Degree of Integration between Brent Oil Spot and Futures Markets: Intraday Evidence*

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We investigate the integration of spot and futures markets using matched, intraday data to avoid non-synchronous trading issues. Our evidence indicates highly integration spot and futures markets. Shocks are transmitted between oil markets fully and quickly, usually within minutes.

Keywords: Natural Resources, Exhaustible Resources, Energy, Futures Markets, Brent, Integration of Markets, Co-integration, Granger Causality

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1. Introduction

The degree to which spot and futures oil markets are integrated is an important issue to producers and consumers of oil, as well as speculators, arbitragers and policy makers. Well-integrated spot and futures markets indicate that oil markets function well in discovering new, important and relevant information necessary for pricing and transferring this information, quickly and fully, to all other related markets. Similarly, closely integrated oil markets will perform the risk transfer function that is essential to hedgers, speculators and arbitrageurs.

Previous research in this area starting with Garbade and Silber (1983) shows that spot and futures markets tend to be well integrated, thereby performing the work of efficient pricing and transferring of risk. Subsequent work focusing on oil spot and futures generally confirms and extends these early findings. Schwartz and Szakmary (1994) find that oil futures markets perform the role of price discovery well. Silvapulle and Moosa (1999) add that both spot and futures market react to new information simultaneously and there is no reliable stable lead-lag relations between spot and futures markets. Moosa (2002) extends and confirms previous work by employing the systems of equations approach. Bekiros and Diks (2008) employ dynamic linear and non-linear effects and confirm that stable lead-lag relations do not exist between spot and futures markets and that both spot and futures markets are equally important in price discovery.

An important limitation of the current literature analyzing integration of different oil markets and possible lead-lag relations between different spot benchmarks or spot and futures prices however is that data frequency is limited to daily intervals. Given the geographic dispersion of oil markets around the globe, and almost continuous around the clock trading, daily data presents a critically important limitation. Daily data does not match different benchmarks in real time and it does not allow adjustment for differences in time zones between different oil markets. For instance, important oil-related news such as oil production or oil inventories that arrive in late afternoon in the U.S. that would affect West Texas Intermediate market today, would appear to be reflected in Brent benchmark or Dubai benchmark with a day delay due to differences in time zones. Second, daily interval results in nonsynchronous closing times. For instance, NYMEX pit trading closes at 2:30PM New York time, while ICE Brent trades electronically more than twenty-two hours a day from 12:55AM to 11PM.

Our main innovation in this paper is to introduce intraday, time-stamped oil futures data. Using exact trading times, we can match the announcement of spot price data to the exact futures trading times.[1] Consequently, using intraday oil futures data, we are able to bypass difficulties arising timing mismatches between spot and futures data as well as issues that arise from differences in time zones.

Using more accurate intraday oil futures data, we extend the literature. Our evidence confirms the previous findings that spot and futures markets are highly integrated. Economic shocks that arise in spot markets are typically transmitted to the futures markets approximately one for one, within the day. Similarly, economic shocks arriving in futures markets are transmitted to spot markets one for one. We also find that lead-lag relations between spot and futures markets do not tend to be stable. Overall, our findings indicate well-functioning, well-integrated spot and futures oil markets that perform the functions of both price discovery and risk transfer quite well.

Our paper is organized as follows. In Section 2, we discuss the conceptual basis for the integration of spot and futures oil markets. Section 3 presents our intraday data and discusses sample characteristics. Empirical results are shown in Section 4. Section 5 concludes.

2. Integration of Spot and Futures Markets

We begin our analysis of the relation between spot and futures prices for oil with the cost-of-carry relation, which states that the price of a given cargo of crude oil for future delivery is based on the current spot price of the same quality and stream of crude oil and the physical cost of buying and storing that oil until the future delivery date. In addition, the net benefit of having ownership of the crude during that time period (convenience yield), and the interest rate

[1] We use local London time to match spot and futures and also adjust for differences arising Greenwich Mean Time (GMT) and British Summer Time (BST).

prevailing between the original purchase date and future delivery date must be taken into account. This relation, known as the "cost of carry" relation between spot and futures prices, has been well-documented empirically in the economic academic literature.

Thus, the futures price of oil is based on the spot price of oil plus a term called cost-of-carry. This relation is based on economic forces and enforced by market discipline. The cost of carry relation tells us that spot and futures prices cannot be independent from each other. If oil futures prices diverge too much from spot oil prices, there would be economic forces to bring them back in line. If the cost of carry relation holds, oil futures are said to be trading at full carry.

Full carry is enforced by arbitrage. For instance, if oil futures prices were to rise significantly above the cost-of-carry, there would be incentives on the part of market participants to sell the oil futures contracts, buy the spot oil, carry the spot oil to maturity and deliver it against the futures contract, thereby profiting from the price differential. Similarly, if oil futures prices were to fall below the cost-of-carry, there would be incentives on the part of market participants to sell the spot oil, buy the futures, and use the futures to replace the oil sold, at maturity. Different actors in the market place are likely to have different storage costs as well as different convenience yields from having physical oil. Thus, how tight this arbitrage relation keeps spot and futures oil prices together is ultimately an empirical question.[2] In general, this literature

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[2] *See, for example,* K. D. Garbade and W. L. Silber, "Price Movements and Price Discovery in Futures and Cash Markets," *Review of Economics and Statistics* Vol. 65, No. 2 (May 1983), J. Quan, "Two-Step Testing Procedure for Price Discovery Role of Futures Prices," *Journal of Futures Markets* Vol. 12, No. 2 (1992), T. V. Schwarz and A. C Szakmary, "Price Discovery in Petroleum Markets: Arbitrage, Cointegration, and the Time Interval of Analysis," *Journal of Futures Markets* Vol. 14, No. 2 (1994), P. Silvapulle and I. A. Moosa, "The Relationship Between Spot and Futures Prices: Evidence from the Crude Oil Market," *Journal of Futures Markets* Vol. 19, No. 2 (1999), I. A. Moosa, "Price Discovery and Risk Transfer in the Crude Oil Futures Market: Some Structural Time Series Evidence," *Economic Notes* Vol. 31, No. 1 (2002), S. Hammoudeh, H. Li, and B. Jeon, "Causality and Volatility Spillovers Among Petroleum Prices of WTI, Gasoline and Heating Oil in Different Locations," *North American Journal of Economics and Finance* Vol. 14 (2003), S. Bekiros and C. G. H. Diks, "The Relationship between Crude Oil Spot and Futures Prices: Cointegration, Linear and Nonlinear Causality," *Energy Economics* Vol. 30 (2008), B.-N. Huang, C. W. Yang, and M. J. Hwang, "The Dynamics of a Nonlinear Relationship between Crude Oil Spot and Futures Prices: A Multivariate Threshold Regression Approach," *Energy Economics* Vol. 31 (2009), C.-C. Lee and J.-H. Zeng, "Revisiting the Relationship between Spot and Futures Oil Prices: Evidence from Quantile Cointegrating Regression," *Energy Economics* Vol. 33 (2011), X. Jin, S. Lin, and M. Tamvakis, "Volatility Transmissions and Volatility Impulse Response Functions in Crude Oil Markets," *Energy Economics* Vol. 34 (2012), R. K. Kaufmann and B. Ullman, "Oil Prices, Speculation and Fundamentals: Interpreting Causal Relations among Spot and Futures Prices," *Energy Economics* Vol. 31 (2009), Liu, Schultz, and Swieringa (2014), *op. cit.*, F.-B. Lu, Y.-M. Hong, S.-Y. Wang, K.-K. Lai, and J. Liu, "Time-Varying Granger Causality Tests for Applications in Global Crude Oil Markets," *Energy Economics* Vol. 42 (2014), K. Shrestha, "Price Discovery in Energy Markets," *Energy Risk* (2014

shows that spot and futures prices are integrated, arbitrage enforces the cost-of-carry, and it provides evidence on bidirectional causality between spot and futures markets.

