Threshold Cointegration in BRENT crude futures market

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Abstract

This paper, using a threshold vector error-correction (TVECM) model, examines whether BRENT crude spot and futures oil prices are cointegrated. By employing this methodology we are able to evaluate the degree and dynamics of transaction costs resulting from various market imperfections. TVECM model is applied on daily spot and futures oil prices covering the period 1990-2009. The hypothesis we test is to what extent BRENT crude is indeed an integrated oil market in terms of threshold effects and adjustment costs. Our findings support that market follows a gradual integration path. We find that BRENT crude spot and futures are cointegrated, though two regimes are clearly identified. This implies that a threshold exists and it is indeed significant. Adjustment costs in the error correction are present, and they are valid at the typical regime that is the dominant, and as a result should not be ignored.

Keywords: Threshold Cointegration, BRENT crude futures, Non-normality, ML Estimation.

JEL Classifications: C53, E27, E37

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1. Introduction

An issue that has been extensively dealt in the literature concerns the long run relationship between spot and futures in energy markets. Serletis and Banack,1990; Quan, 1992; Schwartz and Szakmary,1994 test whether spot and futures prices for oil are linked in a long-run equilibrium relationship using simple cointegration analysis (see Granger, 1987 and Johansen, 1988). More recent studies, using new cointegration tests, examine whether the market efficiency hypothesis holds in energy futures market (see Silvapulle and Moosa,1999; Peroni and McNown,1998; McAleer and Sequeira, 2004) and also the cost of carry hypothesis (see McAleer and Sequeira, 2004). A drawback of such analysis is that this literature fails to account for possible structural break in the cointegrating vector, though clearly there is record of structural breaks in energy price data. This is so as the traditional cointegration analysis cointegrating vectors are assumed to be time invariant. This means that the long-run relationship between variables is assumed to remain stable over time. However, as pointed out by Hansen (1992), this might or might not be true in the presence of structural breaks. It is possible that if the long-run relationship between the series changed due to a break, then the time-invariant formulation of the cointegrating vector will no longer be appropriate. One early study that has employed a cointegration framework that is robust to structural breaks to examine whether there is a long-run relationship between crude spot and futures oil prices is Cunado and Perez de Gracia (2003). They employ the Gregory and Hansen (1996) residual-based cointegration test to examine whether there is a long-run relationship between various combinations of national oil prices, the world oil price, inflation rates and industrial production for 15 European countries. For most countries Cunado and Perez de Gracia (2003) could only establish a relationship between inflation and national oil prices.

The purpose of this article is to augment Cunado and Perez de Gracia (2003) and examine for the first time in the literature whether BRENT crude oil spot and futures prices are cointegrated employing the novel approach of threshold cointegration by Hansen and Seo (2002). To this end our study departs from the existed literature (see for a review Maslyuk and Smyth, 2009) of traditional cointegration. By doing so, we are able to test whether there have been threshold effects in terms of different underlying regimes. A regime shift would be identified whether it occurs in the intercept, trend or the entire cointegration vector. Our analysis is based on high frequency date monthly BRENT data from 1990 to 2009, which has well-developed spot and futures markets. Moreover, in the first step we use maximum likelihood estimation (MLE) of the threshold model. In the second step we test the presence of a threshold effect. Under the null hypothesis the model transforms to a linear VECM.

Our findings are of interest as they allow accounting for the effects of expectations on the underlying relationship between oil futures and spot.[3] Weak form efficiency in markets would imply that oil futures provide expectations about spot prices *'t'* periods ahead (Chance, 1991). Along these lines Gulen (1998) argues that in case of cointegration oil future would be an unbiased predictor of spot. On the other hand, finding cointegration between oil futures and spot may not necessarily imply

[3] For an alternative explanation see Leuthold et al.(1989), referring to the importance of the cost of storage.

efficiency according to Maslyuk and Smyth (2009). This is because oil market could be inefficient if market participants could take advantage of cointegration to earn risk adjusted excess returns. However, there is not much to suggest that cointegration would lead to risk adjusted excess rates of return (Sanders et al., 2008).[4]

The rest of this article is structured as follows: Section 2 presents the theoretical specification of the threshold vector error correction model for the BRENT crude oil market. Section 3 presents recent developments in the BRENT crude oil market and unit root tests, including potential structural breaks. Section 4 reports the results from the threshold cointegration analysis, whilst section 5 offers some conclusions.

2. The BRENT crude Oil Market

The data used in this paper are daily spot and future prices BRENT crude oil derived from Bloomberg covering the period from January 1990 to November 2009 (5040 data). Future prices relate to the 1st, 2nd and 3rd month ahead rolling delivery contract. The data embraces not only the low volatility period from mid '90s to early 2000 but also the highly volatile environment from the 2nd Iraq War (2003) to the historic high area of $145/barel in July 2008 and the subsequent price collapse following the Lehman Brothers bankruptcy (9/2008).

It is evident that the oil price is governed by considerably different regimes: in the 1980s and 1990s are characterized by a fairly volatile, but horizontal movement, a bubble-type behaviour is present in the 2000s (Askari and Krichene, 2008).

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[4] Note that Granger (1987) argues that cointegration between two prices reflects an inefficient market as there exist a common trend in the long-run, implying predictability. This in turn indicates that one market may be caused by another.

The oil price cycle turned upwards in mid 1990s. The United States economy was strong and the Asian Pacific region was booming. From 1990 to 1997 world oil consumption increased 6.2 million barrels per day. Asian consumption accounted for all but 300,000 barrels per day of that gain and contributed to a price recovery that extended into 1997. Declining Russian production contributed to the price recovery. Between 1990 and 1996 Russian production declined over 5 million barrels per day. The price increases came to a rapid end in 1997 and 1998 when the impact of the economic crisis in Asia was either ignored or severely underestimated by OPEC, while the combination of lower consumption and higher OPEC production sent prices into a downward spiral. Oil prices returned to an upward path in early 1999 mainly due to OPEC production cuts while rebounding global economy sustained upward trend up to late 2000. Since 2001, a slowing US economy and increases in non-OPEC production put downward pressure on prices along with negative consequences following the devastating September 11, 2001, (Williams, 2009).

