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Is there a Global Relationship Across Crude Oil Benchmarks?

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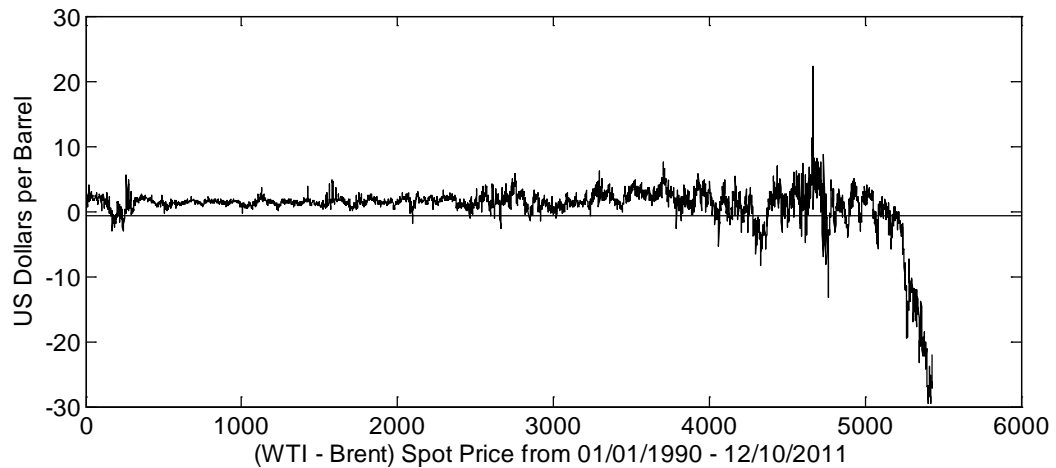
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1. Introduction

“What, exactly, is the price of crude oil?” This question is posed as the title to a recent article from *The Economist* (2011). It reflects a sentiment echoed by traders, index funds, hedgers, bloggers, gasoline consumers, futures exchanges, and policy makers in recent months and stems from the reversal in price premium between the two main global crude oil benchmarks – the WTI and the Brent. Historically the WTI has traded at a premium over the Brent; however, in recent months the Brent has been trading at premium over the WTI, with the premium being larger (in absolute terms) than any of the discounts or premiums ever before. Figure 1 highlights the extent and magnitude of the price premium reversal by depicting the daily WTI–Brent spread from 1990 through 2011. By comparing the spread to the horizontal line it is clear that until the very end of the time period the WTI traded for a premium over the Brent.

The recent reversal in spread is both unprecedented and extreme. The most common explanations for the reversal of relative price positions are: logistical constraints at Cushing, Oklahoma which is the delivery point for the WTI crude oil futures contract; price movements reflecting local rather than global supply and demand; and tension in the Middle East (Fattouh, 2011). The future of the spread between the WTI and the Brent remains unknown, with some industry members believing that the spread will widen, others believing that the spread will reach parity by the summer of 2012 (ICE Futures Europe, 2011), while still others believe that the spread will reach parity in several years (Bank of Canada, 2011). In the meantime, the question remains – “What, exactly, is the price of crude oil?”

Figure 1: Daily Spread between the WTI and Brent Spot Price from 01/01/1990 – 12/10/2011



The purpose of this paper is to empirically examine the relationships and dynamics between the price of the three main crude oil benchmarks, namely the WTI, the Brent, and the Oman. Threshold cointegration is applied to determine whether the pairs of spatially separated spot price series are tied together by a long run relationship and to determine which of the series move to restore the long run relationship. The WTI and the Brent are included in the analysis because they are well known crude oil benchmarks while the Oman is included because it is increasing in popularity and has the potential to become the main crude oil benchmark for Asian markets (Barbajosa, 2010). Due to arbitrage, it is expected that the series are cointegrated; however, there are transaction costs associated with arbitrage that include the cost of transportation, pipeline fees, and tariffs. Differences in quality between crude oil benchmarks must also be taken into account. For periods of time in which the transaction costs plus the quality discount (or minus the quality premium) are less than the gains from arbitrage the price in the spatially separated markets may diverge; however, once the gains from arbitrage exceed

the transaction costs the prices move back toward their long run relationship. Threshold cointegration incorporates the role of transaction costs by allowing the cointegrating relationship to be dormant or modest until the system exceeds a critical upper or lower threshold which triggers the cointegrating relationship and restores the long run relationship.

Threshold cointegration has been used to investigate spatial market integration for many different commodities including: crude oil spreads (Fattouh, 2010); crude oil (Hammoudeh, Ewing & Thompson, 2008); natural gas (Park, Mjelde & Bessler, 2007); heavy oil and petroleum products (Lanza, Manera & Giovannini, 2005); vegetable oil and diesel (Peri & Baldi, 2010); corn and soybeans (Goodwin & Piggott, 2001); dairy products (Awokuse & Wang, 2009); pork (Meyer, 2004); apples (Goetz & von Cramon-Taubadel, 2008) and pepper (Sephton, 2011). One of the primary limitations of previous studies is that most only allow for a single threshold. This eliminates the possibility of a neutral band, termed band-TAR by Balke and Fomby (1997), which is a regime in which arbitrage opportunities exist, but the gains from arbitrage do not outweigh the transaction costs plus the quality discount (or minus the quality premium).