The cost of carry relation can be written mathematically,

Futures Price (t, T) = Spot Price (t) + Cost of Carry (t,T),

where t is current date, T is the maturity date of the futures contract, and,

Cost of Carry (t,T)= Cost of storage (t,T) + (Interest rate (t,T) * Spot(t) – Convenience Yield(t,T)

The cost of carry equation provides the structural (causal) connection between spot and futures oil prices based on economic fundamentals. If spot prices are distorted say by $1 through an economic shock, and assuming that the $1 shock does not affect the cost-of-carry amount in a material way, then the cost of carry relation indicates that on average, the $1 shock would be transmitted one-for-one to the futures prices.

If Spot price2 = Spot price1 + $1 ⇒

Futures price2 = Spot Price2 + Cost of Carry = Spot price1 + $1 + Cost of Carry

⇒ Futures price2= Futures price1 + $1

Thus, if cost of carry relation holds, then it is mathematically true that any shocks in spot prices would be transmitted approximately one for one to the futures prices. Even if the cost of carry relation does not hold exactly, but the shocks in spot prices are independent of the carrying costs, then it is again mathematically true that any shocks would be transmitted one for one. To demonstrate this proposition:

forthcoming), and M. Alzahrani, M. Masih, and O. Al-Titi, "Linear and Non-Linear Granger Causality between Oil Spot and Futures Prices: A Wavelet Based Approach," *SSRN Working Paper* (2014).

$$\text{Futures Price } (t, T) = \text{Spot Price } (t) + \text{Cost of Carry } (t,T) + C, \qquad (1)$$

where C denotes a constant amount by which cost of carry fails. Once again, if

$$\text{Spot price2} = \text{Spot price1} + \$1 \Rightarrow$$

$$\text{Futures price2} = \text{Spot Price2} + \text{Cost of Carry} + C = \text{Spot price1} + 1 + C + \text{Cost of Carry}$$

$$\Rightarrow \text{ Futures price2} = \text{Futures price1} + \$1$$

To sum, from a purely conceptual framework, if the cost-of-carry relation holds, then any shock of the spot prices would be transmitted approximately one-for-one into the futures prices. Thus, the cost-of-carry relation is a sufficient condition for one-for-one transmission of economic shocks from spot prices into futures prices.

Again from a conceptual framework, even if the cost-of-carry relation fails, then any shock of the spot prices would still be transmitted approximately one-for-one into the futures prices as long as any shock is independent of the cost-of-carry. Thus, the independence condition is another sufficient condition for one-for-one transmission of economic shocks from spot prices into futures prices.

Alternatively, if any economic shock occurs in the futures market first, the cost of carry relation indicates that this shock is likely to get transmitted to the spot markets, again approximately dollar for dollar. This is because market participants understand that sometimes, informed traders may prefer to trade in futures markets due to lower trading costs, greater liquidity and greater leverage afforded by the futures markets. Thus, a movement in the futures markets can represent new information and this will be taken into account by the spot market traders.

Finally, in many instances, futures prices will appear to anticipate (lead) future changes in spot prices. This is because future markets are predictive markets. To the extent players in the futures markets understand and recognize any patterns in the spot prices, they will incorporate these expectations into the futures price in advance of any actual price movements in the spot prices.

In some real-world situations, where there can be shocks to interest rates, storage costs and convenience yields over time and these shocks are correlated with levels or changes in spot prices, then one dollar of movement in spot price need not translate into exactly one dollar movement in the futures price. In this case, the exact magnitude of the transmission of these price shocks again becomes an empirical question, depending on current market conditions.

To determine the empirical connection between spot and futures prices in the Brent oil market, we write the following derived cost-of-carry relation, in return form, as follows:

$$\text{Futures Price } (t\text{-}1, T) = \text{Spot Price } (t\text{-}1) + \text{Cost of Carry } (t\text{-}1, T) \tag{2}$$

Subtracting (2) from (1), where Δ denotes the change in prices,

$$\Delta \text{ Futures Price } (t, T) = \Delta \text{ Spot Price } (t) + \Delta \text{ Cost of Carry } (t, T) \tag{3}$$

Dividing (3) by (2),

$$R \text{ (Futures Price } (t, T)) = \alpha + \beta \text{ R(Spot Price } (t) \text{)} \tag{4}$$

In regression form, allowing for an error term, ε;

$$\text{Return to futures price} = \alpha + \beta \text{ Return to spot price} + \varepsilon \tag{5}$$

In this regression Model (5), the β coefficient tells us exactly the magnitude of this transmission between spot prices and futures prices in percent terms. If β equals one, this relation implies that there is one for one transmission between spot and futures in percent terms. A one-percent change in spot price translates into one percent change in futures price. If β equals zero, then this implies that there is no relation between spot and futures prices. Even if there is a shock to spot prices, none of this shock would be transmitted into futures prices. If β is greater than one, this relation implies that there is more than one for one transmission. If β is less than one, this relation implies that there is less than one for one transmission.

Thus, empirically, the degree of integration between spot and futures oil markets can be understood by investigating the regression model in (5). The R-square of this regression tells us the degree to which spot and futures markets are integrated. A high value of R-square indicates highly integrated spot and futures markets. A low R-square means that there is little connection between spot and futures markets. The slope coefficient β tells us the degree to which price shocks are transmitted to the futures prices.

Relation (5) can be estimated between spot and different maturity futures contracts, as well as between different maturity futures contracts. The same cost-of carry relation can be used to derive the pricing relation between futures contracts of different maturities. Therefore, the relation between futures price of different maturities can be explored using a similar regression model as between spot and futures prices. To demonstrate this proposition we lay out

$$\text{Futures Price } (t, T1) = \text{Spot Price } (t) + \text{Cost of Carry } (t,T1)$$
$$\text{Futures Price } (t, T2) = \text{Spot Price } (t) + \text{Cost of Carry } (t,T2)$$

$$\text{Futures Price } (t, T1) = \text{Futures Price } (t, T2) + \text{Cost of Carry } (t,T1) - \text{Cost of Carry } (t,T2)$$

Rearranging this equation as we did for spot and futures markets yields,

$$\text{Return to futures contract1} = \delta + \gamma \text{ Return to futures contract2} + \zeta \qquad (6)$$

Given that there can be non-synchronous trading, other special supply and demand effects and correlations between spot prices and cost of carry amounts, the error terms ε in equation (5) and ζ in equation (6) may not be random noise. To take these effects into account and to ensure that the residuals are well behaved, autoregressive, moving average (ARMA) models are fitted to the residuals where necessary.

3. Data and Sample Characteristics

The first of our two spot prices indices is the Brent Index. Brent Index is the settlement price for the ICE Brent London and ICE Brent NX Futures at their respective expirations. The index is the average trading prices in the 25-day BFOE (Brent-Forties-Oseberg-Ekofisk) market in the related delivery month reported by the industry media. Only the published cargo size trades and assessments are considered in the calculations. The index is the average of (1) weighted average of first month cargo trades in the 25-day BFOE market; (2) weighted average of second month cargo trades in the 25-day BFOE market plus a straight average of the spread trades between the first and second months; (3) average of designated assessments published in media reports.[3]

The second of our two spot oil price indices is Dated Brent Price Index.[4] Dated Brent is a market term for the cargo of the North Sea Brent blend crude oil that has been assigned a date of loading onto a tanker. Cargoes that have this loading date assignment are known as dated or wet cargoes, or wet barrels. Each dated cargo of crude oil is traded more than once as it travels for delivery to the refineries -- where the crude oil is transformed into more refined gasoline, diesel, jet fuel, etc. Cargoes with no loading date are called paper barrels and they are traded for speculation or hedging. Dated Brent Price Index is used as a benchmark for a large proportion of the crude oil that is traded internationally.