The price of oil essentially started its long term uptrend in 2003 fuelled by low inventories in the U.S. and other OECD countries, weak US dollar trend, improving U.S. economic and rapidly growing Asian demand. The above coincided with the US military involvement in Iraq. Oil price trend steepened considerably from 2007 to mid 2008, since world demand was growing strongly but production stagnated. Despite occasional dramatic news such as hurricanes in the Gulf of Mexico in September 2005, turmoil in Nigeria in 2006-2008, and ongoing strife in Iraq, global production has been remarkably stable. The big story has been not a dramatic reduction in supply of the kinds summarized but a failure of production to increase between 2005 and 2007. It is noteworthy that in the 2007 World Energy Outlook, the International

Energy Agency was projecting that the Saudis would be pumping 12 million barrels per day by 2010 but finally Saudi production went down rather than up in 2007. On the demand side, worth mentioning is that oil consumption increase in China, which has been growing at a 7% compound annual rate over the 10 last two decades. Chinese consumption in 2007 was 870,000 barrels per day higher in 2007 than it had been in 2005. At the same time, consumption in other regions declined. Consumption in the U.S. in 2007 was 122,000 b/d below its level in 2005; Europe dropped 346,000 and Japan 318,000. Energy Information Administration (EIA) identified China as a net exporter of petroleum up until 1992, and its imports were only up to 800,000 barrels/day in 1998. But by 2007, China's net imports were estimated to be 3.6 million barrels per day, making it the world's third biggest importer and a dominant factor in current world markets. The magnitude of the global growth in petroleum demand in recent years is thus quite remarkable, and although there have been other episodes when global production stagnated over a two-year period, these were inevitably either responses to falling demand during recessions or physical supply disruptions detailed above.

Real economic activity and the disastrous economic and financial sector developments in the world economy in H2 2008 lead to oil price (BRENT crude spot) collapse from the historic high $145.6/barrel in July 7 2008 to $37.9/barrel in January 5, 2009 (Hamilton, 2009).

2.1 Speculation and Efficiency in BRENT Crude Oil Market

Despite oil supply and demand fundamentals, speculation from financial markets seems that it contributed to the aggressive price swings. Speculation in oil markets is regarded as an important determinant of oil prices. A June 2006 US Senate bipartisan report by Chairman Carl Levin (D-MI) and Ranking Member Norm Coleman entitled 'The Role of Market Speculation in Rising Oil and Gas Prices' mentioned that '.. there is substantial evidence supporting the conclusion that the large amount of speculation in the current market has significantly increased prices'. Moreover on the same study is quoted that "Several analysts have estimated that speculative purchases of oil futures have added as much as $20-25 per barrel to the current price of crude oil, thereby pushing up the price of oil from $50 to approximately $70 per barrel."

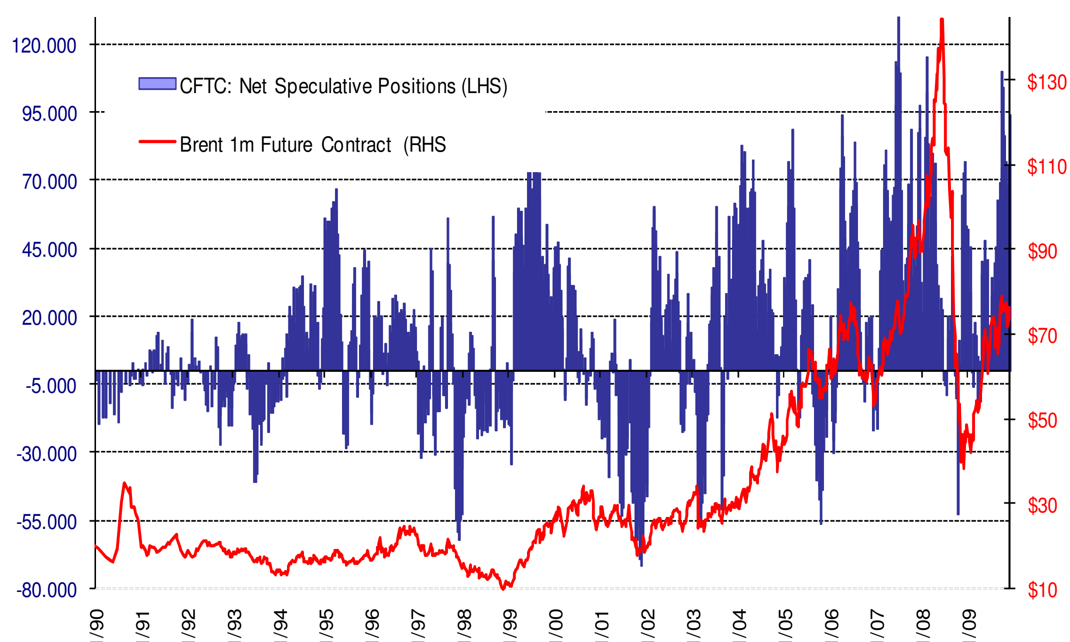
Investment funds poured large amounts of money in the commodity markets and have raised their holdings to $260 billions as of mid 2008 from $13 billions in 2003. During that period the price of crude oil, among other commodities, rose relentlessly, fostering the debate on the role of speculation on oil prices. Empirical evidence on the relevance of speculation is not clear cut. At the end of July 2008 a CFTC report concluded that speculators were not systematically driving oil prices (Cifarelli and Paladino, 2008).

A study from the Japanese Ministry of Economy Trade and Industry (METI) identified that during the second half of 2007, when the physical price of West Texas Intermediate crude averaged $US90 a barrel, market speculation, geopolitical risk and currency factors were responsible for $US30-$US40 of the price. The average WTI "fundamental price," consistent with the underlying supply/demand situation, was around $US60/barrel during the December half-year, according to the paper, citing research for the Institute of Energy Economics in Japan.

An October 2007 Government Accountability Office report, Trends in Energy Derivatives Markets Raise Questions about CFTC's Oversight, determined that futures market speculation could have an upward effect on prices; however, it was hard to quantify the exact totals due to lack of transparency and recordkeeping by the CFTC.

As Figure 1 bellow depicts there are quite a few picks in net long non-commercial (speculative) positions in the CFTC when oil prices when trending upwards since late 2003. The latter is also noted by Weiner (2009) at EIA Annual Conference who cited CFTC (2005) and IMF (2006) studies that do not find any support for any effect from speculation in oil prices.

Figure 1: Net Speculative Positions & Brent Crude 1month Future Contract, 1990-2009



Source: Bloomberg

Efficiency in oil markets states that the futures price is an unbiased predictor of the spot price, in the case of trading in crude oil futures at NYMEX (Gulen, 1998).

A number of earlier studies have addressed the efficiency of the oil futures market (e.g. Crowder and Hamed, 1993, Moosa and Al-Loughani, 1994, and Peroni and McNown, 1998). However, the literature does not provide any clear consensus (Switzer and El-Khoury, 2006).

Abosedra and Baghestani (2004) paper evaluates the predictive accuracy of 1, 3, 6, 9, and 12-month ahead crude oil futures prices for 1991.01–2001.12. In addition to testing for unbiasedness, a *'naïve'* forecasting model is constructed to generate comparable forecasts, as benchmarks. Empirical findings reveal that futures prices and *'naïve'* forecasts are unbiased at all forecast horizons. However, the 1-, and 12-month ahead futures prices are the only forecasts outperforming the naive, suggesting their potential usefulness in policy making.

