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Dynamic Adjustment of Crude Oil Price Spreads

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This paper examines the dynamic adjustment of crude oil price differentials formed by a wide range of popularly traded crude oils which include non-benchmark crudes of different quality. Recent studies have pointed out the fact that the adjustment of oil price spreads is asymmetric in nature. This paper makes a contribution in many ways. Employing econometric procedures that are more powerful than recently applied methods, and on a much wider selection of crude oil pairs than previous studies we establish that the results obtained for price differentials between benchmark crudes are not representative of the behaviour of non-benchmark pairs. Further, our results show that the adjustment of price differentials cannot be fully explained by the quality differentials which are commonly approximated by the difference in API gravity. Finally, we find that short run and long run dynamics do not show a pattern that could be linked to quality differentials.

Keywords: *Crude Oil, Dynamic Adjustment, Momentum Threshold Autoregression*

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1. INTRODUCTION

Standardised crude oil contracts are traded at the major exchanges such as the New York Mercantile Exchange (NYMEX) and Intercontinental Exchange (ICE) Futures Europe in London. An over-the-counter (OTC) market exists for contracts with non-standard terms which may be used by crude oil companies or investment banks for speculation and hedging, particularly at the time of any economic or political turmoil. WTI (40°), Brent (38°) and Dubai/Oman¹ (32°) futures are widely used to hedge against price fluctuations of crudes for which futures contracts are simply not available, and the effectiveness of such a strategy will depend on the strength of the relationship between the crude of interest and the utilised benchmark crude which will often possess different characteristics.

The quality of a crude oil stream is defined by its natural properties, namely sulphur content and API gravity², which determine the usefulness of the crude oil in the production of valuable petroleum products. Light crudes, with a gravity greater than 38°, are usually sweet (low in sulphur) and produce a higher proportion of gasoline and diesel after the refining process. They are benchmarked to WTI (40°)³ and Brent (38°) which are believed to reflect the market conditions in North America and North Sea respectively. Medium crude oils have a gravity between 22° and 38° and are benchmarked to Dubai/Oman (32°). These crude oils are more difficult to separate into chemical elements and yield a lower percentage of valuable products such as diesel. Heavy crude oils, which are benchmarked to Maya (22°), have a gravity of 22° or less, and are usually sour (high in sulphur). The extraction of these crude oils are becoming

¹ This benchmark began to incorporate Oman following a significant decline in production of Dubai in the 1990s.

² American Petroleum Institute (API) gravity is a measure of density of petroleum liquids, usually given in degrees and placed between 10° and 70°. The definitions of light, intermediate and heavy crude, in degrees, have been obtained from Energy Information Administration (EIA).

³ It is worth noting that bottleneck supply and demand issues have recently given landlocked WTI (40°) a status of a 'broken benchmark' (Hammoudeh *et al.*, 2008).

commercially viable due to the recent developments in technology, however their refinery presents special challenges and not all refineries are equipped to work with them.

Substitution of a lighter crude with a heavier crude may be associated with high investment in the adaptation of refineries and the possible setting up of new transportation routes or storage; it is therefore not surprising that lighter crudes are typically traded at a premium to heavier crudes. However, the relative prices of crude oils reflect more than just their natural properties and the equilibrium price differential is not always maintained. There are disparities in the pricing of crudes of similar quality, and such crudes can react very differently to geopolitical events. For instance, WTI (40°) usually trades at a premium to Brent (38°), however the WTI (40°)–Brent (38°) differential turned negative in April 2007 due to an instant reduction in the refining capacity around Cushing where WTI is stored (Bloomberg, 2007).⁴

Previously, most of the evidence on the dynamics of crude oil price differentials has been obtained using the pairs formed by Brent (38°), WTI (40°) and Dubai/Oman (32°). The results were then used to approximate the behaviour of other non-benchmark crudes on the assumption that they follow the lead of the light/medium benchmarks. This assumption may no longer hold. Over the recent years the range of traded crudes expanded rapidly - the 2010 edition of the International Crude Oil Handbook describes over 200 types of crude oil in the global markets ranging from very light to very heavy, an increase from 160 types of crudes recorded in the 2006 edition. The dynamics of benchmark crudes inevitably reflect the unique characteristics and it is possible that they are not representative of other crudes. If this is the

⁴ In recent years a much stronger response of Brent (38°) compared to WTI (40°) to Arab Spring in 2011 has been observed. However, these events pertain to periods which are not included in the sample period of our study.

case, then the results obtained using the benchmark pairs may be less useful than previously thought.

The key contribution of this paper is to offer an analysis of short run and long run dynamic adjustment of differentials between a range of benchmark and non-benchmark crudes of different quality, in pursuit of the following objectives: to qualify whether the behaviour of the benchmarks is representative of non-benchmark crudes; to confirm whether or not the asymmetry found in the price adjustment of benchmark crudes holds for other crudes; and to establish whether observed quality characteristics of crudes affect the path of adjustment of crude oil spreads. We tackle these objectives using the Momentum-Threshold Autoregressive (M-TAR) model due to Enders and Granger (1998) along with its more powerful version, the Generalised Least Squares Momentum-Threshold Autoregressive (GLS-M-TAR) model proposed by Cook (2004). The evidence presented in this paper shows that using benchmarks as a proxy for other crude oils in economic modelling and forecasting can lead to omission of vital information about the oil markets and may provide biased outcomes.

This paper is organised as follows: the review of the key literature is presented in Section 2; a description of the dataset is presented in Section 3; the econometric methodology is explained in Section 4; the results are reported in Section 5; and finally Section 6 concludes.

2. LITERATURE REVIEW

The first attempt to formally analyse the relationship between crude oil prices was undertaken by Weiner (1991), after Adelman (1984) proposed that the world oil market is “like an ocean – one great pool”. Weiner (1991) employed a correlation approach and a switching regression to establish whether prices for seven major crude oils traded in different geographic locations tend to move together, which would imply a unified market. Weiner (1991) finds strong

evidence for regionalisation using monthly prices over the period 1980 to 1987, suggesting that any demand/supply shocks affecting a particular region are largely contained within that region. However, subsequent studies have not confirmed these results.

Sauer (1994) criticised the correlation method for testing market integration. He argued that correlation only allows bivariate comparisons and does not separate the effect of exogenous shocks, neither does it consider lagged responses. Using Johansen's (1991) cointegration method, Sauer (1994) finds strong evidence of unified markets, and suggested that the difference between his and Weiner's (1991) results are most likely explained by the difference in the time allowed for oil price adjustment.

Gülen (1997) and (1999) conducted bivariate and multivariate cointegration analysis of eleven crude oils based on monthly and weekly data respectively. Cointegration analysis provided evidence for a unified market between the crude oils of both similar and different quality. This was demonstrated for both monthly and weekly data. Kleit (2001) used Gülen's (1999) dataset of weekly prices for a slightly longer time period and achieved similar results with the inclusion of an exogenous break in 1993. Kleit (2001) proceeded to estimate arbitrage costs, proposing that transaction costs deter arbitrage by eroding what can be gained from it. Ewing and Harter (2000) use the Engle-Granger (1987) method of cointegration to provide evidence of integration of Alaska North Slope (ANS, 30°) and Brent (38°) markets between 1974 and 1996. Bachmeier and Griffin (2006) estimated a Vector Error Correction Model (VECM) on daily data to test the degree of market integration both within and between crude oil, coal, and natural gas markets. They find that the following crudes were traded in a highly integrated market between 1998 and 2004: Brent (38°), WTI (40°), ANS (30°), Dubai (32°) and Arun (54°). Bentzen (2007) used the VECM to analyse WTI (40°), Brent (38°) and OPEC price between

1988 and 2004. He found evidence of a unified market and bidirectional relationship between the three prices, suggesting that WTI (40°) and Brent (38°) are influenced by the OPEC price.