[3] For more detailed discussion, see www.theice.com: "The first month weighted average is the average of the cargo trade prices reported, and weighted by volume to include multiple trades at any one price level. If media sources do not agree on the number of trades at a given price, then ICE Futures endeavors to clarify the actual amount of trades, while reserving the right to omit trades that cannot be substantiated to the satisfaction of the Exchange. The second month average produces an implied average price for the first month of the 25-day market, by averaging the second month traded cargo prices and an average of the spread trades between the first and second months. Trades in the second month of the 25-day market are also taken into consideration in this second element of the calculation, after being adjusted for the size of the differential between the first and second 25-day months. The average 1st-2nd month spread value is determined by the straight average price of spread trades documented by media sources. The average spread is added to the weighted average trade price for the second month to construct the implied first month price level. The third and final component of the Brent Price Index is obtained from the industry media publications of the 25-day BFOE price assessments throughout the trading day. The mid-point of each quote is used to calculate an average for the whole trading day."

[4] www.platts.com/oil-market-on-close: Information on Platts' assessment of MOC (Market On Close) is disclosed here. Additional links in www.platts.com provide more detailed information. Data on Platts assessment of Dated Brent are purchased from Platts.

Dated Brent is a critical component of the Brent Complex, which includes the trading of actual delivered oil such as Dated Brent, cash BFOE, and financially settled derivatives like Brent Futures, Contracts for differences, Dated to frontlines, or other derivatives. The Brent Complex helps those active in the North Sea crude market to manage the flow of crude oil from beginning to the end refinery, and to manage the price risk in all the production components, including the initial crude oil. Price indicators from the Brent Complex are used with higher frequency as a reference for measuring the value of crude oil all around the world, and also as a reference for the global economic health itself.

The third and the most important data component of the study is the ICE Brent Futures contracts based on the Brent Crude.[5] Brent Crude is a major trading classification of sweet light crude oil that serves as a major benchmark price for purchases of oil worldwide. Brent Crude is extracted from the North Sea and includes Brent Blend, Forties Blend, Oseberg and Ekofisk crudes (known as BFOE). The Brent Crude oil marker is also known as Brent Blend, London Brent, or Brent petroleum. It was originally traded on the open outcry International Petroleum Exchange in London, but since 2005 on the electronic Intercontinental Exchange, ICE. One contract equals 1,000 barrels (159 m3). Contracts are quoted in U.S. dollars. Each tick lost or gained equals $10.[6]

The ICE Brent futures and options are traded at ICE Futures Europe exchange and executed on the WebICE trading platform, which is distributed in more than 70 countries.[7] ICE Brent became the world's largest crude oil futures contract in 2012 in terms of volume, and ICE Brent market share has almost doubled since 2008. The largest category of participants in ICE Brent futures and options is the commercial hedgers (producers, users, processors, merchants), demonstrating Brent's significance as a hedging tool for physical market participants. As an accessible, waterborne crude with a wide geographical access, ICE Brent is indicative of global and local

[5] Tickdata: Global Futures Trade and Quote Data File Format Document, version 1.55, see www.tickdata.com. Intraday data on ICE Brent Futures for price and trading volume from January 2010 to March 2014 has been obtained from tickdata.com.
[6] See, ICE Brent Crude Oil, Key Facts and Summary, FAQ. Brent Index data are made publicly available by ICE. Additional links are available here provide more detailed information. See, www.theice.com/products/219/Brent-Crude-Futures
[7] See www.theice.com.

fundamentals. Global commodity indices have been increasing their allocations to Brent as a result of its growing importance in the pricing of crude oil.

Summary statistics of the data variables are provided in Table 1. Panel A lists the daily time series data, both prices and returns for the Brent Spot Index, Dated Brent Spot Index, and the ICE Brent Crude Futures with 1-month, 2-month, and 3-month maturities. Panel B provides the summary statistics for the intraday 30-minute ICE Brent Futures prices and returns. Finally, Panel C presents the higher frequency 2-minute intraday prices and returns for the ICE Brent Futures with the three maturities.[8] As can be seen, Brent Index and Dates Brent prices are very close to each other, averaging around $103. Similarly, ICE Brent Futures average prices, minimum and maximum prices track the corresponding prices for the spot closely. Interesting, the average price for the 3-month ICE Brent Futures is below that of spot prices, indicating on average, that oil prices are in backwardation.

In Figure 1 we show the entire time series behavior of dated Brent and ICE Brent Futures prices. From the middle of 2010 to early 2011, oil prices exhibit a sharp rise from around $75 to around $125. For the rest of the sample period, oil prices typically remain between $105 and $115. There is a very close relation between spot and futures prices and it is difficult to discern them in Figure 1.

To focus on the price difference between spot and futures, in Figure 2, we plot the basis for Brent oil as the difference between Dated Brent and the 3-month ICE Brent futures price. The basis for oil early in the sample period is negative indicating that oil is in contango. Along with the sharp rise in flat prices, the basis also rises and turns positive by the middle of March 2011 and moves into a backwardation relation. While the basis remains mostly positive (backwardation) for the remainder of the sample period in Figure 2, the basis does turn negative (into contango) for shorter periods of time.

[8] Both 30-minute and 2-minute prices are volume-weighted average of all trading prices observed during the relevant 30-minute or 2-minute interval.

The liquidity in the futures market is examined next. The actual trading volumes for ICE Brent futures contracts are shown in Figure 3. The horizontal axis divides a day into 720 two-minute buckets starting from 12AM, midnight. The vertical axis shows the average total number of contracts traded during that half-hour period.

Visual inspection of Figure 3 immediately reveals that volume is concentrated in certain periods. Relative volume peaks three times during the course of a day, once in the morning, once in late afternoon and once in early evening. The morning peak occurs between 9:28AM and 9:30AM. The afternoon peak occurs during the MOC period between 4:28PM and 4:30PM. The evening peak occurs between 7:28PM and 7:30PM.

4. Empirical Results

Visual inspection of the data in Figure 1 indicates that both spot and futures prices are non-stationary. Therefore, a formal investigation with Augmented Dickey-Fuller tests is conducted and reported in Table 2. Panel A presents daily time series for spot prices and returns, as well as futures prices and returns for 1-month, 2-month, and 3-month maturities. Panel B shows 30-minute intraday ICE Brent Futures prices and returns. Finally, Panel C shows the high frequency 2-minute Futures prices and returns for the three maturities. As expected, the table clearly indicates the presence of unit roots in level data variables. The price series for all the variables have unit roots (UR) according to every version of the Dickey-Fuller tests. On the other hand, when first differenced, the return series of every variable is free from unit roots at 1% significance level.[9]

The initial investigation of unit roots clearly reveal that level series, i.e. prices, do have unit roots while the differenced series, i.e. returns, are free from unit roots. For completeness and for the interactions between Futures data with different maturities, we also conduct co-integration tests to see if spot and futures prices share a common, non-stationary component. Table 3 shows the

[9] For the return series in Table 2, very high rho values are estimated in the ADF tests that also lead to consequent Tau values. In these cases, the rho values all converge together in the three versions of the ADF tests. That is why we see similar/same values for some of the return series in the ADF tests. Similarly, the Tau values are also very close to each other in the three versions of the ADF tests for the return series. As the results indicate, the return series exhibit no evidence of unit roots.

co-integration and rank tests of the interactions between Futures prices of different maturities. Panel A presents the results for daily futures prices, while Panels B and C present the results for intraday 30-minute price ticks and 2-minute price ticks. The co-integration rank test for every pair of futures price series, provide evidence of rank being equal to one. Hence, spot and futures prices share a common, non-stationary component. These results indicate that we can investigate the relations between spot and futures markets either using price levels or returns. We prefer to use returns since this leads to more robust results.[10]

The interaction of the futures contracts with different maturities amongst themselves, as well as with spot index series requires the examination of Granger causality. While Granger causality tests are not helpful in providing economic intuition or tests of economic causality, they are useful in describing the characteristics of the raw data, indicating lead-lag relations. Consequently, we test to see if futures returns Granger caused the spot returns, or whether the Granger causality worked either way, or whether it worked in one direction. To find out any discernible patterns of the interaction between the data series, we conduct Granger causality tests next.