Switzer and El-Khoury (2006) tests the efficiency of the oil futures during periods of extreme conditional volatility (1985-2005). Using regression approach with monthly data, a daily regression tests, as well as cointegration techniques they find that futures prices are unbiased predictors of future spot prices, consistent with the speculative efficiency hypothesis during the recent episodes of extreme volatility from the onset of the Iraqi war until the formation of the new Iraqi government.

Wu and McCallum (2005) conducted a series of forecasting exercises and compare the performance of models that use oil futures and spot prices in an attempt to find the one that perform best. The aforementioned concluded that oil future prices contain important information about future oil price movements, especially in the short term. They noted though that prediction errors are still substantial and accuracy predicting the future price of oil seems as elusive as ever.

Mehara et al. (2009) study uses a GMDH neural network model with moving average crossover inputs to predict price in the crude oil futures market. The significant profitability of the GMDH model casts doubt on the efficiency of the oil futures market.

3. The Threshold Vector Error Correction Model

Hansen and Seo (2002) examine a two-regime vector error-correction model with a single cointegrating vector and a threshold effect in the error-correction term. Let x_t = (P_{ft}, P_{st}) be a 2-dimensional vector of I(1) time series of future and spot BRENT oil prices respectively with t observations. It is assumed that there exists a long-run relationship between these two time series with a cointegrating vector $\beta = (\beta_0, \beta_1)'$.[5]

The two regime threshold model where the γ is the threshold parameter takes the following form,

$$\Delta x_t = \begin{cases} \begin{pmatrix} A_1^{'} X_{t-1}(\beta) + u_t, z_{t-1}(\beta) \leq \gamma \\ A_2^{'} X_{t-1}(\beta) + u_t, z_{t-1}(\beta) \geq \gamma \end{pmatrix} \end{cases}$$

[5] In the empirical section we relax this assumption as we test for the existence of cointegration.

where $X_{t-1}(\beta)=\begin{pmatrix}1\\ z_{t-1}(\beta)\\ \Delta x_{t-1}\\ \Delta x_{t-2}\\ .\\ .\\ .\\ \Delta x_{t-l}\end{pmatrix}$

, $z_t(\beta)$ denote the I(0) error-correction term, the γ is the threshold parameter, $X_{t-1}(\beta)$ is $kx1$ regressor and A is $kx2$ where $k=2l+2$.[6]

This may alternatively be written as

$$\Delta x_t = A_1' X_{t-1}(\beta) d_{1t}(\beta,\gamma) + A_2' X_{t-1}(\beta) d_{2t}(\beta,\gamma) + u_t$$

where

$$d_{1t}(\beta,\gamma) = 1(z_{t-1}(\beta) \leq \gamma)$$

$$d_{2t}(\beta,\gamma) = 1(z_{t-1}(\beta) \geq \gamma)$$

and 1( ) denotes the indicator function and wt-1 is the error correction term between BRENT future and spot price.

There are two regimes defined by the error correction terms value. As described in Hansen and Seo (2002) the parameters A_1 and A_2 are coefficient matrices and require the dynamics in these regimes. If $0\langle P(w_{t-1}(\beta) \leq \gamma)\langle 1$ this signifies the threshold effect; otherwise the model characterizes linear cointegration.

They also form the following constraint,

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[6] Note that as in Hansen and Seo (2002), the error u_t is assumed to be a vector martingale sequence (MDS) with finite covariance matrix $\Sigma = E(u_t u_t')$. $X_{t-1}(\beta)$ and $z_{t-1}(\beta)$ note variables at generic values of β, whilst z_{t-1} and X_{t-1} note variables evaluated at the true value of the cointegrating vector.

$$\pi_0 \leq P(z_{t-1}(\beta) \leq \gamma) \leq 1 - \pi_0$$

where the trimming parameter is $\pi_0 > 0$.

The algorithm for the TVECM estimation involves procedure in three steps. The first step consists of testing for stationarity and cointegration using ADF and Johnansen (1991) tests, respectively. In the second step, the series that are integrated of order one are used in a standard linear error-correction model. In the final step, the TVECM is estimated for the cointegrated series using the maximum likelihood procedure described Hansen and Seo (2002). For this purpose, the threshold parameter γ is determined using the following selection criterion:

$$\xi(\hat{\gamma}) = \min \log \left(\left| \frac{1}{n} \sum_{t=1}^{n} \hat{\varepsilon}_t(\gamma) \hat{\varepsilon}_t(\gamma)' \right| \right)$$

Once the value of γ that minimises the above is chosen, an additional restriction that each regime should contain at least a prespecified fraction of the total sample (π_0) is imposed on this grid search procedure:

$$\pi_0 \leq P(|z_{t-1}| \leq \gamma) \leq 1 - \pi_0$$

The statistical significance of the threshold parameter γ (the nuisance parameter) contains elements of non-standard inference. Therefore, the p-values are calculated using SupLM test and the bootstrapping techniques proposed by Hansen and Seo (2002).

Moreover, Hansen and Seo (2002) proposed two heteroskedastic-consistent LM test statistics to test whether there is linear cointegration under the null against the alternative threshold cointegration. If there is no threshold under the null, the model reduces to a conventional linear VECM. The first test statistic would be used when the true cointegrating vector is known a priori, and is denoted as:

$$SupLM^0 = \underset{\gamma_L \le \gamma \le \gamma_U}{Sup} LM(\beta_0 \gamma),$$

where β_0 is the known value at fixed β (thereafter, set β_0 at unity), while the second case can be used when the true co-integrating vector is unknown, and the test statistic is given by:

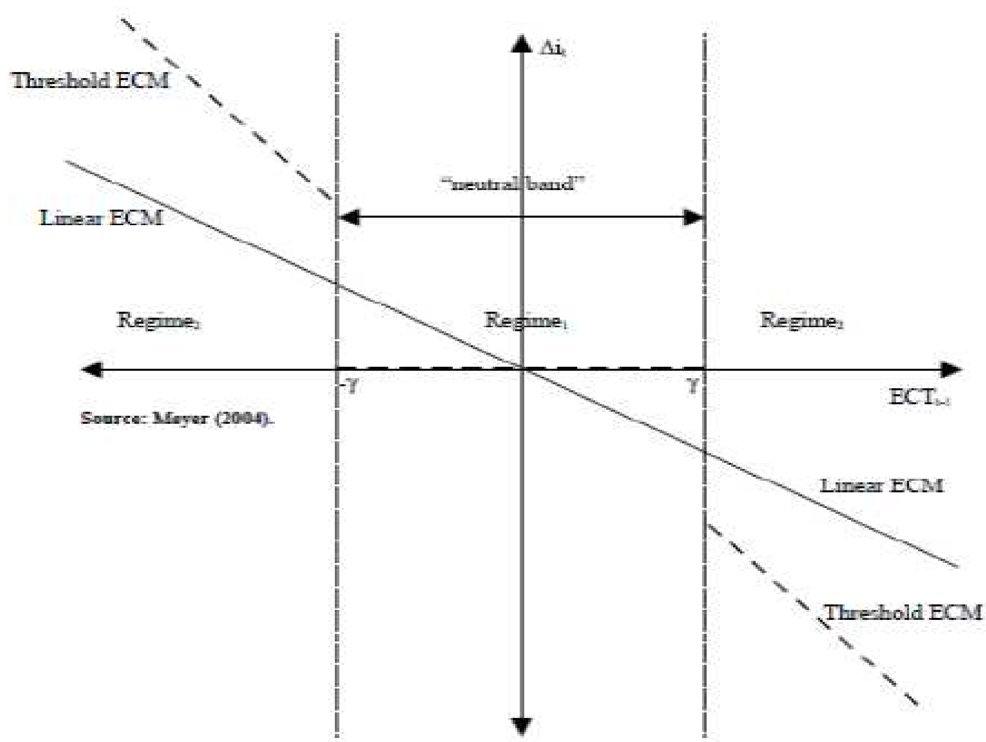
$$SupLM = \underset{\gamma_L \le \gamma \le \gamma_U}{Sup} LM(\tilde{\beta}\gamma),$$

