the futures market, which represent the dominant market in terms of price discovery, with the spot market acting as a satellite trading venue in the terminology of Hasbrouck (1995).

The most interesting results from the estimation of the time-varying measures of price discovery concern Model 3 and Model 4. Figure 3 and Figure 4 reveal strong differences with respect to the patterns for the least deferred futures contracts: first, the price discovery measures are more erratic; second, there is evidence of a greater average contribution of the spot market to the discovery of the full information price; third, the sharp rise and subsequent abrupt fall in oil prices in 2008 is driven mainly by the spot market for crude oil rather than by the futures markets; finally, in contrast to a widely held view, the spot market appears to be the most important for price discovery when the most deferred contract is considered, consistently with the evidence from the time-invariant analysis.

The documented instability in the relative contribution of spot and futures contracts to the process of price discovery (especially during periods of turmoil) calls for caution when assessing the usefulness of 3-month and especially 4-month futures contracts for understanding oil spot price dynamics even in the presence of a cointegration relationship.

[FIGURE 2]

[FIGURE 3]

[FIGURE 4]

[FIGURE 5]

5. Conclusions

This paper investigates the relative contribution of spot and futures markets to oil price discovery and whether these contributions vary over time. The theoretical framework is provided by an augmented cost-of-carry model with an endogenous convenience yield, which

assumes that the spot price is equal to the futures price plus a (possibly non-stationary) term depending on a number of factors such as storage and warehousing costs, interest rates and the convenience yield.

Using daily data on oil spot prices as well as the prices of 1-, 2-, 3-, 4-months futures contracts over the period from January 2, 1990 to December 31, 2008, we document that spot and futures prices are linked to each other by a long-run relationship characterised by symmetry and proportionality. However, the strength of these linkages dramatically decreases as the maturity of futures contracts increases. As pointed out by Garbade and Silber (1983), price discovery and risk transfer are closely related. Stronger futures and spot linkages lead to a more efficient transmission of information and improved hedging opportunities. We also show that the largest share of price discovery occurs in futures markets only for the case of 1-month and 2-month futures, the relative contribution being highly unstable when 3-month and 4-month contracts are considered, with important implications for hedging and forecasting.

Regarding hedging, our findings imply that using futures for hedging a spot position on crude oil is more effective in the case of 1-month or 2-month contracts, rather than those with longer maturities. Essentially, the higher correlation between spot prices and futures prices with short maturities outweighs the lower volatility of futures prices for the most deferred derivative instruments, as also documented by Ripple and Moosa (2005). As for forecasting, cointegration between two prices implies that each market contains information on the common stochastic trends binding prices together, and therefore the predictability of each market can be enhanced by using information contained in the other market (Granger, 1986). Our results indicate that in all cases (but Model 3) price discovery occurs in only one individual market which acts as a long-run (weakly exogenous) driving variable for the system. This finding suggests that indeed valuable information for forecasting spot crude oil

prices is embedded in the long-run spot-futures relationship (see Coppola 2008, among others), but also that it is concentrated mainly in 1-month and 2-month future contracts.

The present study could be extented by analysing the factors behind the time variation in the estimated time-varying price discovery measures. A possible explanation is that crude oil fundamentals evolved due to robust economic growth worldwide as well as capacity constraints in crude oil extraction (Hamilton, 2008). Another extension could investigate the changes in the oil futures market caused by the arrival of new types of market players (for instance, financial traders and energy funds) which may have affected the information content of futures markets in terms of price discovery (Başak and Croitoru, 2006). These issues are left for future research.

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Table 1 – Descriptive statistics

	Levels			First differences		
	Mean	Standard deviation	Correlation wrt spot	Mean	Standard deviation	Correlation wrt spot
s	3.346675	0.568743	1.00000	0.000169	0.032611	1.00000
$f(1)$	3.346379	0.568688	0.999655	0.000167	0.031549	0.907892
$f(2)$	3.344667	0.567330	0.997981	0.000187	0.028590	0.860299
$f(3)$	3.341698	0.566052	0.994439	0.000198	0.025976	0.783939
$f(4)$	3.337975	0.565081	0.989664	0.000204	0.024972	0.782962

Note. s, $f(1)$, $f(2)$, $f(3)$ and $f(4)$ denote the (logarithm of) prices of West Texas Intermediate (WTI) for the spot market and for futures contracts with maturity of 1, 2, 3 and 4 months, respectively.