This paper extends previous research on spatial market integration by employing the combined methodology by Gonzalo and Pitarakis (2002) and Seo (2008) that is described in Mann (2012) and Sephton and Mann (2013) to estimate the number of thresholds and their locations using the TAR specification for pairs of spatially separated price series. The first price pairing is the WTI and Brent (WTI-Brent) and the second price pairing is the WTI and Oman (WTI-Oman). The decision to investigate price pairings follows: Park, Mjelde, and Bessler (2007) who investigate the natural gas market in

North America; Sephton (2003) and Goodwin and Piggott (2001) who investigate corn and soybean markets in North Carolina; and Lo and Zivot (2001) who investigate consumer price indices (CPI) across the United States.

This paper builds on previous research by incorporating the Oman and is the first study to investigate which of the crude oil benchmarks adjust to restore the long run equilibrium, if one exists. The results of the threshold cointegration analysis and threshold ECMs provide insight into the question, “What, exactly, is the price of crude oil?” The analysis in this paper includes daily data from January 1, 2008 through October 12, 2012 which includes over six months of data after the reversal in price premium between the WTI and the Brent.

The results of this paper are of particular interest to central banks such as the Bank of Canada who incorporate the price of crude oil into CPI calculations and global growth projections (Bank of Canada, 2011). The reversal in price premium has increased the importance of the decision about which price series to use as the price of crude oil because incorporating the WTI when it should be the Brent or vice versa results in different CPI calculations and global growth projections.

The remainder of this paper is organized as follows. The next section provides a description of the data. The paper proceeds to section 3 which presents the methodological steps used to investigate the relationships between the three leading spatially separated benchmarks for the price of crude oil. Section 4 presents the results in a numerical and graphical format and provides a discussion of the results. The paper concludes by linking the results to the opening question, “What, exactly, is the price of crude oil?”

2. Data

The daily closing spot price is used to analyze the spatial price transmissions between the three main crude oil benchmarks, namely the WTI, the Brent, and the Oman. The WTI is a light¹ sweet² crude oil futures contract traded on the New York Mercantile Exchange (NYMEX) which is part of the Chicago Mercantile Exchange Group (CME Group). The delivery point for the WTI is free on board (FOB) Cushing, Oklahoma (CME Group, 2011). The Brent is a futures contract traded on IntercontinentalExchange (ICE). It is also a light sweet crude oil futures contract, but it is not as light as the WTI. The delivery point for the Brent is FOB Sullom Voe (ICE, 2011). The Oman is a sour crude futures contract traded on the Dubai Mercantile Exchange (DME) and the delivery point is FOB Mina Al Fahal Terminal, Oman (DME, 2011). The annual trade volume in 2010 for the WTI, Brent, and Oman traded on the NYMEX, ICE, and DME are 168,652,141; 100,051,669; and 744,727 contracts, respectively (Acworth, 2010). Additionally, 46,393,671 WTI contracts were traded on the ICE (Acworth, 2010). The contract unit for the WTI, Brent, and Oman is 1,000 US barrels and their trading unit is US dollars per barrel. This means the prices from the three main crude oil benchmarks can be compared directly and do not need to be adjusted to account for exchange rates or units.

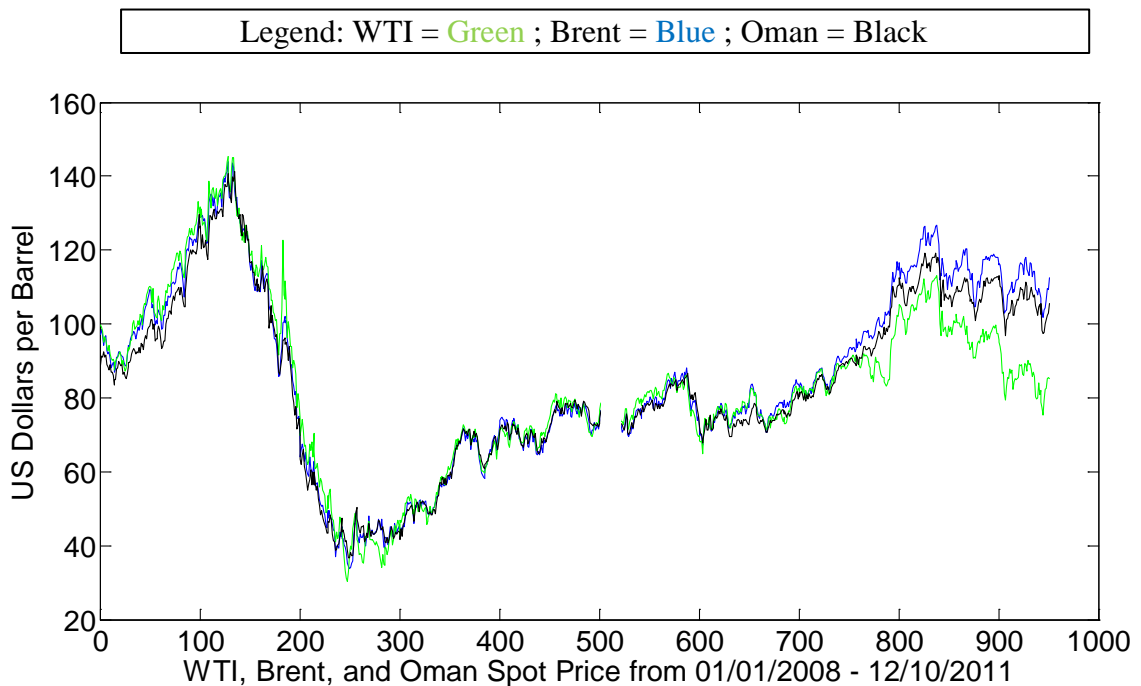
Daily spot price data for the WTI and the Brent are collected from January 1, 2008 through October 12, 2011 from the Commodity Research Bureau Database (CRB) while the data for the Oman is collected from Datastream. The WTI and Brent were listed

¹ Crude oil is classified as light or heavy based on its density. Light crude oil has a low density and yields a larger proportion of higher value products than heavy crude oil using a simple refining process. Heavy crude oil can yield the same proportion of higher value products by using a complex and more costly refining process (Fattouh, 2011).