Fattouh (2010) used Caner and Hansen's (2001) Threshold Autoregressive (TAR) model on daily price data for 7 crudes between 1997 and 2008. The study examined the behaviour of price differentials in two regimes. In one regime the price differential does not exceed transaction costs, and in the other regime the price differential does exceed transactions costs. The results from Fattouh (2010) confirm that mean reversion is only present where the price differential exceeds the cost of carry. Further, the findings show that price differentials are stationary over time for liquid crude oils with similar properties and that the threshold effects are only significant for crudes with quality differentials. We note that Caner and Hansen's (2001) TAR model implicitly implies that transaction costs are constant. However, this cost varies for each importer and is largely dependent largely on whether oil is transported by sea or land. As a result for the oil market where transaction costs are highly variable, the TAR model which implicitly assumes constant transaction costs, may be restrictive.

In the paper central to our study, Hammoudeh *et al.* (2008) use the Enders and Siklos (2001) cointegration with M-TAR adjustment to test benchmark crude oil prices. Their results show strong evidence for asymmetry in the adjustment of price differentials between Brent (38°), WTI (40°), Dubai (32°) and Maya (22°). They further find that the WTI (40°) – Dubai (32°) and WTI (40°) – Brent (38°) differentials widen faster than they contract; the opposite is the case for the other two pairs, Brent (38°) – Dubai (32°) and Brent (38°) – Maya (22°). Additionally, Hammoudeh *et al.* (2008) estimate an ECM to analyse the short-run dynamics and find Granger-causality in all four pairs. The same method, Enders-Siklos (2001) and in addition Hansen-Seo (2002) have been used by Hammoudeh *et al* (2010) to establish the asymmetries

and estimate the precise period of adjustment in four commodities, including WTI (40°), following positive and negative shocks.

This paper makes a contribution to the literature summarised above and builds on the study by Hammoudeh *et al.* (2008) by incorporating a number of non-benchmark crudes into the analysis, which provides a sample that is a better reflection of the composition of the global oil market. We choose not to employ the Enders-Siklos (2001) M-TAR that has been used in past studies which makes an assumption of a functional relationship where the price of the lighter crude is dependent on the price of the heavier crude. Instead we choose to examine the price spreads obviating the need to assume a specific functional relationship. We argue that the complexity of global oil markets makes the assumption of the this functional relationship restrictive by not allowing for possible bidirectional causality. This is particularly true with the inclusion of non-benchmark crudes where there is little prior knowledge of some of the crudes. Besides, as discussed in Section 1, the focus is on the dynamics of price differentials rather than a functional relationship between the crude oil prices. To this end, an Enders-Granger (1998) M-TAR is employed, and particularly the more powerful version, GLS-M-TAR due to Cook (2004). We conclude the empirical analysis by estimating an Error Correction Model with a Granger causality test, both of which take advantage of an updated dataset.

3. DESCRIPTION OF DATA

We employ weekly prices were obtained from the International Energy Agency for 7 crude oils streams, commonly known as follows: Sahara (44°), WTI, (40°), Brent (38°), Bonny (37°),

Dubai/Oman (32°), Maya (22°), and Lloyd⁵ (22°).⁶ Data has been available from 3 January 1997 to 7 January 2011 with a total of 732 observations, measured in USD per barrel.

Weekly data has been chosen due to time differences in the international markets. For instance, Asian and Middle Eastern markets close before the New York market opens, and the Australian market begins trading as soon as New York market closes. There is no natural break in the 24 hour data and too much emphasis is placed on the observations taken at the closing time of just one of the global markets (Aroudi and Rault, 2008). The weekly data is taken on a Friday, which is the last trading day for international commodity markets. It is followed by a 48 hour break in the trading cycle between Friday and Sunday afternoon, providing trading week's closing prices. The 'Friday effect', although found to be significant in certain commodity price series (Hammoudeh, 2004), is not typically large and any effects will be evened out across the dataset. Volatility in the financial markets for crude oil has also been shown to be at its lowest on Friday (Hammoudeh *et al.*, 2004).

Using seven crude oil streams we obtain a total of 21 possible pairs. The data for 21 crude oil price spreads and their descriptive statistics are presented in Table 1. These pairs include the four benchmark pairs used by Hammoudeh *et al.* (2008), and we have also allowed for seventeen further pairs thereby exhausting all possible combinations of the seven crudes chosen in this study.

[Table 1 about here]

⁵ From 6 July 2007, Lloyd became known as Canadian Hardisty.

⁶ Full names: Sahara - Algerian Saharan Blend (44°); WIT - West Texas Intermediate (40°); Brent - North Sea Brent (38°), Bonny - Nigerian Bonny Light (37°), Dubai/Oman - Dubai Fateh / Oman (32°), Maya - Mexican Maya (22°), and Lloyd - Canadian Lloyd Blend (22°).

At a general glance, the mean value of the crude oil price spreads are relatively higher for the combinations where the quality differential is more pronounced. Within the light group, however, negative mean is observed for Sahara (44°) – Bonny (37°) and Brent (38°) – Bonny (37°) pairs, which means that in these pairs the heavier crude Bonny (37°) trades at a premium to the other one on average. These two spreads also have the lowest standard deviation. Most spreads show positive skewness, implying that there are few downward spikes to match the upward spikes. A significant amount of kurtosis is found in the spreads, implying that the spreads contain some extreme values. A considerable amount of variability exists for all the crude oil price spreads given by the coefficient of variation.

4. ECONOMETRIC METHODOLOGY

The standard method to test for stationarity of the crude oil price spread entails using a unit root test on the price differential. This can be carried out by estimating the equation below:

$$P_t^A - P_t^B = \alpha + \varepsilon_t \quad (1)$$

where P_t^A and P_t^B are assumed to be non-stationary I(1) prices representing two different types of crude oils denoted A and B, α is an arbitrary constant that accounts for the differential (transportation costs and quality differences) and ε_t is the error term which may be serially correlated. To test whether the price differential is stationary, in other words whether the crude oil prices are cointegrated, we estimate equation (1) using ordinary least squares (OLS). We then apply an Augmented Dickey-Fuller (ADF) test, or any other standard unit root test⁷ on the estimated residuals of equation (1) of the following kind:

⁷ We also apply the Ng-Perron (2001) and Elliot et al. (1996) tests. For these tests, (2) is appropriately modified. For brevity we do not describe the details here.

$$\Delta \varepsilon_t = \zeta \varepsilon_{t-1} + \sum_{i=1}^p \psi_i \Delta \varepsilon_{t-i} + \omega_t \quad (2)$$

where ω_t is a white noise error term and p denotes the number of lags to whiten the residuals. The number of lags is selected using the Schwartz Bayesian Criteria (SBC). Rejecting the null hypothesis ($H_0 : \zeta = 0$) of a unit root implies that the residuals of (1) are stationary and that any shocks to the price spread would have a transitory effect. Enders and Granger (1998), however, argue that the test for unit roots and its extensions are mis-specified if the adjustment is asymmetric. They consider an alternative specification, called the M-TAR model which allows for asymmetric adjustment, such that the estimated residuals ε_t from (1) can be written as:

$$\Delta \varepsilon_t = I_t \zeta_1 \varepsilon_{t-1} + (1 - I_t) \zeta_2 \varepsilon_{t-1} + \omega_t \quad (3)$$

where I_t is the Heaviside Indicator function such that:

$$I_t = \begin{cases} 1 & \text{if } \Delta \varepsilon_{t-1} \geq \tau \\ 0 & \text{if } \Delta \varepsilon_{t-1} < \tau \end{cases} \quad (4)$$

In this case, the series ε_t exhibits more momentum in one direction than the other. If for example, $|\zeta_1| < |\zeta_2|$, the M-TAR model exhibits little adjustment for $\Delta \varepsilon_{t-i} > \tau$ but substantial decay for $\Delta \varepsilon_{t-i} < \tau$. In other words, increases tend to persist, but decreases tend to revert quickly back to the attractor irrespective of where disequilibrium is relative to the attractor. If the system is convergent, then the long run equilibrium value of the sequence is given by $\varepsilon_t = \tau$. To estimate the threshold τ we use the methodology proposed by Chan (1993)⁸.