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Table 2 – Unit root tests

	DF-GLS		KPSS	
	Levels	First differences	Levels	First differences
s	-1.246	-9.175***	63.411***	0.050
$f(1)$	-1.203	-10.548***	63.588***	0.055
$f(2)$	-0.976	-12.739***	64.919***	0.067
$f(3)$	-0.760	-19.079***	65.812***	0.077
$f(4)$	-0.649	-10.228***	66.330***	0.081

Note. The statistics are the Dickey-Fuller Generalized Least Squares (DF-GLS) test (Elliot et al., 1996) statistics for the unit root null and the KPSS test (Kwiatkowski et al., 1992) statistics for the null of stationarity The variables are defined in Table 1. The number of lags in each regression is chosen according to the AIC criterion. A constant term is included. For the DF-GLS test, the critical values at the 1, 5 and 10 percent level of significance are -2.570, -1.940 and -1.620, respectively. For the KPSS test, the critical values at the 1, 5 and 10 percent significance level are 0.347, 0.463 and 0.739, respectively. Triple asterisks indicate the rejection of the null at the 1 percent significance level.

Table 3 – Bivariate VEC models: cointegration tests

A. Trace test		Test statistics			Critical values	
H_0	Model 1	Model 2	Model 3	Model 4	5 percent	1 percent
$r = 0$	647.36	117.66	82.72	63.24	19.96	24.60
$r \leq 1$	2.21	1.89	1.79	1.82	9.24	12.97
B. λ-max test		Test statistics			Critical values	
H_0	Model 1	Model 2	Model 3	Model 4	5 percent	1 percent
$r = 0$	654.15	115.77	80.93	61.42	15.67	20.20
$r \leq 1$	2.21	1.89	1.79	1.82	9.24	12.97

Note. Under the null there are r cointegration vectors against the alternative of exactly (at most) $r + 1$ cointegration vectors for the maximum eigenvalue (trace) test. The rank r is selected on the basis of the first non-significant statistics, starting from $r = 0$. Model 1, Model 2, Model 3 and Model 4 denote the bivariate system formed by s and $f(1)$, s and $f(2)$, s and $f(3)$ and s and $f(4)$, respectively. The variables are defined in Table 1. Critical values for both trace and maximum eigenvalue tests (Panel A and B, respectively) are taken from Osterwald-Lenum (1992).

Table 4 – Bivariate VEC models: estimation results

|	Model 1	Model 2	Model 3	Model 4
	A. Unconstrained long-run matrix			
β_1	-0.9998	-0.9989	-0.9961	-0.9917
β_2	-0.0008	-0.0048	-0.0155	-0.0314
α^S	-0.3483	-0.0612	-0.0239	-0.0089
α^F	0.0838	0.0113	0.0171	0.0160
	B. Constrained long-run matrix			
β_1	-1	-1	-1	-1
β_2	-0.0003	-0.0013	-0.0023	-0.0036
α^S	-0.3478	-0.0610	-0.0236	-0.0085
α^F	0.0843	0.0115	0.0174	0.0162
H_0: $\beta_1 = -1$	(0.83)	(0.85)	(0.73)	(0.65)
	C. Price discovery measures			
$\alpha_\perp^S$	0.1939	0.1552	0.4172	0.7322
$\alpha_\perp^F$	0.8061	0.8448	0.5828	0.2678
H_0: $\alpha_\perp^S = 0$	(0.05)	(0.35)	(0.01)	(0.00)
H_0: $\alpha_\perp^F = 0$	(0.00)	(0.00)	(0.00)	(0.32)

Note. Panel A reports the unrestricted cointegration vectors with the associated feedback coefficients for the dynamic equations of the models. Panel B presents the cointegration vectors under the over-identifying restriction of symmetry and proportionality between spot and futures prices, as well as the associated feedback coefficients for the dynamic equations of the models. The last row reports the results of the LR test between unrestricted and restricted VEC models. The first two rows of Panel C present the estimated contribution of each market to price discovery along with the test statistics for the null of no contribution (penultimate and bottom rows). The variables are defined in Table 1. The models are defined in Table 3. p-values in parentheses.