These relations are shown in Table 4. As before, Panel A represents daily time series, while Panels B and C show 30-minute and 2-minute intraday tick prices. In general, Granger-causality is strongest at the 2-minute interval level. As we go to 30-minute intervals, Granger causality tests weaken, and mostly disappear at the daily level. This evidence indicates that previously reported lead-lag relations mostly disappear when data are matched precisely in real time.

Moreover, evidence in Table 4 also indicates that lack of sufficient liquidity is also contributing to the appearance of Granger causality. The nearby futures contract (1-month maturity) is the most active, most liquid contract. Both trading volume and trading frequency fall with increasing maturity. Hence, the 3-month futures contract is least liquid both by overall volume as well as trading frequency. Our tests in Table 4 indicate that the more liquid contract appears

[10] The unrestricted Trace hypothesis tests were not conclusive, while the Trace hypothesis test with restrictions showed that the co-integration rank was one. In such circumstances, one can either utilize co-integrating regressions focusing on price series, or alternatively using returns series in the investigation. Since we looked at numerous different issues such as Granger causality, joint VAR analysis, and interactions between futures series and spot series, we used returns of the time series in our investigation.

to Granger-cause the less liquid contracts. This evidence can be seen most strongly at the 30-minute intervals. An alternative, market-microstructure based explanation of this finding is that 1-month contract prices pick up innovations in the data since its prices are updated most frequently. In comparison, the price data for longer maturities appear to be stale. Consequently, we would expect the short-maturity contracts to show Granger-causation against longer maturities consistent with our findings here.

Next, we use a Vector Autoregressive (VAR) technique to explore the integration of oil markets. These results are reported in Table 5. The Granger causality regressions use the contemporaneous return along with six lags of the independent variable and the 6 lags of the dependent variable as explanatory variables. The order of the lags is ultimately determined by the information criteria, such as the Akaike Information Criterion (AIC). There is no pattern of significance that emerges from the causality regressions for the lagged variables. The contemporaneous variable is consistently significant at a one-percent level in every regression with a minimum t-statistics value of 190. In the few cases that the lagged variables are statistically meaningful, they are borderline significant at a five-percent level. As a consequence, only the contemporaneous explanatory variable is reported in the tables.[11]

Table 5 presents the results of the Granger causality regressions as the initial relationship between ICE Brent Futures contracts with different maturities. These regressions use the order of six as the order for the autoregressive and moving average components. The table reports the estimate and the relevant statistics of the contemporaneous explanatory variable. The first two columns report the Granger causality regression results of the daily futures results. The middle two columns are about the 30-minute returns, and the last two columns are about the 2-minute

[11] For the causality regressions using daily returns, 1-m to / from 2-m only has the first two lags of the independent coefficient significant in both directions; 3-m on 1-m exhibits an ARMA(1,4) model, while in the reverse direction fifth lag of the dependent variable and the first two lags of the independent variable are significant; and 3-m on 2-m regression has the first two independent variables significant, while in the reverse direction second lag of the dependent and the first two lags of the independent are significant. For 30-minute return regressions when there is evidence of Granger causality, the 2-m on 1-m regression has the first lags of dependent and independent variable significant, 3-m to 1-m has the first two lags of the dependent and the first lag of the independent variable significant; 3-m to 2-m has the second lag of the dependent and the first lag of the independent significant. Finally, for the 2-minute return regressions, the significant lags seem to be more arbitrary. For example, 1-m on 3-m regression, third lag of the dependent and the fourth lag of the independent is significant. On the other hand, 2-m on 3-m regression has only the first independent lag coefficient significant.

intraday return relationships. We can see from the table that the interaction term, the slope coefficient is highly significant and very close to unity in nearly all of the granger causality regressions. This is indicative of high interaction between futures returns of different maturities regardless of the return frequency. Only some of the estimates for the 2-minute return interactions are not very close to one, but they are positive and highly significant. Overall, the evidence in Table 5 indicates that oil markets are highly integrated. Any shocks to any one contract are transmitted to other contracts almost fully, one-for-one and within minutes.

Next, we conduct single-equation ARIMA (Autoregressive, Integrated, Moving Average) procedures to examine lead-lag relations and understand the behavior of the error models better. The results of these regression analyses for equation (5) are shown in Table 6. We have analyzed the relations between daily Platts assessment of Dated Brent, ICE Brent Index, and ICE Brent futures at 4:30 PM local London time for the nearby contract and two subsequent maturities from January 1, 2010 to March 25, 2014 on a daily basis.[12]

Panel A reports individual ARIMA regressions for each model. Panel B reports the vector auto regression results where the models are regressed jointly to see the full impact of the interactions between the variables. In Panel B, the exogenous variable is Dated Brent Spot Returns, while in Panel C, the exogenous variable is Brent Spot Index returns. The order of the vector regression system is determined by several information criteria as reported in the table. Every information criteria consistently suggested the order of two in Panel B and in Panel C.

In Table 6 Panel A, Model (1), the results of the regression analysis between Brent Index and Dated Brent are shown. As can be seen, the slope coefficient between the returns to Dated Brent and Brent Index is about 0.78. This finding indicates that there is a strong contemporaneous relation between Brent Index and Dated Brent. Approximately 1% change in Dated Brent results in a 0.78% change in Brent Index returns within the same day. The R-square of the regression is also high at 71.8%. In Panel B, model (1) we use the joint VAR approach. In this case, the

[12] ICE Brent Index is published with one day delay. All tests shown in this paper take this one-day reporting delay into account.

estimated coefficient is 0.714, indicating that a 1% change in Dated Brent results in a 0.71% change in Brent Index within the same day.

Model (1) tells us that two different indices for spot oil prices are highly correlated. Both Brent Index and Dated Brent are assessed separately using separate proprietary methods and they try to measure somewhat different delivery aspects of the spot oil markets. Nevertheless, a very high degree of connection between them indicates that they both react to the same set of information, namely prices observed in the physical, spot oil market. Model (1) tells us the different delivery structures spot oil markets are well-integrated. Our evidence also indicates that using single equation ARIMA models results in similar findings as the joint VAR approach.

The next set of tests analyzes the relation between spot and futures markets for various maturities. In Table 6 Panel A, Models (2) through (7), show the relations between ICE Brent futures for 1, 2 and 3 month maturities and Dated Brent and Brent Index. The futures returns are used as dependent variables while spot prices are used as independent variables (in return form).