⁸ The estimated residual series was sorted in ascending order. The largest and smallest 15% of the residual series were eliminated and each of the remaining 70% of the values were considered as possible thresholds. For each of

The sufficient conditions for the stationarity of ε_t are $\zeta_1 < 0$, $\zeta_2 < 0$ and $(1 + \zeta_1)(1 + \zeta_2) < 1$ (Petrucelli and Woolford 1984).

The Φ -statistic for the null hypothesis of stationarity of ε_t , that is, $H_0 : (\zeta_1 = \zeta_2 = 0)$ is obtained from estimating equation (3) and compared to the critical values computed by Enders and Granger (1998). If we can reject the null hypothesis, it is possible to test for asymmetric adjustment since ζ_1 and ζ_2 converge to multivariate normal distributions (Tong 1990). The F statistic is used to test for the null hypothesis of symmetric adjustment, that is, $H_0 : (\zeta_1 = \zeta_2)$. Diagnostic checking of the residuals is undertaken to ascertain whether the ω_t series is a white noise process using the Ljung-Box Q tests. If the residuals are correlated, equation (3) needs to be re-estimated in the following form, and the SBC is used to determine the lag length:

$$\Delta \varepsilon_t = I_t \zeta_1 \varepsilon_{t-1} + (1 - I_t) \zeta_2 \varepsilon_{t-1} + \sum_{i=1}^p \phi_i \Delta \varepsilon_{t-i} + \omega_t \quad (5)$$

In this paper, we also make use of the GLS-M-TAR method proposed by Cook (2004) which is a M-TAR test with increased power.⁹ This test utilises a local-to-unity detrending via generalised least squares due to Elliot *et al.* (1996). In our study, the pairs of crude oil prices represented by P_t^A and P_t^B will be demeaned and we obtain the quasi differenced data as follows:

the these thresholds the equation was estimated using (3) and (4). The estimated threshold yielding the lowest residual sum of squares was chosen as the estimate of the optimal threshold.

⁹ Cook (2003) showed that the power properties of the consistent M-TAR are lower than the modified ADF test which is based on GLS detrending procedure. GLS-M-TAR due to Cook (2004) is based on the same procedure.

$$\bar{P}_{\bar{\alpha}}^A = [P_1^A, P_2^A - \bar{\alpha}P_1^A, \dots, P_T^A - \alpha P_{T-1}^A]$$

$$\bar{P}_{\bar{\alpha}}^B = [P_1^B, P_2^B - \bar{\alpha}P_1^B, \dots, P_T^B - \alpha P_{T-1}^B]$$

$$z_{\bar{\alpha}} = [z_1, z_2 - \bar{\alpha}z_1, \dots, z_T - \alpha z_{T-1}]'$$

Where T denotes the sample size, $\bar{\alpha} = 1 + \bar{c}/T$, where $\bar{c}$ is a constant that determines the extent of local-to-unity detrending. The GLS detrended series $\bar{P}_t^A$ is derived from the expression $P_t^A - \hat{\phi}_0$ where $\hat{\phi}_0$ is obtained by regressing $\bar{P}_{\bar{\alpha}}^A$ on $z_{\bar{\alpha}}$. In the same manner we obtain $\bar{P}_t^B$.

We then estimate the following regression along the lines of (1) as:

$$\bar{P}_t^A - \bar{P}_t^B = \eta_t \tag{6}$$

We then estimate the following model with threshold adjustment:

$$\Delta\eta_t = I_t\gamma_1\eta_{t-1} + (1 - I_t)\gamma_2\eta_{t-1} + \zeta_t \tag{7}$$

$$I_t = \begin{cases} 1 & \text{if } \Delta\eta_{t-1} \geq 0 \\ 0 & \text{if } \Delta\eta_{t-1} < 0 \end{cases} \tag{8}$$

where I_t is the Heaviside Indicator function.

The existence of a stationary price spread justifies estimating an ECM, which nests together the long run and short run dynamics of crude oil price differentials. The ECM is described as follows:

$$\Delta P_t^i = \mu \hat{\varepsilon}_{t-1} + \sum_{k=1}^p \psi_i \Delta P_{t-k}^i + \sum_{k=1}^p \delta_i \Delta P_{t-k}^j + u_t^i \quad (9)$$

$$\Delta P_t^j = \pi \hat{\varepsilon}_{t-1} + \sum_{k=1}^p \eta_i \Delta P_{t-k}^i + \sum_{k=1}^p \lambda_i \Delta P_{t-k}^j + u_t^j \quad (10)$$

where P_t^i and P_t^j denote the prices of crude oils i and j respectively, $\hat{\varepsilon}_{t-1}$ refers to the error correction term, which is effectively the estimated one period lagged error of the long run equilibrium relationship between the pair of crude oil prices, and both u_t^i and u_t^j are white noise errors. Of particular significance are the long run parameters μ and π . In event of any deviation from the long run equilibrium relation in the price differential of a crude oil pair, μ and π denote the time taken (in weeks) for the equilibrium adjustment to take place. The Granger causality tests are carried out by testing for the null hypothesis of $\sum \delta_i = 0$ in (9) and $\sum \eta_i = 0$ in (10). Rejection of the hypotheses indicates that short run causality exists.

Similarly, the finding of cointegration with threshold adjustment justifies the estimation of the following ECM with threshold adjustment (TECM hereafter):

$$\Delta P_t^i = \mu_1 M_t \hat{\varepsilon}_{t-1} + \mu_2 [1 - M_t] \hat{\varepsilon}_{t-1} + \sum_{k=1}^p \psi_i \Delta P_{t-k}^i + \sum_{k=1}^p \delta_i \Delta P_{t-k}^j + u_t^i \quad (11)$$

$$\Delta P_t^j = \pi_1 M_t \hat{\varepsilon}_{t-1} + \pi_2 [1 - M_t] \hat{\varepsilon}_{t-1} + \sum_{k=1}^p \eta_i \Delta P_{t-k}^i + \sum_{k=1}^p \lambda_i \Delta P_{t-k}^j + u_t^j \quad (12)$$

where the Heaviside Indicator function is $M_t = \begin{cases} 1 & \text{if } \Delta \hat{\varepsilon}_{t-1} \geq \hat{\tau} \\ 0 & \text{if } \Delta \hat{\varepsilon}_{t-1} < \hat{\tau} \end{cases}$

P_t^i and P_t^j denote the prices of crude oils i and j respectively, $\hat{\varepsilon}_{t-1}$ refers to the error correction term, which is the estimated one period lagged error of the long run equilibrium relationship between the pair of crude oil prices, and both u_t^i and u_t^j are white noise errors. In this case when considering the dynamics of (11): in the event of any increasing (or decreasing) deviation from the long run equilibrium relation in the price differential of a crude oil pair, μ_1 (or μ_2) denote the time taken (in weeks) for the equilibrium adjustment to take place. The Granger causality tests are carried out by testing for the null hypothesis of $\sum \delta_i = 0$ in (11) and $\sum \eta_i = 0$ in (12). Following Enders and Granger (1998), the number of lags p , for both ECM and TECM is determined using the SBC. The obtained coefficients give information on both short run and long run dynamics of crude oil price differentials.

5. EMPIRICAL RESULTS

Table 2 reports the results of the unit root tests for stationarity of oil prices. Using the ADF and relatively more powerful unit root tests such as Ng and Perron (2001) and GLS version of the Dickey-Fuller test due to Elliot *et al.* (1996), we can confirm that the null of a unit root cannot be rejected in levels.

[Table 2 about here]

We conclude that the crude oil prices are I(1) and proceed to estimate the price differential between crude oil price pairs. We test the residuals of the price spread for stationarity to effectively determine whether the prices are cointegrated. The results of the cointegration test are given in Table 3 below. The second column reports the results of the symmetric ADF test. The M-TAR test due to Enders and Granger (1998) is employed as described in equations (3)

and (4) with the results shown in the third column. Finally we report the GLS based M-TAR tests in the fourth column, which are obtained using equations (6), (7) and (8).

[Table 3 about here]

All pairs in our dataset are found to be cointegrated at the conventional levels of significance using the standard symmetric ADF test and OLS- and GLS-based M-TAR models. This result is in line with the results of the previous studies reviewed earlier in this paper, and shows that prices of different crudes, whether from stable economies or the emerging markets, generally move in line with each other.