Figure 1 – Spot and futures crude oil prices
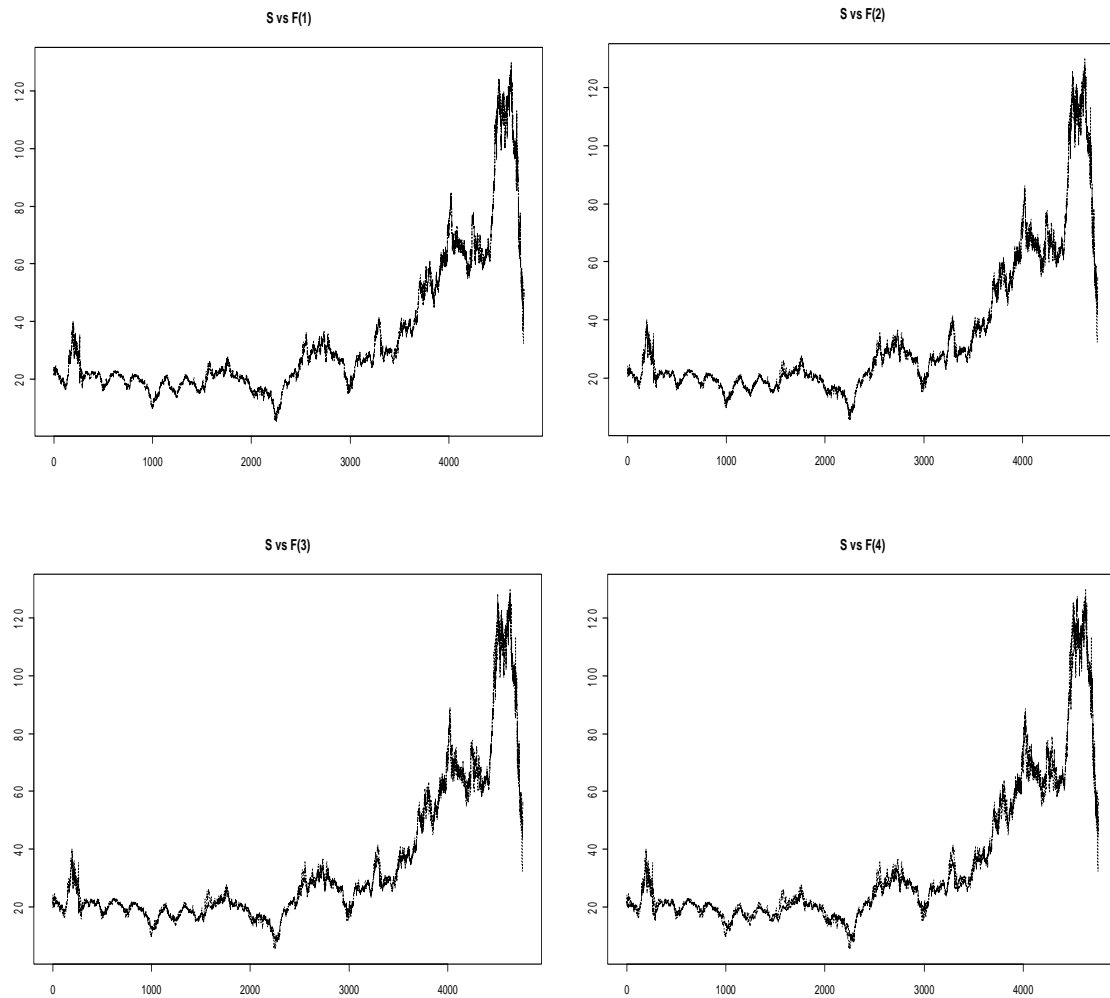
Note. Dotted lines refer to the spot price, while dashed lines are used for futures prices. The vertical axis reports the oil price in US$ per barrel. The horizontal axis reports daily observations from January, 2 1990 to December, 31 2008, for a total of 4758 datapoints: observations #1000, #2000, #3000, #4000 correspond roughly to the end of December 1993, 1997, 2001 and 2005, respectively.