² Crude oil is classified as sweet if it contains a low sulfur content while crude oil is referred to as sour if it contains a high sulfur content. A high sulfur content is undesirable because refiners must remove the sulfur which requires a heavy investment in the refining process (Fattouh, 2011).

in the 1980s; however, the Oman is the limiting price series when establishing the time period under investigation because it was only listed on the DME in the summer of 2007. The trade volume for the WTI and the Brent are much higher than the Oman; however, the Oman's trade volume has been increasing with time. Each of the three series include a price for Monday through Friday of each week. Any date for which there was not an observation due to local market closings in one or more of the series is deleted. A graph of the spot prices for the WTI, Brent, and Oman during the period of time from January 1, 2008 through October 12, 2011 is presented in Figure 2. For the majority of the period of time under investigation the WTI trades at a premium over the Brent and the Oman. The price premium reverses in 2011 and continues until the end of the data series.

Figure 2: Daily WTI, Brent, and Oman Spot Price from 01/01/2008 – 12/10/2011



The summary statistics for the WTI, Brent, and Oman are presented in Table 1. The average price for the WTI is \$83.26 which is lower than the average price for the Brent which is \$86.02 and the Oman which is \$83.91, while the median price for the WTI is \$81.52 which is higher than the Oman which is \$80.02 and only slightly lower than the Brent which is \$81.68. The range in price is the highest for the WTI followed by the Brent and the Oman while the standard deviation is the highest for the Brent followed by the Oman and the WTI.

Table 1: Summary Statistics for Daily WTI, Brent, and (WTI-Brent) Spot Prices

		01/01/2008 – 12/10/2011		
		WTI	Brent	Oman
US Dollars / Barrel	Mean	83.264	86.023	83.906
	Median	81.520	81.680	80.020
	Minimum	30.280	33.730	36.640
	Maximum	145.310	143.950	141.350
	Std Dev	22.556	24.825	23.092
	CV	0.271	0.289	0.275
	Skewness	0.212	0.057	0.076
	Kurtosis	3.086	2.226	2.433

NOTE: Summary statistics for the level value of the daily WTI, Brent, and Oman spot price. There are no observations on Saturdays or Sundays. Any date for which there is not an observation for all three series is deleted. There are 951 observations in the sample from 01/01/2008 – 12/10/2011.

3. Methodology

This section outlines the methodology used to investigate the relationships between the three leading spatially separated benchmarks for the price of crude oil, namely the WTI, Brent, and Oman. The methodology incorporates threshold cointegration analysis and threshold ECMs to answer two primary research questions, the first being to determine whether the series are tied together by a long run relationship and the second being to determine which of the series move to restore the long run relationship.

There are several independent and sequential steps to answering the two primary research questions. The first step is to determine the order of integration of the WTI, Brent, and Oman. This is necessary because the definition of cointegration stipulates that two $I(d)$ series, Y_t and X_t are cointegrated if they are tied together by a long run relationship such as $Y_t = \delta_1 + \delta_2 X_t + \varepsilon_t$ where ε_t is $I(d-1)$. If the series are not integrated of the same order then, by definition, they are not cointegrated and a TAR specification need not be estimated to answer the primary research questions. Three tests are used to evaluate the order of integration: the ADF unit root test (Dickey and Fuller, 1979; 1981); the GLS ADF unit root test whose power is better than the ADF unit root test (Elliott, Rothenberg & Stock, 1996); and the efficient fractional DF (EFDF) unit root test (Lobato & Velasco, 2007) which allows for fractional alternatives. The critical values for the EFDF unit root test are simulated following Sephton (2009). If the tests fail to reject the null hypothesis that the level series contains a unit root the same tests are performed on the differenced price series to determine whether each price series is first difference stationary. The maximum lag length is determined by rounding up $T^{1/3}$ with the optimal lag length for the ADF and the EFDF unit root tests being determined by the minimization of the AIC.

If the series are found to be integrated of the same order the next step is to estimate the cointegrating regression found in equation (1) after which the combined methodology by Gonzalo and Pitarakis (2002) and Seo (2008) introduced by Mann (2012) and Sephton and Mann (2013) is used to select the threshold locations, the number of thresholds, and to test the null hypothesis of a unit root against the alternative of a stationary threshold process using p-values simulated using a residual-based block

bootstrap. A basic form of the TAR specification with m thresholds is found in equation (2). Details of the selection of the threshold locations and the number of thresholds are described in detail in Mann (2012) and Sephton and Mann (2013).

$$Y_t = \delta_1 + \delta_2 t + \delta_3 X_t + \varepsilon_t \quad (1)$$

where

Y_t is the WTI spot price

X_t is the Brent or the Oman spot price

t is a linear time trend

$$\Delta \hat{\varepsilon}_t = \sum_{j=1}^{m+1} \rho_j I_{j,t} \hat{\varepsilon}_{t-1} + \sum_{k=1}^r \xi_k \Delta \hat{\varepsilon}_{t-k} + \mu_t \quad (2)$$

where

$\hat{\varepsilon}_{t-1}$ is the lagged residual from the cointegrating regression