In Panel A, the estimated slope coefficients for all specifications vary between 0.90 and 0.99. This result indicates that between 90% and 99% of the variations in spot price returns are reflected in futures returns during the same day. Hence, a 1% change in spot oil prices as indicated by Dated Brent and Brent Index are reflected between 0.90% and 0.99% in the futures prices during the same day. The fact that these slope coefficients are near one, indicates highly integrated spot and futures markets in crude oil where shocks get transmitted almost fully between spot and futures markets. In the joint vector auto regressive specifications (VAR) in Panels B and C, we see once again similar results and conclusions. A 1% change in the spot oil index (either the Dated Brent or the Brent Index) is reflected to about 90% to 99% in the futures contract prices.

In addition to slope coefficients that are close to 1.0, the regression analysis also indicates that the R-squares of the regression models are quite high in Panel A. The R-squares range between 76% and 93% on a daily basis. R-square of the regression tells us about the strength of the relation between independent and dependent variables. If R-square is 100% that means 100% of the variation in the dependent variable (futures returns) is explained by the variation in independent variable (spot returns) and there is no room for any other variable to explain any remaining variation since none is left. If R-square is 93%, that means 93% of the variation in the dependent variable (futures returns) is explained by the variation in independent variable (spot returns), leaving only 7% of the variations in the dependent variable that can be explained by all other factors. This finding of very high R-square values indicates that variations in spot prices are the most important determinant of the variations in futures prices. Once the effects of spot prices are taken into account, there is not much else left to be explained in daily ICE Brent futures prices.

Once again, the very high degree of positive correlations and slope coefficients near one indicate that crude oil spot and futures prices as well as Brent Index represent a highly integrated market. Any innovations in spot prices whether they are due to fundamental factors or shocks through shocks, are quickly and almost fully reflected futures prices. This finding also indicates that if spot prices are distorted through economic shocks, most if not all of these shocks would be transmitted into the futures prices.

Table 7 investigates the relationship between different-maturity ICE Brent futures contracts on a daily basis. Panel A focuses on the impact on longer maturity futures contracts from shorter maturity futures contracts, while Panel B presents the regression results of how shorter maturity contracts are impacted from longer maturity ICE futures contracts. Since the Granger causality relationships worked both ways for daily futures contracts, the results in both panels are relevant and important.

In Panel A, we see how strong the relationship is between shorter to longer maturity futures returns. Evidence indicates that 96% of the one-month futures returns are reflected to the returns of two-month returns in Model (1), and 95% is reflected to three-month futures contract returns in Model (2). Finally, 97% of the return in two-month contracts is reflected on to the return of the three-month futures contracts in Model (3). The smallest R-square value is 85%.

Model (1) in Panel B shows that the slope coefficient between one-month and two-month ICE Brent futures contracts equals 0.97. This value is highly statistically significant (at better than 1%). The R-square of this relation equals 93%. These findings indicate that there is almost a linear one-to-one relation between one-month ICE Brent returns and two-month ICE Brent returns. Thus, this finding demonstrates that any price shocks to one contract are likely to be reflected in the other contract as well. Model (2) and (3) in Panel B show similar relations between ICE Brent Futures with maturities of 1 and 3 months, and well as maturities of 2 and 3 months. All futures returns appear to be almost linear one-for-one relations. The strength of the relationship between one-month, two-month and three-month futures contracts are just as strong. All R-square values range between 85% and 93%. These findings indicate that any fundamental price shock or any price shock for any one of the futures contracts is pretty much fully reflected in the prices of other contracts on a one-for-one basis.

Next, we examined the relations between various maturity ICE Brent futures using 30-minute returns. These results are shown in Table 8. As before, Panel A presents results where longer maturity futures returns are regressed on shorter maturities, while in Panel B, the regressions are in the opposite direction. We see from Panel A that the slope coefficients range from 0.947 to 0.971. This means any change in the shorter maturity futures price is reflected almost completely to the longer maturity futures prices. As in Table 7, the R-square values are all very high. The futures contracts are highly integrated and any shock in the price of a futures contract is reflected to other contracts extremely quickly.

In Panel B, all slope coefficients are slightly lower, varying between 0.90 and 0.97. Hence, these results indicate that between 90 and 97% of any shocks to one futures price are transmitted to other maturities within the 30 minute interval. The R-squares are once again very high ranging between 85 and 93%. These results indicate that the movements in the other futures prices is the most important factor in determining the price of a given futures contract. Together, these results indicate highly integrated futures markets, where shocks to one futures contract price are quickly (within 30 minutes) and almost fully transmitted to other futures prices.

The next set of tests examines the relations between various maturity ICE Brent futures using only 2-minute returns. These results are shown in Table 9, where Panel A represents short maturities to longer maturities, and Panel B from long maturities to shorter maturities. Panel A shows, once again, how integrated the ICE Brent futures markets are. Any change in the shorter maturity contract price is reflected almost immediately (within two minutes) and almost completely (with 90.2% to 93.8%) in the longer maturity contracts. The R-square values for this extremely high frequency data ranges from 42.4% to 69.1%. From longer to shorter maturities, once again, the slope coefficients are high varying between 0.47 and 0.74. Hence, these results indicate that between 47% and 74% of any shocks to one futures price are transmitted to other maturities within the 2 minute interval. The R-squares are also high ranging between 42% and 69%. These results once again indicate that the movements in the other futures prices is the most important factor in determining the price of a given futures contract. Altogether, these results indicate highly integrated futures markets, where between half and three-quarters of a shock to one futures contract price is quickly (within two minutes) transmitted to the other futures prices.

Next we ask whether the spot prices reflect the intraday information in the futures prices one for one. In Table 10, the relation between daily returns to Dated Brent and intra-day pre-market-on-close (MOC) and MOC period returns to the ICE Brent Futures returns are shown.[13] Pre-MOC period refers to the 23.5 hour return from 4:30PM yesterday to 4:00PM today. MOC returns refer to the 0.5 hour return from 4PM to 4:30PM today. In Model (1), we use the Dated Brent price for spot oil markets. Once again, Model (1) in Table 10 shows a high degree of integration between spot and futures prices intra-day. The evidence shows that the pre-MOC returns in one-month ICE Brent futures are reflected approximately one-for-one in the returns for daily Dated Brent. Similarly, MOC returns in one-month ICE Brent futures are also reflected approximately one-for-one in the returns for daily Dated Brent. These findings also point to a high degree of integration within the day between spot and futures markets. Our findings are consistent with the interpretation that futures markets are predictive markets. Players in futures markets pay

[13] Market-on-Close or MOC Period refers to 4PM to 4:30PM local London Time. Platts assessment of Dated Brent is made available at 4:30PM local London Time.

attention to developments in the spot markets. Any actual or anticipated movements in the spot markets are quickly incorporated into the futures prices.[14]

In Model (2), we use the two-month ICE Brent futures contract. Similar to Model (1), Model (2) in Table 10 also indicates that there is a one-for-one relation between returns to MOC period for the two-month ICE Brent Futures and daily returns to Brent Index. There is also a one-for-one relation between pre-MOC returns for the two-month ICE Brent Futures and daily returns to Brent Index. Once again, these findings are consistent with a high degree of integration between spot and futures price also during intraday period. Again, players in futures markets pay attention to developments in the spot markets as indicated by Dated Brent. Any actual or anticipated movements in the spot markets are quickly incorporated into the futures prices.

Model (3) in Table 10 shows similar relations for the three-month futures contracts and Dated Brent returns. Once again, new information that arrives either during pre-MOC period or MOC period is reflected approximately one-for-one in Dated Brent prices.