where $\tilde{\beta}$ is the null estimate of β .

In both tests, $[\gamma_L, \gamma_U]$ is the search region so that γ_L is the π_0 percentile of $\tilde{w}_{t-1}$, and γ_0 is the $(1-\pi_0)$ percentile.

In terms of diagrammatic analysis Diagram 1 as in Meyer (2004) depicts the two regimes as identified by $[\gamma_L, \gamma_U]$ thresholds. Moreover, Figure 2 shows the discontinuous adjustment within a TVECM. Horizontal axis plots deviations from the long-run equilibrium between BRENT crude oil future and spot price, which is the error-correction term (ECT). The vertical axis plots BRENT crude futures-spot price adjustment. The linear error correction model predicts that the size of this adjustment would be a linear function of the error-correction term (continuous adjustment). Unlike the linear model, the threshold error-correction model predicts that the linear adjustment takes place only in the second regime, in which the deviation from the long-run equilibrium exceeds the threshold in absolute terms. If the deviations from the long run equilibrium are relatively low (the first regime), then the difference between BRENT crude futures and spot prices do not adjust, implying persistent disequilibrium. The larger is the size of the threshold, the greater is the extent to which the persistent disequilibrium can exist, implying lower degree of integration in the BRENT crude oil market. As a result one would interpret the size of the threshold parameter as a measure of integration in the BRENT crude oil market.

Figure 2: The Threshold VECM.



Source: Meyer (2004).

The TVECM has been applied to various financial and commodity prices but not to BRENT spot and future oil prices. Aslanidis and Kouretas (2005) apply Hansen and

Seo to exchange rates (Greece), with two regimes. They reject the null of no thresholds. Clements and Beatriz Galvao (2003) find strong evidence of non-linearities in the response of US interest rates to the spread (i.e. the difference between long and short rates). Meyer (2004) applies a TVECM to pig prices in Germany and the Netherlands. He finds evidence of non-linearities. Ben Kaabia, Gil and Ameur (2005) apply a TVECM to the Spanish poultry sector, and Ben Kaabia and Gil (2007) apply a similar model to the Spanish lamb sector. Chung, et al (2005) apply the version of Hansen and Seo (2002) to American Depository Receipts (ADRs), with symmetric regimes. They reject the null of no thresholds. Finally, Wu and Chen (2006) apply a symmetric TVECM model to quotations on the FW20 and the underlying WIG20 index on the Warsaw Stock Exchange. They find evidence of threshold non-linearities.

4. Data and empirical results

We use data set that comprises daily data of spot and futures prices for BRENT crude oil. The principal source is Bloomberg, covering the period from January 1990 to November 2009 that is 5040 observations in total. Future prices relate to the 1st, 2nd, and 3rd month ahead rolling delivery contract. These prices are for physical shipment.

Note, that the estimation of TVECM depends crucially on the assumption that the underlying data generating process of our variables is I(1) (Im et al., 2003). We would expect that our variables are not stationary, given that there is an underlying premium in futures. To this end, unit roots tests were carried out, providing evidence of non stationarity. Table 1 reports DF-GLS, KPSS, Phillips-Perron, and Ng-Perron stationarity tests for BRENT oil spot, one-month, two-month and three-month futures. All stationarity tests report evidence that our time series are I(1).

Table 1: Unit Root Tests for Sport Future BRENT Crude Oil

Spot	In levels		In first difference	
	Statistic	Prob.	Statistic	Prob.
DF – GLS	-1.304138		-10.84566	
KPSS	1.439373		0.056488	
Phillips-Perron	-1.546220	0.5085	-11.30253	0.0000
Ng-Perron	-1.35608		-7.24378	
one-month future	In levels		In first difference.	
	Statistic	Prob.	Statistic	Prob.
DF – GLS	-1.336561		-10.16058	
KPSS	1.444019		0.058320	
Phillips-Perron	-1.483971		-10.26955	
Ng-Perron	-1.40448		-7.07630	
two-month futures	In levels		In first difference	
	Statistic	Prob.	Statistic	Prob.
DF - GLS	-1.270979		-10.05009	
KPSS	1.447988		0.061186	
Phillips-Perron	-1.415636	0.5744	-10.04217	0.0000
Ng-Perron	-1.34483			-7.04670
three-month futures	In levels		In first difference	
	Statistic	Prob.	Statistic	Prob.
DF - GLS	-1.204821		-9.956707	
KPSS	1.449846		0.064262	
Phillips-Perron	-1.354288	0.6043	-9.936968	0.0000
Ng-Perron	-1.28195		-7.02012	

Notes. DF – GLS is based on Elliott-Rothenberg-Stock statistic. Critical values for DG-GLS test (see Elliott et al., 1996) are -2.56 and -1.94 at 1% and 5% significance level respectively. Critical values for KPSS test are 0.73 and 0.46 at 1% and 5% significance level respectively, whilst for Ng-Perros test are -2.58 and -1.98 at 1% and 5% significance level respectively.

Given the above evidence of our series being first-difference stationary next we test for the existence of threshold effects and two-regime cointegration vector.