Given that we find evidence of cointegration allowing for asymmetric adjustment, we proceed to test whether the difference in adjustment is statistically significant. The results are contained in Table 4, where autoregressive coefficients are ζ_1 and ζ_2 in the case of the M-TAR model given by equation (3) and (4); and γ_1 and γ_2 in the case of GLS-M-TAR given by equations (7) and (8), along with their associated p-values.

[Table 4 about here]

The key observations concerning the adjustment dynamics can be summarised as follows: First, the OLS-based M-TAR test detects asymmetric adjustment in 18 out of 21 pairs. The more powerful GLS-based M-TAR test has offered evidence of asymmetry in adjustment in 20 out of 21 pairs at 10% level of significance, and 19 out of 21 pairs at 5%. This evidence echoes and extends the results of previous studies including Hammoudeh *et al.* (2008) who have found asymmetric adjustment of crude oil price differentials between benchmarks. It is interesting to

note that the adjustment is symmetric in the Maya (22°) – Lloyd (22°) pair; this is the only one of our pairs where both crude oils are of the same gravity.

Secondly, the quality differential cannot explain the adjustment dynamics fully, since crudes paired first with Maya (22°) and then with Lloyd (22°) do not show any similarity given by the adjustment coefficients, even though these two heavy crudes have the same gravity. For instance, the Dubai (32°) – Maya (22°) and the Dubai (32°) – Lloyd (22°) pairs adjust differently following a disturbance. This suggests that although the quality differentials are reflected in the long-run price differentials, they do not drive the dynamics of adjustment strongly, as implied by Hammoudeh *et al.*'s (2008) analysis. We do find however, that the adjustment coefficients tend to be higher for pairs made up of two light crudes which are better substitutes, compared to the adjustment coefficients of light-heavy pairs.

Thirdly, the speed of adjustment shown by the benchmarks is not representative of the speed of adjustment shown by other crudes, even if they are of similar quality to the benchmarks in question. In fact, we find that there is no particular pattern within the group consisting of pairs denoted “light-light”, or indeed the “light-medium”, “light-heavy” and “heavy-heavy” groups. The implication is that it is not feasible to draw conclusions about the relationships between different types crudes based on the benchmarks in these groups. These results are interesting because most recent studies, with the exception of Fattouh (2010), have focused on the benchmarks alone on the basis that these crudes lead the prices in their respective groups.

Fourthly, we have found slower adjustment to take place between the crude oil pairs using the M-TAR model in comparison to those estimated by Hammoudeh *et al.* (2008); this is true for the four benchmark pairs, for which comparison is possible. These pairs are WTI (40°) – Brent (38°), WTI (40°) – Dubai (32°), Brent (38°) – Dubai (22°) and WTI (40°) – Maya (22°). This is

an unexpected result because previous studies have found that the markets become better connected with time due to development of futures markets (Ripple and Williamovski, 1995). Greater readiness for accepting heavier crudes as a result of investment in refining technology could also encourage trading and result in increased adjustment coefficients; however we do not find evidence of this in our results.

In order to analyse the short run dynamics alongside the long run equilibrium relationship between the pairs of crude oil prices, we estimate an Error Correction Model (ECM). The ECM was run on all twenty one price pairs. Lag length was chosen according to the SBC. The results are reported in full in Tables 5a, b and c. Besides the long run and short run adjustment dynamics of crude oil prices, we have also tested the pairs for Granger-causality.

[Table 5 a,b,c, about here]

We begin with the evidence of Granger-Causality in our sample of 21 pairs. Bi-directional Granger-causality was found in 13 pairs which included crudes of similar quality as well as crudes of different quality. This provides evidence for inter-connectedness of global market where prices of all crudes both carry and reflect information about the market irrespective of quality differentials. In the remaining 8 pairs, Granger-causality was found for the relatively heavier oils which are influenced by the behaviour of the relatively lighter oil in the pair, but not vice versa. In general, no clear pattern emerges from the results for individual pairs. However, it is worth noting that WTI (40°) is the only crude in our sample which has shown bidirectional Granger-causality with every crude in our dataset. This is an interesting result which means that WTI (40°) may still find itself at the centre of price-making despite physical delivery problems, lack of confidence from investors and anomalies in its pricing since 2007 (Hammoudeh *et al.*, 2008).

We now turn to evidence for the long run dynamics in our dataset and the data in the second and third rows of Tables 5a, b and c. The figures in the second row show the adjustment of each of the crudes when the spread is widening towards the equilibrium. The figures in the third row tell us how the prices adjust when the spread is narrowing towards the equilibrium. The ECM results for Maya (22°) – Lloyd (22°) pair were removed as the pair adjusts symmetrically and the use of an asymmetric ECM is therefore not warranted. That leaves us with 20 sets of results for long run asymmetric adjustment. Following a deviation from equilibrium, in 11 out of 20 pairs only one of the two crudes adjusts to bring the spread back to equilibrium. Notably, in 6 of these pairs the lighter crude takes on the active role compared to 5 pairs where the heavier crude shows adjustment. The active role is taken on by Sahara (44°) in four pairs, by Bonny (37°) in two pairs, by WTI (40°) in two pairs, by Brent (38°) in one pair and by Lloyd (22°) in all six pairs. We can compare our results to those obtained by Hammoudeh *et al.*'s (2008) for the long run adjustment in four benchmark pairs. Our results for three of those pairs reveal interesting changes in the long-run dynamics. In WTI (40°) – Dubai (32°) and Brent (38°) – Dubai (32°) pairs, the medium crude Dubai (32°) shows no adjustment to long run disequilibrium, which is in line with the findings of Hammoudeh *et al.* (2008). However we find that both WTI (40°) and Brent (38°) do not respond to narrowing and widening of the spread within these pairs. For the WTI (40°) – Brent (38°) pair, we find that whilst Brent (38°) still adjusts to a narrowing of the spread with a significant long run parameter (π_2), WTI (40°) evolves independently as μ_2 is insignificant. Equally, we find that whilst WTI (40°) adjusts to a widening of the spread with a significant negative long run parameter (μ_1), Brent (38°) changes freely so π_1 is not significant. This dynamic behaviour shown by lighter benchmarks could be attributed to the use of the more recent data, which may reflect the

developments in the physical or financial crude markets, such as the growing role of non-benchmark crudes.

The short run dynamics revealed by the ECM lead us to conclude that the short run adjustment cannot be linked to quality differentials. The changes in the price of the lighter crude in the pair affect the relatively heavier crude in most cases, with the exception of the WTI (40°) – Bonny (37°) pair, and equally, the changes in the relatively heavier crudes can affect prices of the relatively lighter crudes, although the evidence of this in the case of the Lloyd (22°) – Maya (22°) pair is limited. Interestingly, the lightest crude in our sample, Sahara (44°), fails to respond to past changes in Lloyd (22°), Bonny (37°), and Brent (38°) (crudes ranging from heavy to light), but does respond to past changes in the other three crudes from heavy, medium and light categories - Maya (22°), Dubai (32°) and WTI (40°). Therefore, its reaction to past changes in the other crudes appears to be independent of the levels of liquidity, benchmark status and quality differentials of these crudes.

6. CONCLUSION

In the introduction, we set out the following objectives: to qualify whether the behaviour of the benchmarks is representative of the global oil markets; to confirm whether the asymmetry found in the adjustment of benchmark crudes holds for other crude oils; and to establish whether observed quality characteristics of crudes affect the path of adjustment of crude oil spreads. We employ econometric procedures that are more powerful than recently applied methods, and on a much wider selection of crude oil pairs than previous studies. Our findings can be summarised as follows.

First, all pairs of crude oils were found to be cointegrated. This result is in line with the previous studies by showing that all crudes, irrespective of their properties, are traded in highly integrated markets.

Secondly, we have found that price differentials of twenty out of twenty one pairs adjust asymmetrically following a disturbance. This means that markets respond differently to positive shocks and negative shocks. The type of asymmetry differs from one oil price spread to another.