Table 11 shows similar relations for the Brent Index and ICE Brent futures contracts. Again, the evidence is consistent with the conclusion that spot and futures in oil are highly integrated. Any fundamental information that comes in during the MOC window as well as prior to the MOC window is reflected approximately one-for-one in the physical spot prices. This finding shows that market participants pay attention to developments during the MOC window as well as pre-MOC window and reflect these in the future prices one for one.

We also examine the lead-lag relations between spot oil and futures oil prices. These analyses are shown in Tables 12 and 13. For futures prices, we use one, two, and three-months to maturity ICE Brent futures prices measured at 4:30PM local London time. For spot oil, again, we used daily Dated Brent as well as the daily Brent Index.

[14] It would have been interesting to do similar exercises using intra-day physical spot prices and intra-day futures prices. Unfortunately, we are not aware of any publicly available database for intraday physical spot oil prices (actual transactions, bids, asks or other trading interest). Consequently, such an exercise is not possible.

In Table 12, Model (1), the return to Brent futures is regressed against one-day lag of the return to Brent futures, as well as contemporaneous and lagged returns to the Dated Brent.[15] The evidence is, once again, strongly supportive of integrated markets. The contemporaneous relationship between Dated Brent and Brent Futures remains very strong. The slope coefficient is about 0.94. The R-square of the relation is again high, around 93%. Since the model was well specified as given, no error model was fitted to the residuals.

In Model (1), the one-day lagged value of the return to Dated Brent also comes in as positive and significant. This finding is consistent with the interpretation that futures markets react to the information in dated Brent that comes out yesterday at 4:30PM. After the spot price is announced, the future price does react to the new information in the spot price. Even if the future market participants take additional one or two minutes to digest some of the new information in dated Brent, this would show up in the next-day's closing futures prices. However, the lagged value of Dated Brent has a coefficient of only 0.08. Thus, the predictive ability of one-day lagged dated Brent is quite small relative to the contemporaneous information.

Model (2) in Table 12 regresses the returns to Dated Brent against one-day lag of the return to Dated Brent, as well as contemporaneous and lagged returns to the ICE Brent Futures. Again, the contemporaneous relation between Dated Brent and Brent Futures remains very strong, around 0.99. In Model (2), one-day lagged value of ICE Brent Futures predicts the next day's Dated Brent change. The magnitude of the predictive coefficient is small, about 0.09. This finding is consistent with the interpretation that futures markets anticipate developments in the spot prices and react in advance of the changes in spot prices. The remainder of the models in Table 12 is similar for two-months to maturity as well as three-months to maturity futures.

In Table 13, we use the Brent Index as the spot oil price and explore lead-lag relations between spot and futures oil prices. Table 13 typically shows similar relations as Table 12. Contemporaneous relations between spot and futures oil prices are again strong and dominant. Also similar to Table 12, one-day lagged value of ICE Brent Futures predicts the next day's

[15] We also used higher lags of both dependent as well as independent variables as well, however, these were not statistically significant and therefore not shown.

Brent Index change. Once again, the magnitude of the predictive coefficient is small, about 0.17. This finding is again consistent with the interpretation that futures markets anticipate developments in the spot prices and react in advance of the changes in spot prices.[16] The remainder of the models in Table 13 also shows similar relations for two-months to maturity as well as three-months to maturity ICE Brent futures.

Table 14 provides the results of our sensitivity analysis. Given the evidence in Figure 2, we divide our sample into contango and backwardation periods. During contango periods, the futures contract price is higher than the cash price, while during the backwardation period the cash price is higher than the futures price. Our evidence from Figure 2 indicates that the period from January 1, 2010 to March 14, 2011 is characterized by contango. From March 15, 2011 to the end of the sample period is characterized by backwardation. We want to investigate whether our prior results continue to hold in these two sub-samples.

Granger causality relationships between futures contracts are reported in Table 14, Panel A (contango period) and in Table 14, Panel B (backwardation period). The contango period does not exhibit Granger causality, while the backwardation period provides some evidence of causality. Causality regression results are provided in Panel C (contango) and in Panel D (backwardation). In both panels, we see again the close integration between futures contracts with the slope coefficient being very close to one. This, as before, indicates that a shock in one futures contract will propagate to other futures contracts with very little attenuation during both contango and backwardation periods. Finally, Panel E reports the joint vector autoregression results of the three futures contracts on Dated Brent Index. Regardless of whether there is

[16] Finance literature is full of examples where predictive markets such as the stock market or the futures markets anticipate developments in the markets and react to these expectations in advance of the actual developments. To give some examples, stock prices rise and fall in advance of the economic expansions and economic contractions. See Eugene F. Fama, 1981, Stock Returns, Real Activity, Inflation and Money, The American Economic Review, vol. 71, No. 4, pp. 545-565. Fed Funds futures prices predict the likely changes in Fed funds target rates. See, Robertson John and Thornton L. Daniel, "Using the Federal Funds Futures rates to predict Federal Reserve Actions, The Review of the Federal Reserve Bank of St. Louis, November/ December 1997, 45-53. Richard Roll shows that orange juice (OJ) futures prices predict the forecasting errors in the temperature forecasts issued by the National Weather Service for the central Florida region. Thus, OJ futures contract do a better job of forecasting temperatures than the National Weather Service. See Richard Roll, 1984, "Orange Juice and Weather", The American Economic Review, vol. 74, No. 5, 861-880. No one would argue that OJ futures would cause temperatures.

contango or backwardation, the slope coefficient of the spot index is very close to one, indicating the close integration of spot and futures markets in oil.

5. Conclusions

In this paper, we revisit the question of whether the spot and futures oil markets are well integrated. This is an important issue to producers and consumers of oil, as well as speculators, arbitragers and policy makers since well-integrated spot and futures markets indicate that oil markets function well in discovering new, important and relevant information necessary for pricing and transferring this information, quickly and fully to all related markets. Similarly, closely integrated oil markets will perform the risk transfer function that is essential to hedgers, speculators and arbitrageurs.

Our important innovation in this paper is to introduce and utilize intraday data. An important limitation of the current literature analyzing integration of markets and possible lead-lag relations between spot and futures prices, however, is that data frequency is limited to daily intervals which can lead to erroneous inferences regarding lead-lag relations between spot and futures markets. Consequently, using intraday data, and precise time-matching between different price series, we are able to bypass difficulties arising from daily data and differences in time zone.

Using more accurate intraday data, we extend the literature. Our evidence confirms the previous findings that spot and futures markets are highly integrated. Economic shocks that arise in spot markets are typically and quickly transmitted to the futures markets approximately one for one. Our evidence shows that most of the reaction takes place within minutes. Similarly, economic shocks arriving in futures markets are transmitted to spot markets one for one, once again, within minutes. We also find that lead-lag relations between spot and futures market do not tend to be weak or non-existent at the daily level. Overall, our findings indicate well-functioning, well-integrated spot and futures oil markets that perform the functions of both price discovery and risk transfer.

References

M. Alzahrani, M. Masih, and O. Al-Titi, "Linear and Non-Linear Granger Causality between Oil Spot and Futures Prices: A Wavelet Based Approach," *SSRN Working Paper* (2014).

S. Bekiros and C. G. H. Diks, "The Relationship between Crude Oil Spot and Futures Prices: Cointegration, Linear and Nonlinear Causality," *Energy Economics* Vol. 30 (2008).

E. F. Fama, "Stock Returns, Real Activity, Inflation and Money," *The American Economic Review*, Vol. 71, No. 4 (1981).

K. D. Garbade and W. L. Silber, "Price Movements and Price Discovery in Futures and Cash Markets," *Review of Economics and Statistics* Vol. 65, No. 2 (May 1983).