4.1 The TVECM findings

Following Hansen and Seo (2002), we use maximum likelihood estimation (MLE) of the following threshold model:

$$\begin{pmatrix} \Delta P_{ft} \\ \Delta P_{st} \end{pmatrix} = \mu_1 - \beta_1 z_{t-1} - \Gamma_1 \begin{pmatrix} \Delta P_{ft} \\ \Delta P_{st} \end{pmatrix} + u_{1t}, v_{t-1} \leq \gamma$$

$$\begin{pmatrix} \Delta P_{ft} \\ \Delta P_{st} \end{pmatrix} = \mu_2 - \beta_2 z_{t-1} - \Gamma_2 \begin{pmatrix} \Delta P_{ft} \\ \Delta P_{st} \end{pmatrix} + u_{2t}, v_{t-1} \rangle \gamma$$

In terms of our empirical findings we have three set of results: for the BRENT one-month future, for the BRENT two-month futures, and finally for the BRENT three-month futures. First, we present the findings for the BRENT one-month futures.[7]

$$\Delta P_{ft} = \begin{cases} 0.003 \ + 0.041 z_{t-1} - 0.34 \Delta P_{ft-1} + 0.33 \Delta P_{st-1} + u_{1t} \\ (0.02) \quad (0.012) \qquad (0.07) \qquad (0.07) \end{cases}, z_{t-1} \leq 0.73$$

$$\Delta P_{ft} = \begin{cases} -0.08 \ - 0.06 z_{t-1} - 0.14 \Delta P_{ft-1} + 0.07 \Delta P_{st-1} + u_{1t} \\ (0.14) \quad (0.16) \qquad (0.11) \qquad (0.13) \end{cases}, z_{t-1} \rangle 0.73$$

$$\Delta P_{st} = \begin{cases} 0.08 \ + 0.025 z_{t-1} - 0.02 P_{st-1} + 0.05 \Delta P_{ft-1} + u_{1t} \\ (0.03) \quad (0.01) \qquad (0.075) \qquad (0.07) \end{cases}, z_{t-1} \leq 0.73$$

$$\Delta P_{st} = \begin{cases} 0.21 \ - 0.31 z_{t-1} + 0.04 \Delta P_{st-1} - 0.11 \Delta P_{ft-1} + u_{1t} \\ (0.16) \quad (0.18) \qquad (0.12) \qquad (0.13) \end{cases}, z_{t-1} \rangle 0.73$$

The estimated threshold value is γ= 0.73.[8] Next we test the significance of the threshold coefficient. The LM test gave a value of 29.13 with 5% critical value of 23.99 (0.01), whilst the 5% bootstrap critical value is 22.08 (0.02).[9] These tests imply

[7] The Eicker-White standard errors are given in parentheses for the estimated Threshold VAR model. The number of bootstrap replications are set to 1000, while the number of Gridpoints for CI vector to 300.

[8] Appendix presents Figure A1-A3, depicting the threshold parameter γ in relation to the negative log-likelihood.

[9] P-values in parentheses.

that the threshold effect is indeed significant and a simple cointegration analysis would have been misleading.

The first regime takes place when $P_{ft} \leq 0.99 P_{st} + 0.73$, that is the BRENT one-month futures is more than 0.73 percentage points above the BRENT spot price. This is something that one would expect as futures price is mostly above the spot price. This point is verified by the present findings as 82.4 percent of the observations fall within the first regime. So, this is the *'typical'* regime case. Consequently, the first regime obtained from the analysis is the dominant as it contains 82.4 percent of the whole period. Thus, based on this evidence the second regime ($P_{ft} \rangle 0.99 P_{st} + 0.73$) is what we call the *'extreme'* regime, containing 17.6 percent of the observations. Note that the *'extreme'* regime covers a substantial portion of the sample and as such it should not be ignored.

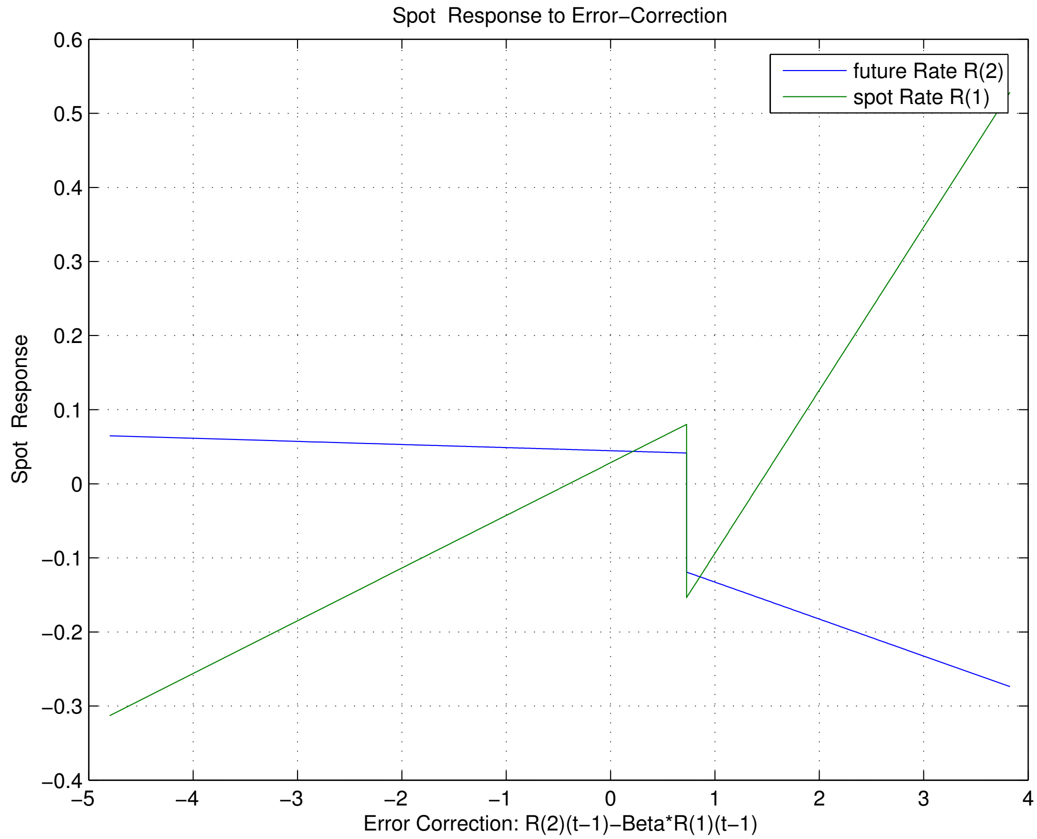
Note that in the case of the *'typical'* regime, there exist significant error-correction effects and dynamics both for ΔP_{ft} and ΔP_{st} equations. On the other hand, for the *'extreme'* regime, the error-correction effects are not significant, whilst also dynamics both for ΔP_{ft} and ΔP_{st} equations are absent. These findings, in turn, imply that that ΔP_{ft} and ΔP_{st} are close to white noise in the second regime, insinuating that P_{ft} and P_{st} are close to driftless random walks.

Note that under the *'typical'* regime, where the BRENT crude one-month oil futures is much above spot price, error correction in terms of magnitude can not be ignored.[10]

[10] Note that one should interpret parameter estimates of the first regime with extreme caution due to small sample properties.