Thirdly, we have found that within our sample, the speed of adjustment tends to be higher in the pairs which do not include heavy crudes. The implication is that the behaviour of benchmark crudes, which are mostly high quality, are not representative of the non-benchmark crudes.

Fourthly, the results show that the quality differential cannot explain the adjustment dynamics fully. This observation is important because it indicates that there are other factors determining the adjustment of crude oil spreads and opens the door to further analysis of the movement in crude oil spreads.

Finally, the ECM which nests the short and long run dynamics, suggests that no particular pattern has been identified despite a large number of pairs employed in our investigation. Thus conclusions drawn from an investigation involving benchmarks must be treated with care in their application to the wider crude oil market.

REFERENCES

Adelman, M., 1984. "International Oil Agreements", *The Energy Journal* 5(3).

Aroudi, M. And Rault, C., 2008, "On the Influence of Oil Prices on Stock Markets: Evidence from Panel Analysis in GCC Countries" (working paper). *Laboratoire d'Economie d'Orléans, France*. Available online at: http://193.49.79.89/leo/images/espace_perso/rault/WP_1939.pdf

Bachmeier, L.J. and J.M. Griffin, 2006. "Testing for Market Integration: Crude Oil, Coal, and Natural Gas." *Energy Journal* 27: 55-71.

Bentzen, J., 2007. "Does OPEC Influence Crude Oil Prices? Testing For Co-Movements And Causality Between Regional Crude Oil Prices." *Applied Economics*, 39 (11): 1375-1385.

Bloomberg, 2007. "Crude Oil in New York Falls on Increasing Supplies in Oklahoma". Accessed online on 18 June 2011 at:

http://www.bloomberg.com/apps/news?pid=newsarchive&sid=a_T5lNxayQ14&refer=energy

Caner, M. and Hansen, B.E., 2001. Threshold autoregression with a unit root. *Econometrica* 69: 1555–1596.

Chan, K.S. 1993. 'Consistency and Limiting Distribution of the Least Squares Estimator of a Threshold Autoregressive Model', *The Annals of Statistics* 21(1), 520 – 533.

Cook, S. 2003. "Modified Unit Root Tests and Momentum Threshold Autoregressive Processes." *Statistics and Probability Letters*, 64: 83 – 88.

Cook, S. 2004. "A Momentum-Threshold Autoregressive Unit Root Test with Increased Power." *Statistics and Probability Letters*, 67: 307 – 310.

Elliot, G., Rothenberg, T.J., Stock, J.H., 1996. Efficient tests for an autoregressive unit root. *Econometrica* 64 (4): 813–836.

Enders, W. and Granger, C. W. J., 1998. "Unit-Root Tests and Asymmetric Adjustment with an Example Using the Term Structure of Interest Rates", *Journal of Business & Economic Statistics*, 16 (3): 304-311

Enders. W., and PL. Siklos (2001). "Cointegration and threshold adjustment." *Journal of Business and Economic Statistics*, 19:166-176.

Ewing, B.T., and Harter, C.L., 2000. "Co-movements Of Alaska North Slope And UK Brent Crude Oil Prices." *Applied Economics Letters*, 7 (8): 553-558.

Fattouh B., 2010 "The Dynamics Of Crude Oil Price Differentials", *Energy Economics*, 32: 334–342

Gülen, S.G., 1997. "Regionalization In The World Crude Oil Market." *Energy Journal*, 18: 109-126.

Gülen, S.G.,1999. "Regionalization In The World Crude Oil Market: Further Evidence." *Energy Journal* 20: 125-139.

Hamilton, J., 2009. "Understanding Crude Oil Prices". University of California Energy Institute's (UCEI) *Energy Policy and Economics Working Paper Series*, 023.

Hammoudeh, S., Chen L-H and Fattouh B., 2010. "Asymmetric Adjustments in Oil and Metals Markets." *The Energy Journal*, 31 (4): 183-203.

Hammoudeh, S. M., Dibooglu, S., and Aleisa, E. 2004. "Relationships Among U.S. Oil Prices And Oil Industry Equity Indices", *International Review of Economics & Finance*, 13 (4): 427-453

Hammoudeh, S. M., Ewing B.T., and Thompson, M.A. 2008. "Threshold Cointegration Analysis Of Crude Oil Benchmarks." *Energy Journal*, 29 (4): 79-95.

Hammoudeh, S. and Li, H., 2004. "The impact of the Asian crisis on the behavior of US and international petroleum prices". *Energy Economics*, 26(1): 135-160

Hansen, B. E. and Seo B. (2002). "Testing for two regime threshold cointegration in vector-correction models." *Journal of Econometrics*, 110: 293-318.

Johansen, S., 1991. "Cointegration and Hypothesis Testing of Cointegration Vectors in Gaussian Vector Autoregressive Models", *Econometrica*, 59 (6): 1551–1580.

Kleit, A.N., 2001. "Are Regional Oil Markets Growing Closer Together? An Arbitrage Cost Approach." *Energy Journal*, 22: 1–15.

Ng, S., Perron, P., 2001. “Lag Length Selection And The Construction Of Unit Root Test With Good Size And Power”, *Econometrica*, 69: 1519–1554.

Petrucelli, J. D. and Woolford, S. W., 1984. A threshold AR(1) model. *Journal of Applied Probability*. 21: 270-286.

Ripple, R. and Wilamoski, P. 1995. “Is The World Oil Market ‘One Great Pool?’: Revisted.” *OPEC Review* 19 (4): 283-292.

Sauer, D. 1994. “Measuring Economic Markets for Imported Crude Oil.” *Energy Journal* 15 (2): 107-123

Tong, H. (1990). *Non Linear Time Series: A Dynamical System Approach*. Oxford: Oxford University Press.

Weiner, R. J., 1991. ‘Is The World Oil Market ‘One Great Pool?’ *Energy Journal*, 12 (3): 95.

TABLES

TABLE 1 Crude Oil Spreads*								
Pairs (Gravity)	Crude Oil Group	Mean	S.D.	Skew.	Kurt.	C.V.	Min	Max
Sahara (44°) - WTI (40°)	Light-Light	0.89	2.09	-1.23	6.37	2.36	-9.69	9.68
Sahara (44°) – Brent (38°)	Light – Light	0.42	0.85	0.36	3.98	2.03	-2.42	3.41
Sahara (44°) – Bonny (37°)	Light-Light	-0.43	0.88	-0.63	7.34	-2.05	-3.84	5.76
Sahara (44°) – Dubai (32°)	Light - Medium	2.82	2.43	1.05	4.24	0.86	-1.68	14.04
Sahara (44°) – Lloyd (22°)	Light - Heavy	10.56	7.35	1.05	3.42	0.7	-6.06	34.86
Sahara (44°) – Maya (22°)	Light-Heavy	8.35	4.74	0.7	2.38	0.57	1.34	22.83
WTI (40°) – Brent (38°)	Light-Light	1.3	1.94	-0.86	5.5	1.49	-8.23	9.71
WTI (40°) – Bonny (37°)	Light - Light	0.46	2.45	-1.12	5.32	5.34	-11.85	9.71
WTI (40°) – Dubai (32°)	Light-Medium	3.71	3.03	0.63	5.73	0.82	-8.13	17.09
WTI (40°) – Lloyd (22°)	Light – Heavy	11.45	6.87	1.09	3.54	0.6	-3.72	35.08
WTI (40°) – Maya (22°)	Light-Heavy	9.23	4.46	0.83	2.84	0.48	-0.39	23.56
Brent (38°) – Bonny (37°)	Light – Light	-0.84	1.32	-0.57	4.48	-1.56	-5.97	5.78
Brent (38°) – Dubai (32°)	Light-Medium	2.4	2.37	1.02	4.57	0.99	-3.16	14.1
Brent (38°) – Maya (22°)	Light – Heavy	7.93	4.51	0.73	2.46	0.57	0.87	22.19
Brent (38°) – Lloyd (22°)	Light – Heavy	10.14	7.16	1.05	3.46	0.71	-4.57	33.79
Bonny (37°) – Dubai (32°)	Light - Medium	3.25	2.73	0.95	3.31	0.84	-1.03	13.76
Bonny (37°) – Maya (22°)	Light – Heavy	8.77	5.2	0.74	2.56	0.59	1.94	25.77
Bonny (37°) – Lloyd (22°)	Light - Heavy	10.99	7.69	0.96	3.11	0.7	-5.61	35.55
Dubai (32°) – Maya (22°)	Medium-Heavy	5.53	3.23	0.65	2.75	0.59	-2.79	16.82
Dubai (32°) – Lloyd (22°)	Medium-Heavy	7.74	6.01	1.22	4.2	0.78	-5.43	31.21
Maya (22°) – Lloyd (22°)	Heavy-Heavy	2.21	4.48	0.97	5.07	2.02	-11.53	20.42
Prices for individual crude oil streams were obtained from the EIA, expressed in USD per barrel. S.D Denotes Standard Deviation, Skew denotes skewness; Kurt denotes kurtosis; C.V. denotes coefficient of variation; Min denotes minimum value and Max denotes maximum value.								