S. Hammoudeh, H. Li, and B. Jeon, "Causality and Volatility Spillovers Among Petroleum Prices of WTI, Gasoline and Heating Oil in Different Locations," *North American Journal of Economics and Finance* Vol. 14 (2003).

B.-N. Huang, C. W. Yang, and M. J. Hwang, "The Dynamics of a Nonlinear Relationship between Crude Oil Spot and Futures Prices: A Multivariate Threshold Regression Approach," *Energy Economics* Vol. 31 (2009).

G. Jarrell and A. Poulsen, "Stock Trading before the Announcement of Tender Offers: Insider Trading or Market Anticipation?" Journal of Law, Economics, and Organization, Vol. 5, No. 2 (1989).

X. Jin, S. Lin, and M. Tamvakis, "Volatility Transmissions and Volatility Impulse Response Functions in Crude Oil Markets," *Energy Economics* Vol. 34 (2012).

R. John and Thornton L. Daniel, "Using the Federal Funds Futures Rates to Predict Federal Reserve Actions," *The Review of the Federal Reserve Bank of St. Louis*, November/ December 1997.

R. K. Kaufmann and B. Ullman, "Oil Prices, Speculation and Fundamentals: Interpreting Causal Relations among Spot and Futures Prices," *Energy Economics* Vol. 31 (2009).

C.-C. Lee and J.-H. Zeng, "Revisiting the Relationship between Spot and Futures Oil Prices: Evidence from Quantile Cointegrating Regression," *Energy Economics* Vol. 33 (2011).

I. A. Moosa, "Price Discovery and Risk Transfer in the Crude Oil Futures Market: Some Structural Time Series Evidence," *Economic Notes* Vol. 31, No. 1 (2002).

J. Quan, "Two-Step Testing Procedure for Price Discovery Role of Futures Prices," *Journal of Futures Markets* Vol. 12, No. 2 (1992).

Liu, Schultz, and Swieringa (2014), *op. cit.*, F.-B. Lu, Y.-M. Hong, S.-Y. Wang, K.-K. Lai, and J. Liu, "Time-Varying Granger Causality Tests for Applications in Global Crude Oil Markets," *Energy Economics* Vol. 42 (2014).

T. V. Schwarz and A. C Szakmary, "Price Discovery in Petroleum Markets: Arbitrage, Cointegration, and the Time Interval of Analysis," *Journal of Futures Markets* Vol. 14, No. 2 (1994).

K. Shrestha, "Price Discovery in Energy Markets," *Energy Risk* (2014 forthcoming).

P. Silvapulle and I. A. Moosa, "The Relationship Between Spot and Futures Prices: Evidence from the Crude Oil Market," *Journal of Futures Markets* Vol. 19, No. 2 (1999).

R. Roll, "Orange Juice and Weather", *The American Economic Review* Vol. 74, No. 5 (1984).

Table 1. Summary Statistics

Raw values for the return periods are provided in the table.

Panel A. Daily Time Series Data					
	N	Mean	Std.Dev	Min	Max
Brent Index Spot	1066	103.1509	14.22045	69.07	126.14
Dated Brent Spot	1067	103.0495	14.62849	67.58	128.17
Brent Index Spot Return	1065	0.0003	0.01227	-0.04918	0.04322
Dated Brent Spot Return	1066	0.00039	0.0147	-0.05661	0.05146
ICE Brent Crude Futures (CO)					
1-month Futures prices	1085	103.1771	14.15366	69.09813	126.3941
2-month Futures prices	1085	102.8244	13.72918	69.94526	125.8953
3-month Futures prices	1084	102.5678	13.34154	70.65286	125.652
1-month Futures returns	894	0.00004	0.01479	-0.05741	0.04781
2-month Futures returns	924	0.00027	0.01429	-0.05725	0.04775
3-month Futures returns	966	0.00022	0.01397	-0.05773	0.04817

Panel B. 30-Minute Intraday Data					
ICE Brent Crude Futures (CO)	N	Mean	Std.Dev	Min	Max
1-month Futures prices	45648	103.4969	13.93815	68.31357	127.3761
2-month Futures prices	41346	103.1628	13.45866	69.20139	126.46
3-month Futures prices	33301	103.3742	12.80124	69.79	125.8933
1-month Futures returns	45647	0.00001	0.0023	-0.03088	0.02606
2-month Futures returns	41345	0.00001	0.00237	-0.03008	0.02627
3-month Futures returns	33300	0.00001	0.00261	-0.02904	0.02753

Panel C. 2-Minute Intraday Data					
ICE Brent Crude Futures (CO)	N	Mean	Std.Dev	Min	Max
1-month Futures prices	615016	103.6368	13.83686	68.15662	128.1415
2-month Futures prices	529936	103.2819	13.37263	68.63523	126.8092
3-month Futures prices	386062	103.8541	12.44023	69.13940	125.9800
1-month Futures returns	615015	0.0000	0.00138	-0.0939	0.10242
2-month Futures returns	529935	0.0000	0.00148	-0.09386	0.10258
3-month Futures returns	386061	0.0000	0.00169	-0.0941	0.10322

Table 2. Augmented Dickey-Fuller Tests for the Presence of Unit Roots in the Time Series

Three different Dickey-Fuller test results are provided in the table. The last column indicates whether there are unit roots (UR) or not based on 5% significance.

Panel A. Daily Data						
	Type	Rho	Pr < Rho	Tau	Pr < Tau	
Brent Index	Zero Mean	0.12	0.7115	0.26	0.7608	UR
	Single Mean	-7.27	0.2581	-2.09	0.2473	UR
	Trend	-9.67	0.459	-2.16	0.51	UR
Dated Brent	Zero Mean	0.12	0.71	0.24	0.755	UR
	Single Mean	-7.33	0.2546	-2.11	0.2412	UR
	Trend	-9.56	0.4665	-2.15	0.5193	UR
Brent Index Return	Zero Mean	-965.22	0.0001	-21.95	<.0001	No UR
	Single Mean	-966.49	0.0001	-21.95	<.0001	No UR
	Trend	-967.81	0.0001	-21.95	<.0001	No UR
Dated Brent Return	Zero Mean	-1029.3	0.0001	-22.67	<.0001	No UR
	Single Mean	-1031.3	0.0001	-22.68	<.0001	No UR
	Trend	-1033.2	0.0001	-22.69	<.0001	No UR
ICE Brent Crude Futures (CO)						
1-month Futures prices	Zero Mean	0.12	0.7111	0.26	0.7606	UR
	Single Mean	-7.24	0.26	-2.1	0.2455	UR
	Trend	-9.32	0.4842	-2.12	0.5318	UR
2-month Futures prices	Zero Mean	0.12	0.7109	0.26	0.7612	UR
	Single Mean	-7.29	0.2569	-2.1	0.2464	UR
	Trend	-9.36	0.481	-2.13	0.5267	UR
3-month Futures prices	Zero Mean	0.11	0.7096	0.25	0.7587	UR
	Single Mean	-7.44	0.248	-2.11	0.2423	UR
	Trend	-9.51	0.4701	-2.15	0.5158	UR
1-month Futures returns	Zero Mean	-911.14	0.0001	-21.32	<.0001	No UR
	Single Mean	-911.14	0.0001	-21.31	<.0001	No UR
	Trend	-911.4	0.0001	-21.3	<.0001	No UR
2-month Futures returns	Zero Mean	-915.97	0.0001	-21.38	<.0001	No UR
	Single Mean	-916.79	0.0001	-21.38	<.0001	No UR
	Trend	-916.98	0.0001	-21.37	<.0001	No UR
3-month Futures returns	Zero Mean	-915.58	0.0001	-21.38	<.0001	No UR
	Single Mean	-916.15	0.0001	-21.38	<.0001	No UR
	Trend	-916.65	0.0001	-21.37	<.0001	No UR