$I_{j,t}$ from $j = 1$ to $m + 1$ is the Heaviside indicator function:

$$\text{TAR: } I_{j,t} = \begin{cases} 1 & \text{if } q_{t-1} \leq \tau_j \text{ and } 0 \text{ otherwise for } j = 1 \\ 1 & \text{if } \tau_{j-1} < q_{t-1} \leq \tau_j \text{ and } 0 \text{ otherwise for } j = 2, \dots, m \\ 1 & \text{if } q_{t-1} > \tau_j \text{ and } 0 \text{ otherwise for } j = m+1 \end{cases}$$

τ_j is threshold location for the j^{th} threshold such that $\underline{\tau} \leq \tau_1 < \dots < \tau_{m+1} \leq \bar{\tau}$

$\underline{\tau}$ and $\bar{\tau}$ are the lower and upper threshold boundaries

$q_{t-d} = \hat{\varepsilon}_{t-d}$ is the threshold indicator variable

m is the number of thresholds

r is order of the lagged dependent variable

If the null hypothesis of a unit root is not rejected, the answer to the first and second research questions are trivial because this finding would indicate that the series are not tied together by a long run relationship; hence, none of the series adjust to restore the long run equilibrium. In addition to testing the null hypothesis of a unit root jointly across all regimes, the null hypothesis of a unit root is tested for each individual regime. This gives insight into whether a long run equilibrium exists across all regimes or if the phenomena of band-TAR, as introduced by Balke and Fomby (1997), exists. If band-TAR exists, the spot prices are free to diverge until the threshold indicator variable (i.e., residuals from the lagged cointegration regression) is squeezed or stretched beyond a lower or upper threshold.

The second primary research question investigates which of the spot price series adjust to restore the long run equilibrium when the system is out of balance. When the null hypothesis of a unit root is rejected in favour of the alternative, this question is answered by estimating the threshold ECM in equation (3) which allows the error terms ($v_{1,t}$ and $v_{2,t}$) to follow the Glosten, Jagannathan and Runkle (GJR)-GARCH(1,1) specification (1993). The GJR-GARCH(1,1) specification is selected so that the relationship between volatility and price changes can be investigated. The lag length g in the threshold ECM is selected based on the minimization of the BIC with a maximum lag length of $G = 4$. The coefficient estimates on the lagged cointegrating residuals ($\gamma_{1,j}$, and $\gamma_{2,j}$) are used to determine which series adjust to restore the long run equilibrium when the system is out of balance. The test statistics for the parameters are based on heteroscedasticity consistent covariance matrices.

$$\Delta Y_t = \sum_{j=1}^{m+1} \gamma_{1,j} I_{j,t} \hat{\varepsilon}_{t-1} + \sum_{i=1}^g \beta_{1,i} \Delta X_{t-i} + \sum_{i=1}^g \beta_{2,i} \Delta Y_{t-i} + v_{1,t} \quad (3)$$

$$\Delta X_t = \sum_{j=1}^{m+1} \gamma_{2,j} I_{j,t} \hat{\varepsilon}_{t-1} + \sum_{i=1}^g \beta_{3,i} \Delta X_{t-i} + \sum_{i=1}^g \beta_{4,i} \Delta Y_{t-i} + v_{2,t}$$

where

Y_t is the WTI spot price

X_t is the Brent or the Oman spot price

$I_{j,t}$ is the Heaviside indicator function for the TAR specification:

$$I_{j,t} = \begin{cases} 1 & \text{if } q_{t-d} \leq \tau_j \text{ and } 0 \text{ otherwise for } j = 1 \\ 1 & \text{if } \tau_{j-1} < q_{t-d} \leq \tau_j \text{ and } 0 \text{ otherwise for } j = 2, \dots, m \\ 1 & \text{if } q_{t-d} > \tau_j \text{ and } 0 \text{ otherwise for } j = m+1 \end{cases}$$

$q_{t-d} = \hat{\varepsilon}_{t-d}$ is the threshold indicator variable

$\hat{\varepsilon}_{t-1}$ is the lagged residual from the cointegrating regression

d is the delay parameter on the indicator variable

$\gamma_{1,j}$, and $\gamma_{2,j}$ are the adjustment parameters for $j = 1$ through $m+1$

$v_{h,t}$ follows a GJR-GARCH(1,1) process for $h = 1$ and 2

The conditional variance equation for GJR-GARCH(1,1) following standard notation is found in equation (4) and assumes the conditional distribution is normal. The coefficient estimate on the GJR component ($\alpha_{h,2}$) of the GJR-GARCH(1,1) process allows the relationship between volatility and price changes to be investigated (Glosten, Jagannathan & Runkle, 1993). If the null hypothesis that $\alpha_{h,2} = 0$ is rejected in favour of the alternative that $\alpha_{h,2} > 0$ then the volatility and price changes are negatively correlated, a phenomenon that is termed a leverage effect.

$$\sigma_{h,t}^2 = \omega_h + \alpha_{h,1}v_{h,t-1}^2 + \alpha_{h,2}S_{h,t-1}^-v_{h,t-1}^2 + \zeta_h\sigma_{h,t-1}^2 \quad (4)$$

where

$v_{h,t}$ is the residual from the threshold ECM in equation (3)

$\sigma_{h,t}^2$ is the conditional variance

$S_{h,t}^-$ is a dummy variable = 1 if $v_{h,t} < 0$ and zero otherwise

4. Results and Discussion

This section presents the results in the same order that the methods were presented. The first table presents the findings from the three tests used to evaluate the order of integration of the WTI, Brent, and Oman spot price series. The second table and first figure provide the results for the TAR specification estimated using the combined Gonzalo and Pitarakis (2002) and Seo (2008) methodology and the second figure depicts the Heaviside indicator function $(I_{j,t}\hat{\varepsilon}_{t-1})$. The third table presents the results for the threshold ECM. These results are used to determine which of the three series best represents the crude price in North America.