TABLE 2 Unit Root Tests				
Crude Oil	ADF	ERS	Ng-Perron	
			Mza	MZt
Sahara (44°)	-0.86 (1)	-0.32 (1)	-0.49 (4)	-0.24 (4)
Δ Sahara	-21.59**(0)	--10.16**(2)	-154.92**(2)	-8.80**(2)
WTI (40°)	-0.94 (3)	-0.33 (3)	-0.98 (8)	-0.44 (8)
Δ WTI	-13.85**(2)	-4.46**(8)	-17.99*(8)	-2.97**(8)
Brent (38°)	-0.80 (1)	-0.21 (1)	-0.41 (4)	-0.20 (4)
Δ Brent	-24.06**(0)	-22.75**(0)	-353.70**(0)	-13.30**(0)
Bonny (37°)	-0.84 (1)	-0.30 (1)	-0.18 (6)	-0.09 (6)
Δ Bonny	-22.31**(0)	-10.25**(2)	-152.75**(2)	-8.74**(2)
Dubai (32°)	-0.66 (1)	0.00 (1)	-0.24 (6)	-0.12 (6)
Δ Dubai	-21.92**(0)	-3.93**(8)	-17.68**(8)	--2.96**(8)
Lloyd (22°)	-1.26 (1)	-0.83 (0)	-2.37 (0)	-0.83 (0)
Δ Lloyd	-26.65**(0)	-22.54**(0)	-352.58**(0)	-13.28**(0)
Maya (22°)	-1.18 (3)	-0.66 (3)	-1.17 (6)	-0.50 (6)
Δ Maya	-12.67**(2)	-11.84**(2)	-201.40**(2)	-10.03**(2)
*and ** denotes significance at 5% and 1% level respectively.				
ADF denotes Augmented Dickey Fuller and ERS denotes Elliot Rothenberg and Stock unit root tests.				

Table 3
Cointegration Tests

Pairs	ADF	M-TAR			GLS-M-TAR		
		Φ : $H_0: \rho_1=\rho_2=0$ No cointegration	LB-Q	LB Lag	Φ : $H_0: \rho_1=\rho_2=0$ No cointegration	LB-Q	LB Lag
Sahara (44°) - WTI (40°)	-3.82**	16.73**	5.45 [0.24]	3	15.67**	2.60 [0.63]	2
Sahara (44°) - Brent (38°)	-6.90**	49.89**	6.75 [0.15]	3	27.10**	7.10 [0.13]	5
Sahara (44°) - Bonny (37°)	-5.59**	60.69**	6.57[0.16]	0	34.73**	7.78 [0.10]	2
Sahara (44°) – Dubai (32°)	-6.70**	23.89**	5.36 [0.25]	1	10.64**	4.43 [0.35]	0
Sahara (44°) – Lloyd (22°)	-5.24**	16.42**	4.31 [0.37]	2	25.60**	4.86 [0.30]	0
Sahara (44°) - Maya (22°)	-3.49**	18.15**	4.05 [0.40]	3	15.67**	0.26 [0.99]	4
WTI (40°) - Brent (38°)	-4.84**	12.98**	2.19 [0.70]	2	16.03**	1.73 [0.78]	2
WTI (40°) – Bonny (37°)	-3.27**	12.71**	2.09 [0.72]	4	13.6**	3.95 [0.41]	2
WTI (40°) - Dubai (32°)	-3.70**	9.10**	3.90 [0.42]	3	6.46**	1.15 [0.89]	2
WTI (40°) - Maya (22°)	-3.35**	10.89**	4.12 [0.39]	2	9.93**	0.85 [0.93]	3
WTI (40°) – Lloyd (22°)	-4.74**	12.57**	7.19 [0.13]	2	17.88**	4.18 [0.38]	2
Brent (38°) – Bonny (37°)	-5.98**	42.22**	4.45 [0.35]	3	25.28**	5.45 [0.24]	4
Brent (38°) – Dubai (32°)	-6.00**	21.37**	7.00 [0.14]	2	12.49 **	0.87 [1.21]	4
Brent (38°) – Maya (22°)	-3.73**	8.06**	6.02 [0.20]	2	9.16**	1.99 [0.74]	2
Brent (38°) – Lloyd (22°)	-5.59**	18.19**	5.86 [0.21]	2	26.94**	5.08 [0.28]	0
Bonny (37°) – Dubai (32°)	-6.04**	25.49**	1.76 [0.78]	2	11.67**	4.45 [0.30]	2
Bonny (37°) – Lloyd (22°)	-5.23**	15.42**	4.46 [0.34]	2	25.14**	6.92 [0.14]	1
Bonny (37°) – Maya (22°)	-3.89**	11.79**	0.48 [0.98]	4	12.80**	7.78 [0.10]	3
Dubai (32°) –Maya (22°)	-4.30**	16.82**	1.51 [0.82]	2	17.88**	4.33 [0.36]	0
Dubai (32°) – Lloyd (22°)	-5.41**	16.84**	4.04 [0.40]	2	20.08**	7.40 [0.12]	1
Maya (22°) - Lloyd (22°)	-7.14**	26.26**	5.57 [0.23]	2	41.84**	3.840.43]	0

* and ** denote significance at 5% and 1% level respectively.

Critical values for ADF test: 5%: -1.95, 1%: -2.58 (Dickey-Fuller, 1981)

Critical values for M-TAR test: 5%: 3.21; 1%: 4.85 (Enders and Granger, 1998)