Figure 3 provides diagrammatic evidence of the discontinuous and asymmetric adjustment within the TVECM of the BRENT crude oil market. Horizontal axis plots deviations from the long-run equilibrium, which is the error-correction term (ECT). The vertical axis plots BRENT crude oil futures-spot price adjustment. The linear error correction model predicts that the size of this adjustment would be a linear function of the error-correction term in the case of continuous adjustment. Unlike the linear model, the threshold error-correction model predicts that the linear adjustment takes place in the second regime, in which the deviation from the long-run equilibrium exceeds the threshold in absolute terms. If the deviations from the long run equilibrium are relatively low (the first regime), then the difference between BRENT crude futures and spot prices do not adjust, implying persistent disequilibrium. To this end, the larger is the size of the threshold, the greater is the extent to which the persistent disequilibrium can exist, implying higher adjustment costs and lower degree of integration in the BRENT crude oil market. As a result one would interpret the size of the threshold parameter as a measure of integration in the BRENT crude oil market.

Figure 3: BRENT crude one-month futures and spot responses to error correction term.



Moreover, Figure 3 depicts the error correction effect that is the estimated regression functions of BRENT crude one-month futures rate, *ΔR(2)*, and spot price, *ΔR(1)*, as a function of the error correction term, z_{t-1}. The Figure shows that there is a positive effect of the error correction term on the left hand side of the threshold on the spot rate, while for futures is stable. However, interestingly, on the right hand side, there is clear evidence of asymmetry and break as the effect of the error correction term is positive (negative) for the BRENT crude spot (futures).

For the case of BRENT crude two-month futures with spot results come as follows.[11]

$$\Delta P_{ft} = \begin{cases} 0.011 + 0.03z_{t-1} - 0.26\Delta P_{ft-1} + 0.23\Delta P_{st-1} + u_{1t} \\ (0.01) \quad (0.01) \qquad (0.08) \qquad (0.06) \end{cases}, z_{t-1} \leq 1.59$$

$$\Delta P_{ft} = \begin{cases} -0.16 + 0.17z_{t-1} - 0.16\Delta P_{ft-1} + 0.08\Delta P_{st-1} + u_{1t} \\ (0.12) \quad (0.28) \qquad (0.14) \qquad (0.15) \end{cases}, z_{t-1} \rangle 1.59$$

$$\Delta P_{st} = \begin{cases} 0.038 + 0.02z_{t-1} - 0.26\Delta P_{st-1} + 0.23\Delta P_{ft-1} + u_{1t} \\ (0.01) \quad (0.01) \qquad (0.08) \qquad (0.06) \end{cases}, z_{t-1} \leq 1.59$$

$$\Delta P_{st} = \begin{cases} 0.013 - 0.16z_{t-1} + 0.17\Delta P_{st-1} - 0.26\Delta P_{ft-1} + u_{1t} \\ (0.14) \quad (0.31) \qquad (0.13) \qquad (0.14) \end{cases}, z_{t-1} \rangle 1.59$$

The estimated threshold value is quite large, γ= 1.59, compared to the γ in the case of BRENT crude two-month futures.[12] This implies that the adjustment costs are much higher in the case of BRENT crude two-month futures. The test for the significance of the threshold coefficient LM gave a value of 36.21 with 5% critical value of 18.52 20.59 (0.00), whilst the 5% bootstrap critical value is 22.76 (0.00).[13]

Moreover, the first regime takes place when $P_{ft} \leq P_{st} + 1.59$, that is the BRENT crude two-month futures is more than 1.59 percentage points above the BRENT crude spot price. This is the *'typical'* regime confirmed by the data as 89 percent of the observations fall within this first regime. The second regime captures 10.8 percent of the whole period, still substantial to be ignored. Based on this evidence the second regime ($P_{ft} \rangle P_{st} + 1.59$) is the *'extreme'* regime. Note that in the case of the

[11] The Eicker-White standard errors are given in parentheses for the estimated Threshold VAR model. The number of bootstrap replications are set to 1000, while the number of Gridpoints for CI vector to 300.

[12] Appendix presents Figure A2, depicting the threshold parameter γ in relation to the negative log-likelihood.

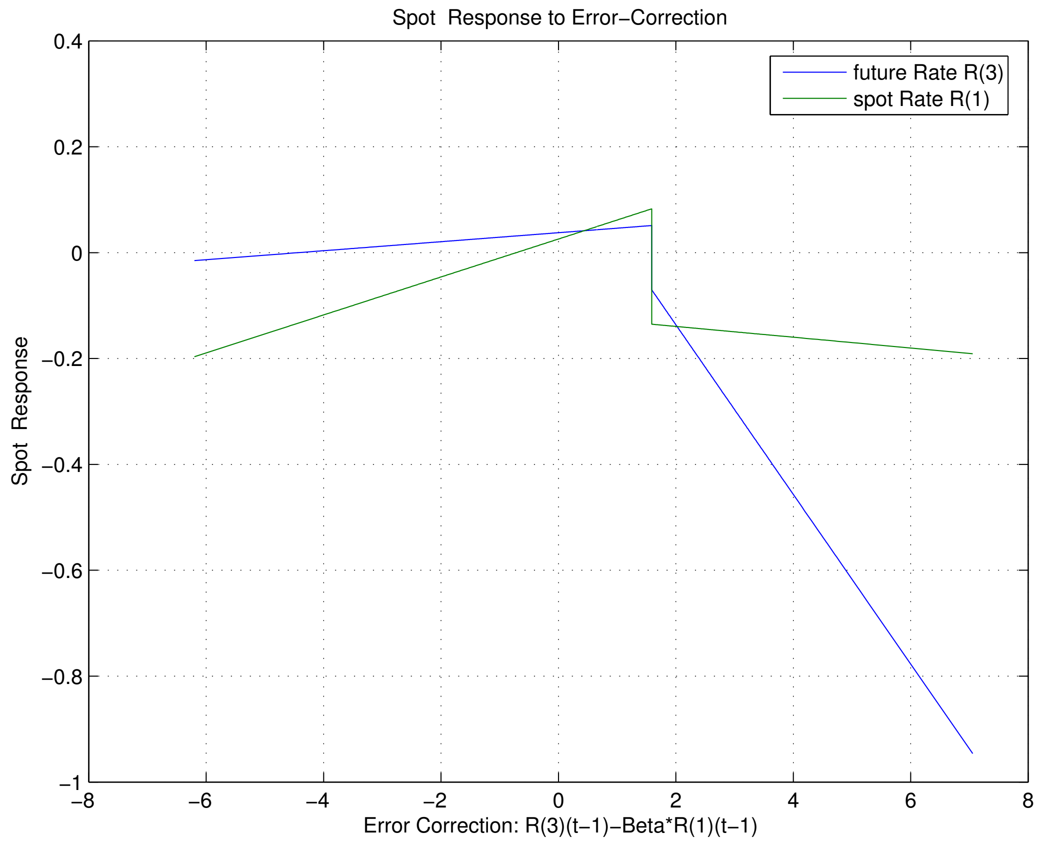
[13] P-values in parentheses.