4.1 Order of Integration

The results from the ADF, GLS-ADF, and EFDF unit root tests for the level and differenced price series for the WTI, Brent and Oman are presented in Table 2. The unit root tests on the level series include a constant and trend while the unit root tests on the differenced series include only a constant. All three unit root tests indicate the null

hypothesis, the series contains a unit root, should not be rejected in favour of the alternative hypothesis at five and ten percent levels of significance. The unit root test results from the level series provide evidence that the WTI, Brent, and Oman are integrated of an order greater than zero. All three unit root tests indicate the null hypothesis, the differenced series contains a unit root, should be rejected in favour of the alternative hypothesis for each of the differenced price series at five and ten percent levels of significance, with the sole exception of the ADF unit root test for Δ Oman which rejects the null hypothesis at a 10 percent level of significance. Together, the ADF, GLS ADF and EFDF unit root tests provide evidence that each spot price series is I(1); hence, the dependent and independent variables in the cointegrating regression are integrated of the same order. This finding concurs with Maslyuk and Smyth (2008) who find the Brent and WTI to be I(1).

Table 2: Unit Root Tests for WTI, Brent and Oman Spot Price

	01/01/2008 – 14/03/2011					
	WTI	Δ WTI	Brent	Δ Brent	Oman	Δ Oman
ADF	-1.641	- 31.643 ^{*,**}	-1.048	-29.329 ^{*,**}	-1.072	-30.612 ^{**}
GLS- ADF	-1.356	-7.692 ^{*,**}	-1.129	-3.671 ^{*,**}	-1.270	-1.832 ^{*,**}
EFDF	0.876	14.239 ^{*,**}	1.510	-12.392 ^{*,**}	1.445	-11.513 ^{*,**}

NOTE: Results for three unit root tests with a null hypothesis of a unit root and a maximum lag length of $T^{1/3} = 10$ to whiten the covariance matrix. Critical values for the GLSD ADF test follow Table 1 in Elliott, Rothenberg, and Stock (1996). The alternative hypothesis for the EFDF test allows for fractional alternatives and the critical values are simulated following Sephton (2009). The AIC method is used to select the lag lengths for the ADF and EFDF unit root tests. Significance at $\alpha = 0.05$ and 0.10 denoted by * and **, respectively.

4.2 Results for TAR Specification and Threshold ECM

The results for the m threshold locations (τ_j), $m + 1$ parameters (ρ_j), delay parameter (d), and Seo test statistic are presented in Table 3. The results from Table 3 are depicted graphically in Figure 3 and the Heaviside indicator function ($I_{j,t}\hat{\varepsilon}_{t-1}$) is depicted graphically in Figure 4. The results from the TAR specification provide several interesting insights into the global crude oil benchmarks. The first insight comes from the rejection of the null hypothesis of a unit root in favour of the alternative hypothesis of a stationary threshold process for both the WTI-Brent and Brent-Oman spot price pairings. This indicates that both pairs are cointegrated and are tied together by a long run relationship. The second insight is the tendency to move toward the long run equilibrium does not occur within regimes for which ρ_i is not significant in Table 3. This means that the tendency to move toward the long run equilibrium relationship does not occur in every time period. The regimes in which the tendency to move toward the long run equilibrium does not occur are identified with an **x** in Figures 3 and 4.

For both the WTI-Brent and the WTI-Oman price pairings the bottom regime and the regime that is third from the bottom do not have a tendency to move toward the long run equilibrium. The finding that the regime third from the bottom does not have a tendency to move toward the long run equilibrium confirms the expectation of band-TAR; however, it is somewhat troubling that the bottom regime is not moving toward the long run equilibrium because, unlike band-TAR, the results indicate that arbitrage opportunities exist in which the gains from arbitrage outweigh the transaction costs plus the quality discount (or minus the quality premium). Before becoming too troubled consider Figure 4. The gray shaded area represents the time period in which the price

premium between the WTI and the Brent was reversed. Notice that only observations within the gray shaded area fall into the bottom regime. This means that in the period of time after the reversal in the price premium there is not a tendency for the WTI-Brent or WTI-Oman to move toward the long run equilibrium relationship, but for the period of time before the reversal in the price premium, band-TAR prevailed. This result is comforting because it means that spatial arbitrage theory held for the majority of the time period under investigation.

Given that the series are cointegrated across the entire sample, it is likely that a combination of turmoil in the Middle East and logistical constraints at Cushing, Oklahoma are impeding the ability to arbitrage. One specific culprit is the Seaway pipeline which is currently moving crude oil from the Gulf Coast to Cushing, Oklahoma. The reversal of the Seaway pipeline flow would reduce the stockpile of crude oil in Cushing, Oklahoma and would remove an impediment to arbitrage. It is anticipated that the flow of the Seaway pipeline will be reversed in the late spring of 2012 (Sethuraman, 2012) after which it is likely that the relationship will revert back to band-TAR in which the spot prices are free to diverge until $\hat{\varepsilon}_{t-d}$ is squeezed or stretched beyond a lower or upper threshold. Apart from reverting back to band-TAR, the results do not provide evidence as to whether the reversal in price premium is permanent or whether it will disappear once the impediments to arbitrage subside.