Square parentheses contain p-values for Ljung-Box Q statistic

Table 4 Asymmetric Adjustment					
Pairs	OLS M-TAR H0: $\rho_1 = \rho_2$ (Symmetry)	GLS M-TAR H0: $\rho_1 = \rho_2$ (Symmetry)	GLS τ Threshold	GLS ρ_1 Positive Adjustment	GLS ρ_2 Negative Adjustment
Sahara (44°) - WTI (40°)	4.89 [0.03]	5.20 [0.02]	-0.023	-0.20 [0.00]	-0.09 [0.00]
Sahara (44°) - Brent (38°)	3.64 [0.06]	30.52 [0.00]	0.01382	-0.54 [0.00]	-0.13 [0.00]
Sahara (44°) - Bonny (37°)	53.80 [0.00]	39.72 [0.00]	0.00451	-0.36 [0.00]	-0.05 [0.02]
Sahara (44°) - Dubai (32°)	2.77 [0.10]	4.23 [0.04]	0.01719	-0.10 [0.00]	-0.04 [0.00]
Sahara (44°) - Lloyd (22°)	5.22 [0.02]	4.54 [0.03]	-0.055	-0.10 [0.00]	-0.19 [0.00]
Sahara (44°) - Maya (22°)	21.55 [0.00]	14.94 [0.00]	-0.0093	-0.02 [0.16]	-0.10 [0.00]
WTI (40°) - Dubai (32°)	2.47 [0.12]	2.97 [0.09]	0.0099	-0.09 [0.00]	-0.03 [0.12]
WTI (40°) - Brent (38°)	2.50 [0.11]	6.39 [0.01]	0.02988	-0.25 [0.00]	-0.10 [0.00]
WTI (40°) - Lloyd (22°)	2.65 [0.10]	9.29 [0.00]	-0.0612	-0.07 [0.00]	-0.21 [0.00]
WTI (40°) - Maya (22°)	10.41 [0.00]	9.01 [0.00]	-0.0217	-0.02 [0.11]	-0.09 [0.00]
WTI (40°) - Bonny (37°)	3.20 [0.07]	7.15 [0.01]	-0.0111	-0.05 [0.04]	-0.15 [0.00]
Brent (38°) - Bonny (37°)	13.85 [0.00]	7.14 [0.00]	-0.0205	-0.24 [0.00]	-0.47 [0.00]
Brent (38°) - Dubai (32°)	6.53 [0.01]	6.55 [0.01]	0.02364	-0.21 [0.00]	-0.07 [0.00]
Brent (38°) - Lloyd (22°)	4.94 [0.03]	4.57 [0.03]	-0.038	-0.11 [0.00]	-0.20 [0.00]
Brent (38°) - Maya (22°)	4.47 [0.03]	5.68 [0.02]	0.0255	-0.01 [0.78]	-0.08 [0.00]
Bonny (37°) - Dubai (32°)	13.88 [0.00]	4.75 [0.00]	-0.0108	-0.03 [0.02]	-0.10 [0.00]
Bonny (37°) - Lloyd (22°)	3.36 [0.07]	8.31 [0.00]	-0.0674	-0.09 [0.00]	-0.23 [0.00]
Bonny (37°) - Maya (22°)	4.86 [0.03]	10.47 [0.00]	0.0227	+0.03 [0.23]	-0.06 [0.00]
Dubai (32°) - Lloyd (22°)	4.24 [0.03]	5.13 [0.02]	-0.0608	-0.08 [0.00]	-0.18 [0.00]
Dubai (32°) - Maya (22°)	14.83 [0.00]	15.46 [0.00]	-0.0053	-0.01 [0.34]	-0.10 [0.00]
Maya (22°) - Lloyd (22°)	1.54 [0.22]	1.70 [0.19]	-0.0669	-0.19 [0.00]	Symmetric
The numbers in square parentheses are p-values					

Table 5a Error Correction Model														
	Sahara (44°) - Maya (22°)		Sahara (44°) - Bonny (22°)		Maya (22°) - Lloyd (22°)		WTI (40°) - Maya (22°)		Sahara (44°) - WTI (40°)		WTI (40°) - Brent (38°)		WTI (40°) - Dubai (32°)	
	ΔP_t^S	ΔP_t^M	ΔP_t^S	ΔP_t^B	ΔP_t^M	ΔP_t^L	ΔP_t^W	ΔP_t^M	ΔP_t^S	ΔP_t^W	ΔP_t^W	ΔP_t^{BR}	ΔP_t^W	ΔP_t^D
EC_{t-1}^+	-0.01 [0.52]	0.01 [0.75]	0.26 [0.16]	0.59 [0.00]	0.00 [0.80]	0.13 [0.00]	-0.03 [0.08]	0.01 [0.75]	0.10 [0.00]	0.02 [0.59]	-0.19 [0.00]	0.06 [0.41]	-0.10 [0.00]	-0.02 [0.60]
EC_{t-1}^-	-0.05 [0.09]	0.05 [0.14]	-0.12 [0.26]	-0.07 [0.48]	N/A	N/A	0.05 [0.07]	0.11 [0.00]	0.11 [0.07]	-0.06 [0.38]	-0.03 [0.44]	0.09 [0.02]	-0.01 [0.75]	0.02 [0.30]
ΔP_{t-1}^i	0.03 [0.65]	-0.09 [0.25]	0.14 [0.42]	0.44 [0.01]	0.26 [0.00]	0.33 [0.00]	0.25 [0.00]	0.54 [0.00]	-0.09 [0.14]	0.00 [0.97]	-0.03 [0.59]	0.37 [0.00]	0.19 [0.00]	0.56 [0.00]
ΔP_{t-2}^i	0.01 [0.89]	0.13 [0.10]	0.16 [0.35]	0.33 [0.06]	-0.08 [0.05]	0.19 [0.00]	-0.22 [0.00]	-0.15 [0.03]	0.11 [0.03]	0.31 [0.00]	-0.32 [0.00]	0.00 [0.94]	-0.21 [0.00]	-0.02 [0.64]
ΔP_{t-3}^i	-0.09 [0.16]	-0.03 [0.65]	0.06 [0.71]	0.18 [0.30]	0.16 [0.00]	0.38 [0.00]	0.08 [0.21]	0.05 [0.45]	-	-	-	-	-	-
ΔP_{t-4}^i	-0.08 [0.24]	-0.19 [0.01]	-0.19 [0.22]	-0.11 [0.45]	-	-	-	-	-	-	-	-	-	-
ΔP_{t-1}^j	0.22 [0.00]	0.34 [0.00]	0.11 [0.53]	-0.19 [0.26]	-0.02 [0.55]	-0.13 [0.00]	-0.12 [0.04]	-0.12 [0.06]	0.44 [0.00]	0.16 [0.01]	0.21 [0.00]	-0.10 [0.07]	-0.06 [0.36]	-0.20 [0.00]
ΔP_{t-2}^j	-0.07 [0.23]	-0.18 [0.01]	-0.20 [0.23]	-0.38 [0.03]	-0.01 [0.78]	-0.10 [0.01]	0.17 [0.00]	0.10 [0.11]	-0.10 [0.07]	-0.32 [0.00]	0.26 [0.00]	0.02 [0.70]	0.26 [0.00]	0.08 [0.06]
ΔP_{t-3}^j	0.19 [0.00]	0.19 [0.01]	0.03 [0.88]	0.08 [0.63]	-0.04 [0.11]	-0.00 [0.90]	-0.01 [0.82]	0.07 [0.20]	-	-	-	-	-	-
ΔP_{t-4}^j	-0.04 [0.50]	0.07 [0.28]	0.09 [0.55]	0.03 [0.83]	-	-	-	-	-	-	-	-	-	-
Lung Box Q	0.266 [0.99]	0.317 [0.99]	0.002 [0.99]	0.157 [0.99]	3.31 [0.51]	2.95 [0.57]	1.06 [0.90]	1.77 [0.78]	2.29 [0.68]	3.12 [0.54]	6.73 [0.15]	3.70 [0.45]	1.24 [0.87]	4.18 [0.38]
Granger Causality	5.41 [0.00]	2.74 [0.03]	1.10 [0.36]	2.38 [0.05]	0.89 [0.44]	24.94 [0.00]	4.52 [0.00]	24.27 [0.00]	38.72 [0.00]	16.50 [0.00]	17.56 [0.00]	21.94 [0.00]	13.82 [0.00]	97.21 [0.00]