'typical' regime there are significant error-correction effects and dynamics both for ΔP_{ft} and ΔP_{st}.[14]

Figure 4 bellow depicts the error correction effect that is the estimated regression functions of BRENT crude two-month futures rate, *ΔR(3)*, and spot price, *ΔR(1)*, as a function of the error correction term, z_{t-1}. The Figure shows that there is a positive effect of the error correction term on the left had side of the threshold, whilst the effect becomes negative on the right hand side, in particular for the case of BRENT crude two-month futures.

[14] Note that one should interpret parameter estimates of the first regime with extreme caution due to small sample properties.

Figure 4: BRENT crude two-month futures and spot responses to error correction term.



For the case of BRENT crude three-month futures with spot results come as follows.[15]

$$\Delta P_{ft} = \begin{cases} -0.30 - 0.02z_{t-1} + 0.98\Delta P_{ft-1} - 0.37\Delta P_{st-1} + u_{1t} \\ (0.41) \quad (0.37) \quad (0.39) \quad (0.15) \end{cases}, z_{t-1} \leq 1.02$$

$$\Delta P_{ft} = \begin{cases} 0.89 - 0.44z_{t-1} - 0.2\Delta P_{ft-1} + 0.11\Delta P_{st-1} + u_{1t} \\ (0.64) \quad (0.09) \quad (0.39) \quad (0.9) \end{cases}, z_{t-1} \rangle 1.02$$

$$\Delta P_{st} = \begin{cases} -0.071 + 0.07z_{t-1} + 0.11\Delta P_{st-1} - 0.51\Delta P_{ft-1} + u_{1t} \\ (0.46) \quad (0.03) \quad (0.5) \quad (0.77) \end{cases}, z_{t-1} \leq 1.02$$

$$\Delta P_{st} = \begin{cases} 1.36 - 0.41z_{t-1} - 0.14\Delta P_{st-1} - 0.28\Delta P_{ft-1} + u_{1t} \\ (0.61) \quad (0.75) \quad (0.6) \quad (0.17) \end{cases}, z_{t-1} \rangle 1.02$$

[15] The Eicker-White standard errors are given in parentheses for the estimated Threshold VAR model. The number of bootstrap replications is set to 1000, while the number of Gridpoints for CI vector to 300.

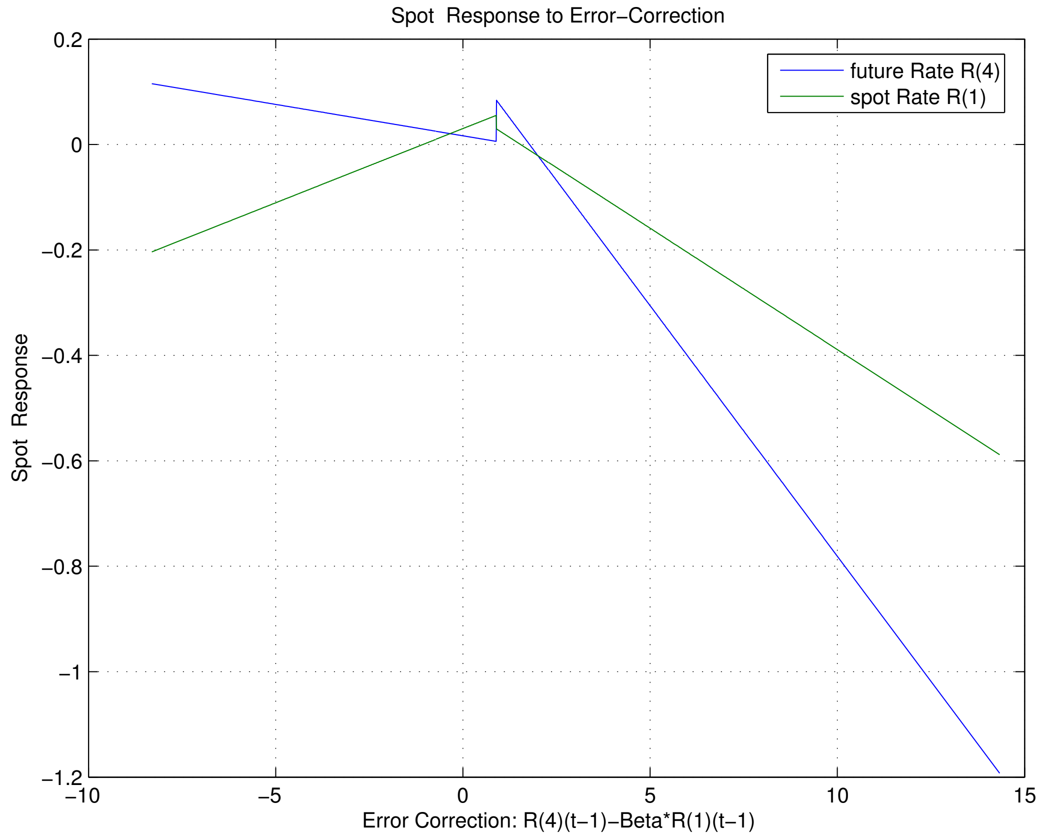
The estimated threshold value is quite large, γ= 1.02, compared to the γ in the case of BRENT crude three-month futures.[16] This implies that the adjustment costs are less than in the two-month futures. The test for the significance of the threshold coefficient LM gave a value of 35.51 with 5% critical value of 21.54 (0.00), whilst the 5% bootstrap critical value is 24.51 (0.00).[17]

Moreover, the first regime takes place when $P_{ft} \leq P_{st} + 1.02$, that is the BRENT crude three-month futures is more than 1.02 percentage points above the BRENT crude spot price. This is the *'typical'* regime confirmed by the data as 74 percent of the observations fall within this first regime. The second regime is much less dominant as it corresponds to 26 percent of the whole period. Based on this evidence the second regime ($P_{ft} \rangle P_{st} + 1.02$) is the *'extreme'* regime. Note that in the case of the *'typical'* regime there are minimal non-significant error-correction effects and dynamics both for ΔP_{ft} and ΔP_{st}.[18]

Figure 5 depicts the error correction effect that is the estimated regression functions of BRENT crude three-month futures rate, *ΔR(4)*, and spot price, *ΔR(1)*, as a function of the error correction term, z_{t-1}. The Figure shows threshold effects and asymmetry as there is a positive (negative) effect of the error correction term on the spot (three-month futures) on the left had side of the threshold, whilst the effect becomes negative for both spot and futures on the right hand side.

[16] Appendix presents Figure A2, depicting the threshold parameter γ in relation to the negative log-likelihood.
[17] P-values are in parentheses.
[18] Note that one should interpret parameter estimates of the first regime with extreme caution due to small sample properties.

Figure 5: BRENT crude three-month futures and spot responses to error correction term.