The results from the TAR specification have answered the first primary research question; the WTI-Brent and the WTI-Oman spot price series are tied together by a long run relationship despite there being no tendency for the WTI-Brent or WTI-Oman to move toward the long run equilibrium in the period of time after the reversal in price

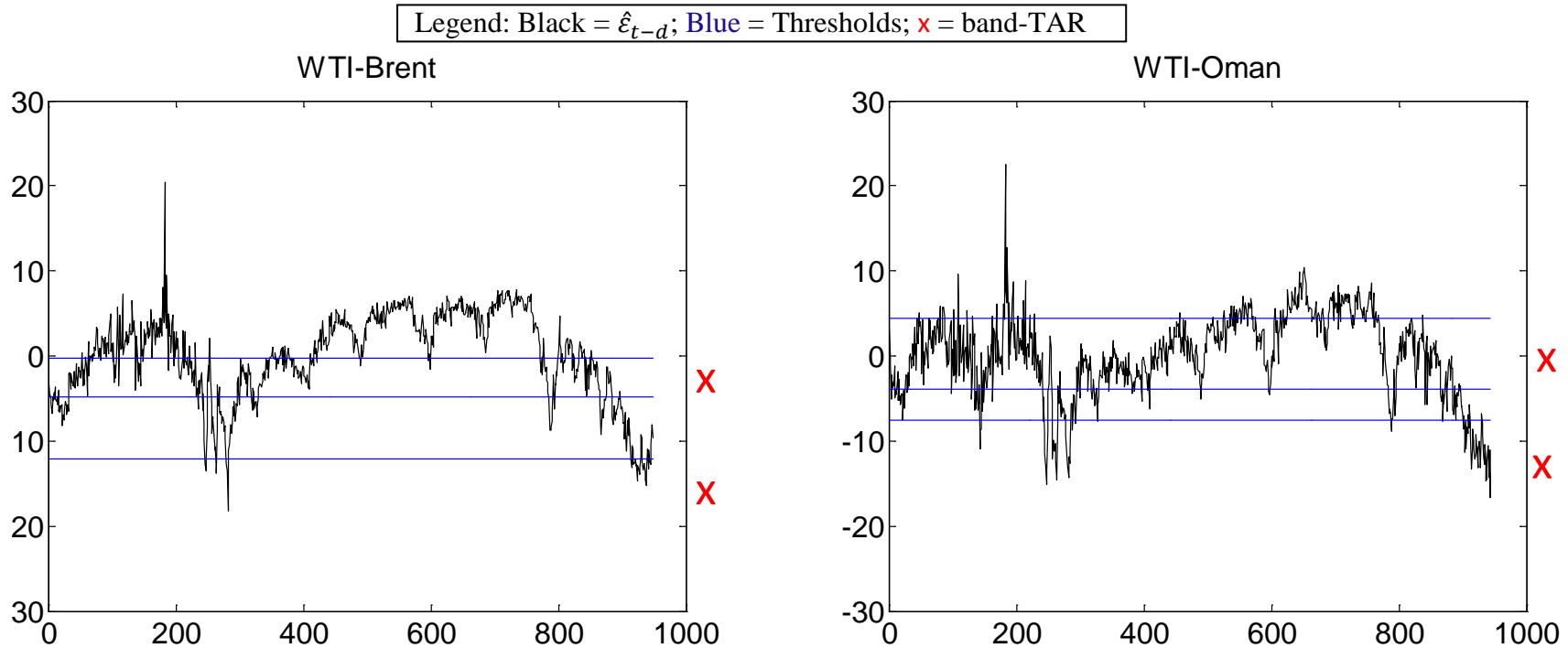
premium. The second primary research question is to determine which of the series move to restore the long run relationship. This research question can be answered using the results from the threshold ECMs presented in Table 4. The threshold ECMs indicate that both the WTI and the Brent spot price series move to restore the long run equilibrium in the WTI-Brent spot price pairing. In the WTI-Oman spot price pairing the WTI moves to restore the long run equilibrium in the top regime while the Oman spot price series moves to restore the long run equilibrium in the second regime from the bottom. Despite the trading volume of WTI and Brent contracts vastly outnumbering the trading volume of Oman contracts, all three series move to restore the long run equilibrium in at least one regime for either or both of the WTI-Brent and WTI-Oman pairing. This indicates that none of the three price series can be considered the global benchmark for the price of crude oil. One additional insight from the threshold ECMs is that the GJR coefficient is significant for both the WTI-Brent and WTI-Oman spot price series. This means that a leverage effect exists; hence, the spot price volatility is higher when the spot prices are decreasing than when they are increasing.

Table 3: Results from TAR Specification using Daily Data from 01/01/2008 – 12/10/2011

WTI-Brent	-12.083, -4.839, -0.258
Thresholds (τ_i)	$\rho_A = -0.004$ $\rho_B = -0.320^*$ $\rho_C = 0.017$ $\rho_D = -0.051^*$
Seo Test Statistic	55.607*
Delay Parameter (d)	3
WTI-Oman	-7.610, -3.859, 4.391
Thresholds (τ_i)	$\rho_A = -0.019$ $\rho_B = -0.367^*$ $\rho_C = -0.016$ $\rho_D = -0.237^*$
Seo Test Statistic	61.094*
Delay Parameter (d)	7