	Dubai (32°) - Maya (22°)		Dubai (32°) - Lloyd (22°)		Brent (38°) - Dubai (22°)		Sahara (44°) – Brent (38°)		WTI (38°) – Bonny (22°)		Brent (38°) - Bonny (37°)		Brent (38°) - Maya (22°)	
	ΔP_t^D	ΔP_t^M	ΔP_t^D	ΔP_t^S	ΔP_t^{BR}	ΔP_t^W	ΔP_t^{BO}	ΔP_t^{BR}	ΔP_t^{BO}	ΔP_t^{BR}	ΔP_t^M	ΔP_t^L	ΔP_t^{BR}	ΔP_t^D
EC_{t-1}^+	0.02 [0.20]	0.03 [0.20]	0.01 [0.28]	-0.75 [0.00]	-0.08 [0.56]	0.01 [0.75]	0.07 [0.04]	-0.04 [0.57]	0.19 [0.00]	0.06 [0.15]	0.06 [0.13]	0.06 [0.00]	-0.29 [0.00]	-0.06 [0.25]
EC_{t-1}^-	-0.03 [0.19]	0.08 [0.01]	0.02 [0.42]	-0.25 [0.00]	-0.03 [0.67]	-0.01 [0.76]	0.10 [0.02]	0.19 [0.24]	0.62 [0.00]	-0.04 [0.05]	0.03 [0.18]	0.14 [0.00]	-0.08 [0.03]	0.00 [0.78]
ΔP_{t-1}^i	-0.17 [0.00]	-0.14 [0.10]	0.19 [0.00]	-0.10 [0.08]	0.14 [0.04]	0.16 [0.01]	0.46 [0.00]	0.08 [0.36]	0.50 [0.00]	-0.07 [0.22]	0.35 [0.00]	0.45 [0.00]	0.17 [0.00]	0.48 [0.00]
ΔP_{t-2}^i	-0.00 [0.92]	0.12 [0.14]	-0.06 [0.16]	-	-	-0.29 [0.00]	-0.04 [0.46]	0.15 [0.10]	0.36 [0.00]	-0.03 [0.60]	0.18 [0.00]	0.40 [0.00]	0.07 [0.25]	0.18 [0.00]
ΔP_{t-3}^i	-0.01 [0.77]	0.10 [0.19]	0.12 [0.00]	-	-	-	-	0.18 [0.02]	0.21 [0.00]	-0.04 [0.46]	-0.00 [0.87]	0.40 [0.00]	0.04 [0.56]	0.04 [0.35]
ΔP_{t-4}^i	-	-	-	-	-	-	-	-	-	-0.13 [0.03]	-0.08 [0.16]	-	-	-
ΔP_{t-1}^j	0.39 [0.00]	0.35 [0.00]	0.03 [0.18]	0.31 [0.00]	-0.01 [0.10]	0.00 [0.98]	-0.13 [0.03]	0.03 [0.72]	-0.33 [0.00]	0.25 [0.00]	0.01 [0.81]	-0.14 [0.00]	-0.06 [0.37]	-0.26 [0.00]
ΔP_{t-2}^j	-0.06 [0.23]	-0.13 [0.04]	-0.01 [0.56]	-	-	0.27 [0.00]	0.05 [0.36]	-0.16 [0.07]	-0.36 [0.00]	0.02 [0.76]	-0.19 [0.00]	-0.10 [0.00]	-0.01 [0.87]	-0.15 [0.01]
ΔP_{t-3}^j	0.13 [0.01]	0.08 [0.21]	-0.01 [0.83]	-	-	-	-	-0.13 [0.05]	-0.10 [0.09]	0.10 [0.07]	0.16 [0.00]	-0.00 [0.98]	-0.03 [0.70]	0.06 [0.16]
ΔP_{t-4}^j	-	-	-	-	-	-	-	-	-	0.00 [0.98]	-0.00 [0.98]	-	-	-
Lung Box Q	5.13 [0.27]	4.80 [0.31]	3.98 [0.41]	7.06 [0.13]	7.76 [0.10]	3.22 [0.52]	4.21 [0.38]	2.88 [0.58]	0.80 [0.94]	0.14 [0.99]	0.32 [0.99]	4.33 [0.36]	5.24 [0.26]	1.78 [0.78]
Granger Causality	23.05 [0.00]	2.31 [0.08]	0.81 [0.49]	25.22 [0.00]	4.05 [0.04]	13.39 [0.00]	36.19 [0.00]	2.80 [0.04]	14.35 [0.00]	4.59 [0.00]	10.48 [0.00]	32.40 [0.00]	0.37 [0.77]	39.76 [0.00]

	Bonny (37°) - Maya (22°)		Brent (38°) - Lloyd (22°)		WTI (40°) - Lloyd (22°)		Sahara (44°) - Lloyd (22°)		Bonny (37°) - Lloyd (22°)		Sahara (44°) - Dubai (32°)		Bonny (37°) - Dubai (32°)	
	ΔP_t^{BO}	ΔP_t^M	ΔP_t^{BR}	ΔP_t^L	ΔP_t^W	ΔP_t^L	ΔP_t^S	ΔP_t^L	ΔP_t^B	ΔP_t^L	ΔP_t^S	ΔP_t^D	ΔP_t^{BO}	ΔP_t^D
EC_{t-1}^+	-0.01 [0.81]	0.01 [0.85]	-0.00 [0.89]	0.06 [0.00]	0.01 [0.41]	0.05 [0.00]	-0.00 [0.98]	0.06 [0.00]	0.01 [0.68]	0.07 [0.00]	-0.13 [0.04]	-0.04 [0.47]	-0.10 [0.00]	-0.06 [0.03]
EC_{t-1}^-	0.03 [0.15]	-0.04 [0.09]	0.02 [0.38]	0.17 [0.00]	-0.02 [0.34]	0.14 [0.00]	-0.00 [0.92]	0.16 [0.00]	-0.01 [0.54]	0.17 [0.00]	-0.05 [0.05]	-0.02 [0.37]	-0.07 [0.14]	0.03 [0.47]
ΔP_{t-1}^i	0.31 [0.00]	0.26 [0.00]	0.10 [0.01]	0.36 [0.00]	0.17 [0.00]	0.61 [0.00]	0.22 [0.00]	0.38 [0.00]	0.19 [0.00]	-0.13 [0.00]	0.37 [0.00]	0.36 [0.00]	0.28 [0.00]	0.28 [0.00]
ΔP_{t-2}^i	-0.12 [0.08]	-0.02 [0.73]	0.04 [0.30]	0.26 [0.00]	-0.12 [0.00]	0.31 [0.00]	-0.03 [0.44]	0.30 [0.00]	-0.05 [0.20]	-0.09 [0.00]	-0.03 [0.74]	-0.02 [0.78]	-0.11 [0.16]	-0.04 [0.54]
ΔP_{t-3}^i	0.19 [0.00]	0.21 [0.00]	0.05 [0.19]	0.47 [0.00]	0.13 [0.00]	0.65 [0.00]	0.09 [0.03]	0.46 [0.00]	0.09 [0.02]	0.00 [0.99]	-0.12 [0.12]	-0.06 [0.37]	-0.06 [0.35]	-0.02 [0.72]
ΔP_{t-4}^i	0.06 [0.41]	-0.03 [0.59]	-	-	-	-	-	-	-	-	-0.16 [0.04]	-0.11 [0.12]	-	-
ΔP_{t-1}^j	-0.05 [0.52]	-0.03 [0.61]	0.01 [0.76]	-0.14 [0.00]	-0.01 [0.71]	-0.18 [0.00]	0.01 [0.66]	-0.14 [0.00]	0.02 [0.35]	0.32 [0.00]	-0.19 [0.04]	-0.14 [0.06]	-0.11 [0.25]	-0.08 [0.35]
ΔP_{t-2}^j	0.04 [0.58]	-0.06 [0.33]	0.02 [0.37]	-0.09 [0.01]	0.03 [0.21]	-0.23 [0.00]	-0.22 [0.35]	-0.10 [0.00]	-0.01 [0.64]	0.34 [0.00]	0.01 [0.82]	-0.01 [0.90]	0.10 [0.25]	0.01 [0.93]
ΔP_{t-3}^j	-0.03 [0.64]	-0.09 [0.17]	0.04 [0.13]	0.00 [0.79]	-0.05 [0.02]	-0.01 [0.63]	-0.03 [0.15]	0.00 [0.98]	-0.03 [0.26]	0.43 [0.00]	0.27 [0.00]	0.20 [0.01]	0.19 [0.03]	0.14 [0.06]
ΔP_{t-4}^j	-0.17 [0.02]	-0.07 [0.29]	-	-	-	-	-	-	-	-	0.06 [0.47]	0.05 [0.52]	-	-
Lung Box Q	0.33 [0.99]	0.44 [0.98]	3.83 [0.43]	4.74 [0.32]	4.06 [0.40]	1.065 [0.40]	5.32 [0.26]	3.50 [0.48]	4.51 [0.34]	3.51 [0.48]	0.44 [0.98]	0.18 [0.52]	6.72 [0.15]	3.07 [0.55]
Granger Causality	1.64 [0.16]	6.29 [0.00]	1.04 [0.37]	38.02 [0.00]	2.80 [0.04]	68.82 [0.00]	1.07 [0.36]	35.29 [0.00]	0.81 [0.45]	33.13 [0.00]	3.76 [0.00]	7.76 [0.00]	2.64 [0.05]	5.93 [0.00]