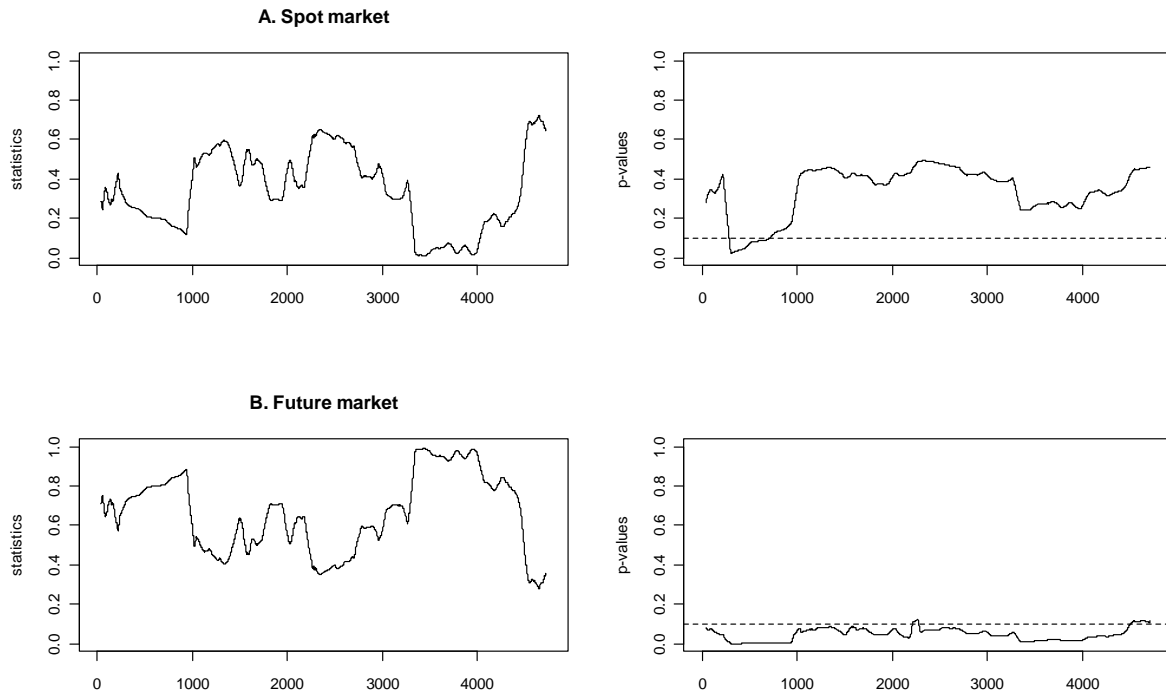*Figure 2 – Model 1: time-varying price discovery measures*
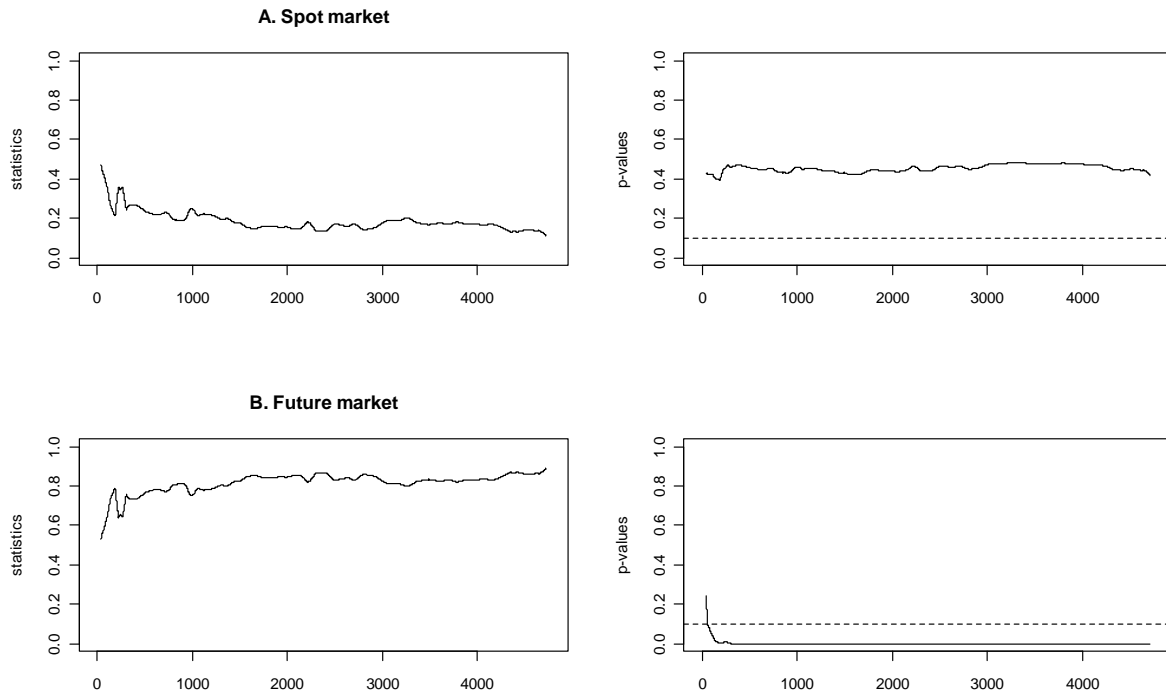
Note. Panel A reports the time-varying spot market's contribution to price discovery (on the left) and the associated p-value for the test of the null of no contribution of that market to price discovery (on the right). Panel B reports the time-varying 1-month future market's contribution to price discovery (on the left) and the associated p-value for the test of the null of no contribution of that market to price discovery. The dashed line indicates the 10 percent level threshold. The horizontal axis reports daily observations from January, 2 1990 to December, 31 2008, for a total of 4758 data-points: observations #1000, #2000, #3000, #4000 correspond roughly to the end of December 1993, 1997, 2001 and 2005, respectively.