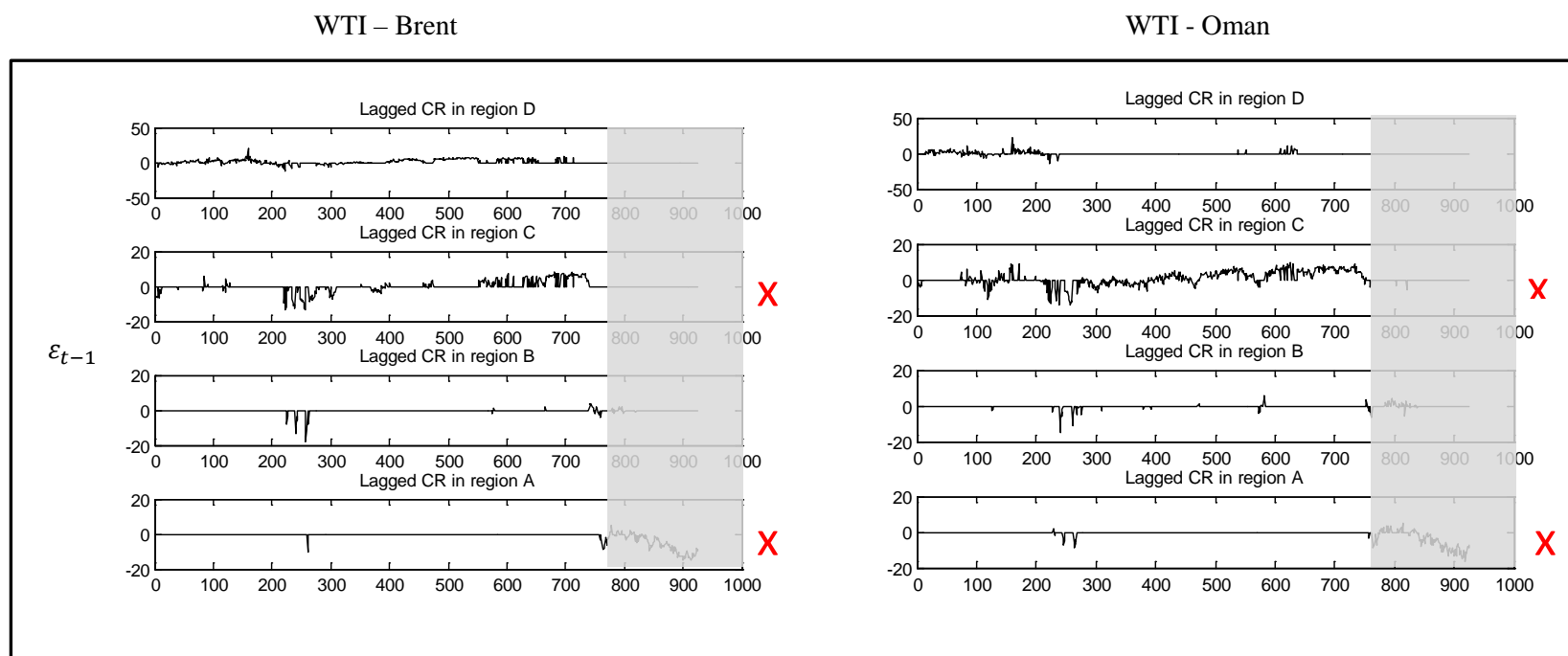
NOTE: Notation follows Mann (2012). Results of TAR specification following the combined Gonzalo and Pitarakis (2002) and Seo (2008) methodology with a maximum of $M=3$ thresholds. The parameter for the region below the bottom threshold is ρ_A , the parameter for the region above the bottom threshold is ρ_B , and so forth. Threshold boundaries set so that 15 percent of observations fall below τ and 15 percent of observations fall above $\bar{\tau}$. The maximum delay parameter is $D = 10$ (i.e., two, five day weeks). The order for the lagged dependent variable in the testing equation is selected using the BIC with a maximum lag length of $R = T^{1/3} = 10$. Critical values follow the residual-based block bootstrap methodology outlined by Seo (2008) with block length 6 and 200 replications under the null. Significance at $\alpha = 0.05$ is denoted by $*$. If the level of significance with 200 replications fell between 0.03 and 0.07 the residual-based block bootstrap was repeated with 800 replications. The results are identical using $\lambda = AIC$ and $\lambda = BIC$ which indicates the results have good properties (Mann 2012; Sephton and Mann 2013).

Figure 3: Graphical Representation of Results from TAR Specification using Daily Data from 01/01/2008 – 12/10/2011 with $\lambda = \text{BIC}$ and $\lambda = \text{AIC}$



NOTE: Notation follows Mann (2012). Results of the TAR specification following the combined Gonzalo and Pitarakis (2002) and Seo (2008) methodology with a maximum of $M = 3$ thresholds. Horizontal lines represent threshold values (τ_j). Red x indicates tendency to move toward the long run equilibrium does not occur within specified regime (i.e., ρ_j is not significant at $\alpha = 0.05$). The parameter for the region below the bottom threshold is ρ_A , the parameter for the region above the bottom threshold is ρ_B , and so forth. Threshold boundaries set so that 15 percent of observations fall below τ_1 and 15 percent of observations fall above τ_3 . The maximum delay parameter is $D = 10$ (i.e., two, five day weeks). The order for the lagged dependent variable in the testing equation is selected using the BIC with a maximum lag length of $R = T^{1/3} = 10$. Critical values follow the residual-based block bootstrap methodology outlined by Seo (2008) with block length 6 and 200 replications under the null. If the level of significance with 200 replications fell between 0.03 and 0.07 the residual-based block bootstrap was repeated with 800 replications.