This evidence shows that the dominant regime is the first (*'typical'* regime), though the *'extreme'* regime is not negligible as above 26 percent of observations fall within this regime. Thus, non-linearities in the cointegration vector may not be ignored for 74 percent of the sample. Once again, therefore, results show that persistent disequilibrium should raise serious concerns. Moreover, regime one describes the situation when BRENT crude oil futures are priced much above spot. One would expect that spot price should be more variable than futures price in the short run as i.e. seasonal factors may temporally increase demand that in turn may decrease inventory levels (Fama and French, 1988). Despite spot and futures price might significantly diverge in the short run, futures price should converge to spot price once the contract expires as both are driven by the same fundamentals. The present results verify this as spot and futures price are threshold cointegrated.[19]

In addition, our analysis by estimating the threshold parameter suggests that the underlying adjustment costs related to deviations between spot prices and future prices is not negligible as it depends on the size of gamma, γ. Many factors can contribute to the adjustment costs that in turn lead to deviations of futures from spot price i.e. thin trading, lags in information transmission, insufficient inventory levels and seasonal patterns of consumption. These factors are, though, reported to impact mostly in the short run.

5. Conclusion

The hypothesis we test is to what extent BRENT crude spot and futures are indeed integrated, insinuating a more efficient and integrated oil market. However, we depart from the literature (Maslyuk and Smyth, 2009) as we opt for a threshold vector error-correction (TVECM) model that allows identifying different regimes, threshold parameters and thus adjustment costs. Our findings support the gradual integration hypothesis. Moreover, we find that BRENT crude spot and future of one, two and three months prices are cointegrated and two regimes are identified. This implies that a threshold exists and it is indeed significant. Thus, adjustment costs in the error correction are present, and they are valid at the typical regime one that is the dominant, and as a result should not be ignored.

[19] The reported cointegration relationship between futures and spot comes in line with Serletis and Banack, 1990; Quan, 1992; Schwartz and Szakmary, 1994, and McAleer and Sequeira, 2004. However, there exist significant threshold effects, being ignored in the literature up to date, that imply a positive relationship between the error correction term and BRENT futures-spot.

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APPENDIX

Figure A1: Concentrated negative log likelihood and threshold gamma, *'γ'*, for BRENT crude one-month futures and spot.

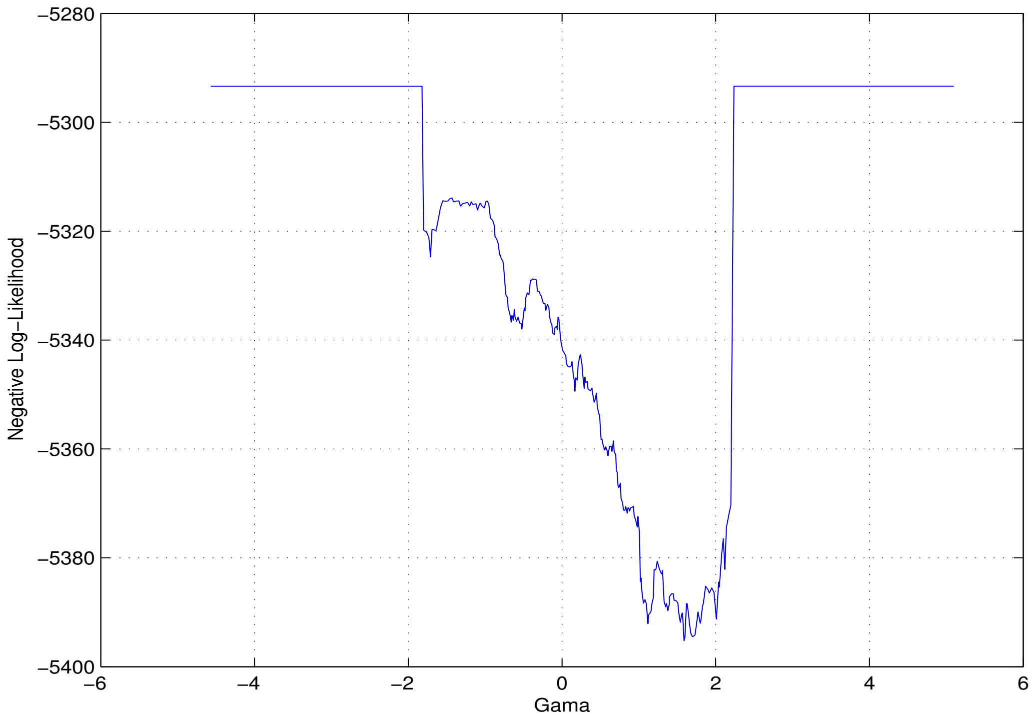

Figure A2: Concentrated negative log likelihood and threshold gamma, *'γ'*, for BRENT crude two-month futures and spot.

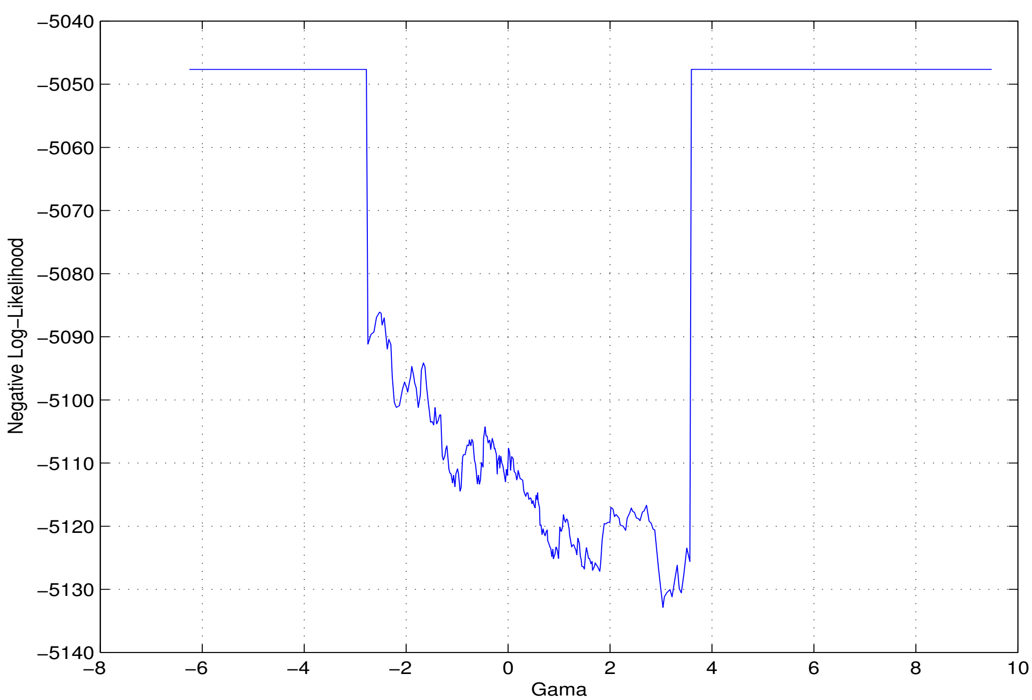

Figure A3: Concentrated negative log likelihood and threshold gamma, *'γ'*, for BRENT crude three-month futures and spot.