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Figure 3 – Model 2: time-varying price discovery measures
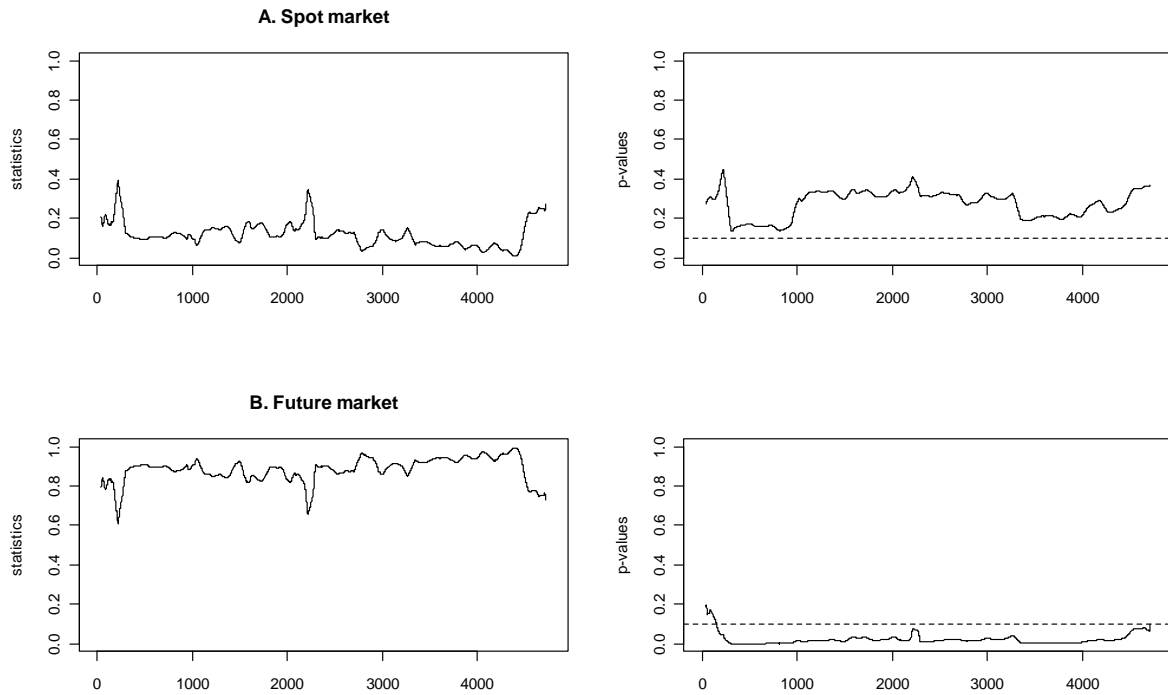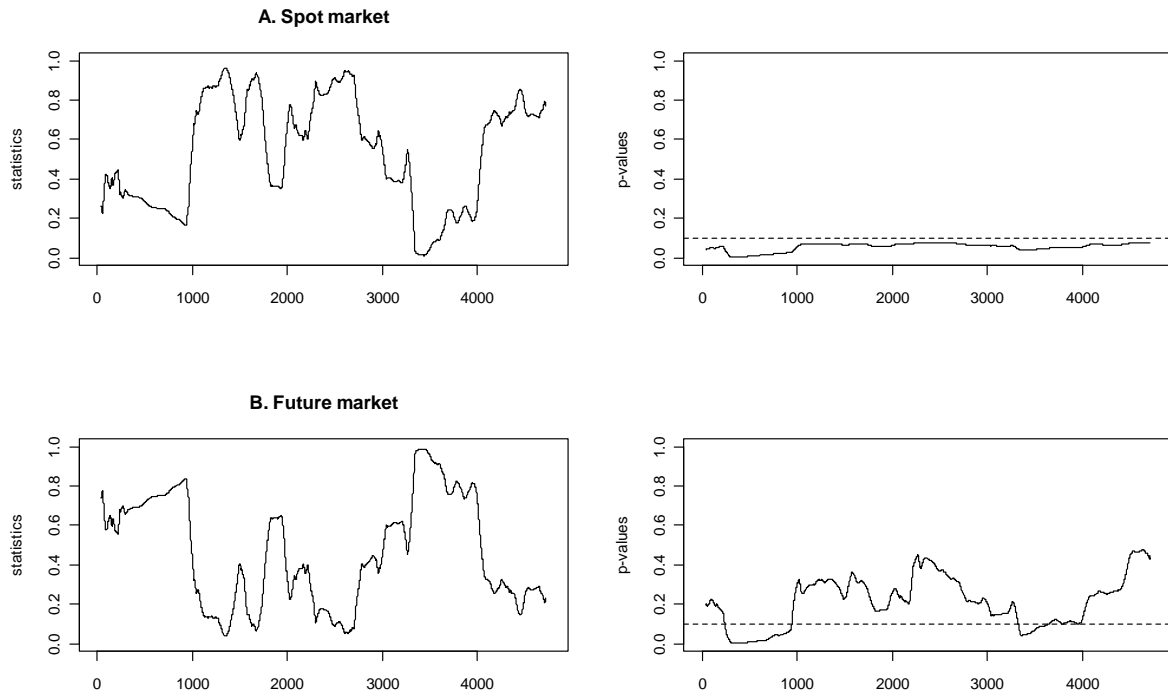
Note. Panel A reports the time-varying spot market's contribution to price discovery (on the left) and the associated p-value for the test of the null of no contribution of that market to price discovery (on the right). Panel B reports the time-varying 2-months future market's contribution to price discovery (on the left) and the associated p-value for the test of the null of no contribution of that market to price discovery. The dashed line indicates the 10 percent level threshold. The horizontal axis reports daily observations from January, 2 1990 to December, 31 2008, for a total of 4758 datapoints: observations #1000, #2000, #3000, #4000 correspond roughly to the end of December 1993, 1997, 2001 and 2005, respectively.