Figure 4: Graphical Depiction of $I_{j,t}\hat{\varepsilon}_{t-1}$ using Daily Data from 01/01/2008 – 12/10/2011



NOTE: Notation follows Mann (2012). Figure depicts $I_{j,t}\hat{\varepsilon}_{t-1}$ with the Heaviside indicator function ($I_{j,t}$) based on thresholds (τ_j) from TAR specification following the combined Gonzalo and Pitarakis (2002) and Seo (2008) methodology. The lagged cointegrating regression residuals in the region A correspond with $I_{1,t} = 1$ (i.e., $q_{t-d} \leq \tau_1$) and the parameter ρ_A ; the lagged cointegrating regression residuals in the region B correspond with $I_{2,t} = 1$ (i.e., $\tau_1 < q_{t-d} \leq \tau_2$) and the parameter ρ_B ; regions C and D follow. Red **x** indicates the tendency to move toward the long run equilibrium does not occur within specified regime (i.e., ρ_j is not significant at $\alpha = 0.05$). If the level of significance with 200 replications fell between 0.03 and 0.07 the residual-based block bootstrap was repeated with 800 replications.

Table 4: Results from Threshold ECMs for WTI-Brent and WTI-Oman for Data from 01/01/2008 – 12/10/2011

	WTI-Brent		WTI-Oman		
	$Y_t = \text{WTI}_t$	$X_t = \text{Brent}_t$	$Y_t = \text{WTI}_t$	$X_t = \text{Oman}$	
$I_{A,t}\hat{\epsilon}_{t-1}$	-0.008	-0.004	$I_{A,t}\hat{\epsilon}_{t-1}$	-0.005	0.005
$I_{B,t}\hat{\epsilon}_{t-1}$	-0.153*	0.172*	$I_{B,t}\hat{\epsilon}_{t-1}$	-0.13	0.197*
$I_{C,t}\hat{\epsilon}_{t-1}$	0.008	-0.002	$I_{C,t}\hat{\epsilon}_{t-1}$	0.032	0.043*
$I_{D,t}\hat{\epsilon}_{t-1}$	-0.048	0.016	$I_{D,t}\hat{\epsilon}_{t-1}$	-0.218*	-0.037
ΔBrent_{t-1}	N/A	-0.280*	ΔOman_{t-1}	N/A	-0.314*
ΔWTI_{t-1}	N/A	0.382*	ΔWTI_{t-1}	N/A	0.547*
ΔBrent_{t-2}	N/A	-0.125*	ΔOman_{t-2}	N/A	-0.018
ΔWTI_{t-2}	N/A	0.170*	ΔOman_{t-2}	N/A	0.180*
Constant (ω)	0.088	0.025	Constant (ω)	0.049	0.011
ARCH	0.050*	0.041*	ARCH	0.047*	0.071*
GARCH	0.063	0.003	GARCH	0.034	-0.023
GJR	0.903*	0.951*	GJR	0.927*	0.938*

NOTE: Coefficient estimates and significance levels using standard errors based on a heteroscedasticity consistent covariance matrix for threshold ECMs with GJR-GARCH(1,1) errors. Heaviside indicator functions ($I_{j,t}$) are based on thresholds (τ_j) from the TAR specification following the combined Gonzalo and Pitarakis (2002) and Seo (2008) methodology with a maximum of $M = 3$ thresholds. Threshold boundaries set so that 15 percent of observations fall below $\underline{\tau}$ and 15 percent of observations fall above $\bar{\tau}$. The maximum delay parameter is $D = 10$ (i.e., two, five day weeks). Lag length for the threshold ECMs selected using the BIC with a maximum lag length of $G = 4$. Significance at $\alpha = 0.05$ is denoted by *.

5. Concluding Remarks

This paper concludes by providing several remarks regarding the two primary research questions. The conclusion also makes a recommendation on which of the three price series best represents the crude price in North America.

The first primary research question was to determine whether the WTI, Brent, and Oman are tied together by a long run relationship. The combined methodology by Gonzalo and Pitarakis (2002) and Seo (2008) rejects the null hypothesis of a unit root in favour of the alternative of a stationary threshold process for both the WTI-Brent and the WTI-Oman spot price pairings indicating that they are tied together by a long run relationship between January 1, 2008 and October 12, 2011; however, the recent reversal in price premium between the two main

global crude oil benchmarks – the WTI and the Brent has resulted in a period of time in which the WTI-Brent and the WTI-Oman crude price series did not have a tendency to move toward the long run equilibrium relationship. The combined Gonzalo and Pitarakis (2002) and Seo (2008) methodology is crucial in reaching this conclusion because this findings would not have come about if the a single threshold was allowed as in previous studies.

The second primary research question was to determine which of the series move to restore the long run relationship. The results from the threshold ECM indicate that all three series move to restore the long run equilibrium in at least one regime for either or both of the WTI-Brent and WTI-Oman pairings. This means that the threshold ECM does not provide an answer to question posed in the first sentence of this paper, “What, exactly, is the price of crude oil?” (The Economist, 2011). It is recommended that this paper be replicated once the data series contain a larger proportion of observations in which the price premium is reversed. Given the results of the first and second primary research questions it is clear that there is not enough evidence to recommend that either the Brent or Oman represent the crude price series in North America better than the WTI after the reversal in price premium.

The results of this paper provide interesting insights into the global crude oil benchmarks but they do not provide insight into whether the reversal in price premium is permanent or whether it will disappear once impediments to arbitrage in the crude oil market subside. Once again, it is recommended that this paper be replicated once the data series contain a larger proportion of observations after the initial reversal in the price premium. In the meantime, policy makers and regulators are encouraged to find ways to remove impediments to arbitrage in the crude oil market. Although it is not realistic to recommend that policy makers resolve tensions in the Middle East, policy makers should work toward removing logistical constraints at Cushing,

Oklahoma. If the reversal of the direction of flow in the Seaway pipeline does not remove impediments to arbitrage it is recommended that regulators within the CME Group consider adding a second delivery region for the WTI in the Gulf Coast region of the US.

6. References

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