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Figure 4 – Model 3: time-varying price discovery measures

Note. Panel A reports the time-varying spot market's contribution to price discovery (on the left) and the associated p-value for the test of the null of no contribution of that market to price discovery (on the right). Panel B reports the time-varying 3-months future market's contribution to price discovery (on the left) and the associated p-value for the test of the null of no contribution of that market to price discovery. The dashed line indicates the 10 percent level threshold. The horizontal axis reports daily observations from January, 2 1990 to December, 31 2008, for a total of 4758 data-points: observations #1000, #2000, #3000, #4000 correspond roughly to the end of December 1993, 1997, 2001 and 2005, respectively.

[27]

Figure 5 – Model 4: time-varying price discovery measures

Note. Panel A reports the time-varying spot market's contribution to price discovery (on the left) and the associated p-value for the test of the null of no contribution of that market to price discovery (on the right). Panel B reports the time-varying 4-months future market's contribution to price discovery (on the left) and the associated p-value for the test of the null of no contribution of that market to price discovery. The dashed line indicates the 10 percent level threshold. The horizontal axis reports daily observations from January, 2 1990 to December, 31 2008, for a total of 4758 data-points: observations #1000, #2000, #3000, #4000 correspond roughly to the end of December 1993, 1997, 2001 and 2005, respectively.