Panel B. 30-minute Intraday Data						
	Type	Rho	Pr < Rho	Tau	Pr < Tau	
1-month Futures prices	Zero Mean	0.13	0.7127	0.26	0.7631	UR
	Single Mean	-7.92	0.2225	-2.22	0.1972	UR
	Trend	-9.83	0.4498	-2.21	0.4847	UR
2-month Futures prices	Zero Mean	0.12	0.7122	0.27	0.7634	UR
	Single Mean	-8	0.2182	-2.22	0.1974	UR
	Trend	-9.89	0.4462	-2.22	0.4792	UR
3-month Futures prices	Zero Mean	0.12	0.7108	0.26	0.761	UR
	Single Mean	-8.53	0.1924	-2.3	0.1732	UR
	Trend	-10.11	0.4305	-2.26	0.4557	UR
1-month Futures returns	Zero Mean	-46937	0.0001	-153.19	0.0001	No UR
	Single Mean	-46940	0.0001	-153.19	0.0001	No UR
	Trend	-46942	0.0001	-153.2	0.0001	No UR
2-month Futures returns	Zero Mean	-42206	0.0001	-145.27	0.0001	No UR
	Single Mean	-42208	0.0001	-145.27	0.0001	No UR
	Trend	-42210	0.0001	-145.27	0.0001	No UR
3-month Futures returns	Zero Mean	-34247	0.0001	-130.85	0.0001	No UR
	Single Mean	-34249	0.0001	-130.85	0.0001	No UR
	Trend	-34251	0.0001	-130.86	0.0001	No UR

Panel C. 2-minute Intraday Data						
	Type	Rho	Pr < Rho	Tau	Pr < Tau	
1-month Futures prices	Zero Mean	0.12	0.7112	0.24	0.7566	UR
	Single Mean	-8.63	0.1881	-2.31	0.1697	UR
	Trend	-10.78	0.3875	-2.32	0.4209	UR
2-month Futures prices	Zero Mean	0.12	0.7108	0.24	0.7568	UR
	Single Mean	-8.74	0.1831	-2.31	0.1686	UR
	Trend	-10.90	0.3795	-2.34	0.4121	UR
3-month Futures prices	Zero Mean	0.11	0.7092	0.23	0.7542	UR
	Single Mean	-9.86	0.1401	-2.46	0.1258	UR
	Trend	-11.47	0.3460	-2.43	0.3622	UR
1-month Futures returns	Zero Mean	-620704	0.0001	-557.09	0.0001	No UR
	Single Mean	-620706	0.0001	-557.09	0.0001	No UR
	Trend	-620707	0.0001	-557.09	0.0001	No UR
2-month Futures returns	Zero Mean	-546073	0.0001	-522.53	0.0001	No UR
	Single Mean	-546075	0.0001	-522.53	0.0001	No UR
	Trend	-546076	0.0001	-522.53	0.0001	No UR
3-month Futures returns	Zero Mean	-425582	0.0001	-461.29	0.0001	No UR
	Single Mean	-425584	0.0001	-461.29	0.0001	No UR
	Trend	-425586	0.0001	-461.29	0.0001	No UR

Table 3. Co-integration Tests of ICE Brent Crude Futures Contract Prices

Co-integration test results are provided in the table. Panel A is for daily data, Panel B is for 30-minute intraday frequency, and Panel C is about 2-minute intraday frequency.

Panel A. Daily Futures Prices					
ICE Brent Crude Futures Prices: 1-Month vs. 2-Months					
H0: Rank=r	H1: Rank>r	Eigenvalue	Trace	5% Crit Val	
0	0	0.0324	40.7115	19.99	
1	1	0.0046	5.0373	9.13	
Hypothesis Test of the H0: Restriction					
Rank	E-value	Rest. E-value	DF	Chi-Square	Pr > Chi Sq
0	0.0324	0.0324	2	0.30	0.8608
1	0.0044	0.0046	1	0.28	0.5950
ICE Brent Crude Futures Prices: 1-Month vs. 3-Months					
H0: Rank=r	H1: Rank>r	Eigenvalue	Trace	5% Crit Val	
0	0	0.0251	32.569	19.99	
1	1	0.0047	5.1139	9.13	
Hypothesis Test of the H0: Restriction					
Rank	E-value	Rest. E-value	DF	Chi-Square	Pr > Chi Sq
0	0.025	0.0251	2	0.31	0.8557
1	0.0044	0.0047	1	0.3	0.5833
ICE Brent Crude Futures Prices: 2-Month vs. 3-Months					
H0: Rank=r	H1: Rank>r	Eigenvalue	Trace	5% Crit Val	
0	0	0.0198	26.7586	19.99	
1	1	0.0047	5.1174	9.13	
Hypothesis Test of the H0: Restriction					
Rank	E-value	Rest. E-value	DF	Chi-Square	Pr > Chi Sq
0	0.0198	0.0198	2	0.37	0.8325
1	0.0198	0.0198	2	0.37	0.8325

Panel B. 30-minute Intraday Futures Prices					
ICE Brent Crude Futures Prices: 1-Month vs. 2-Months					
H0: Rank=r	H1: Rank>r	Eigenvalue	Trace	5% Crit Val	
0	0	0.0024	101.728	19.99	
1	1	0.0001	5.4757	9.13	
Hypothesis Test of the H0: Restriction					
Rank	E-value	Rest. E-value	DF	Chi-Square	Pr > Chi Sq
0	0.0024	0.0024	2	0.32	0.8529
1	0.0001	0.0001	1	0.31	0.5807
ICE Brent Crude Futures Prices: 1-Month vs. 3-Months					
H0: Rank=r	H1: Rank>r	Eigenvalue	Trace	5% Crit Val	
0	0	0.0016	58.5668	19.99	
1	1	0.0002	5.7255	9.13	
Hypothesis Test of the H0: Restriction					
Rank	E-value	Rest. E-value	DF	Chi-Square	Pr > Chi Sq
0	0.0016	0.0016	2	0.32	0.854
1	0.0002	0.0002	1	0.29	0.5873
ICE Brent Crude Futures Prices: 2-Month vs. 3-Months					
H0: Rank=r	H1: Rank>r	Eigenvalue	Trace	5% Crit Val	
0	0	0.0026	91.751	19.99	
1	1	0.0002	5.855	9.13	
Hypothesis Test of the H0: Restriction					
Rank	E-value	Rest. E-value	DF	Chi-Square	Pr > Chi Sq
0	0.0026	0.0026	2	0.32	0.854
1	0.0002	0.0002	1	0.31	0.5781

Panel C. 2-minute Intraday Futures Prices					
ICE Brent Crude Futures Prices: 1-Month vs. 2-Months					
H0: Rank=r	H1: Rank>r	Eigenvalue	Trace	5% Crit Val	
0	0	0.0004	222.053	19.99	
1	1	0.0000	5.7198	9.13	
Hypothesis Test of the H0: Restriction					
Rank	E-value	Rest. E-value	DF	Chi-Square	Pr > Chi Sq
0	0.0004	0.0004	2	0.30	0.8593
1	0.0000	0.0000	1	0.30	0.5865
ICE Brent Crude Futures Prices: 1-Month vs. 3-Months					
H0: Rank=r	H1: Rank>r	Eigenvalue	Trace	5% Crit Val	
0	0	0.0004	145.57	19.99	
1	1	0.0000	6.5541	9.13	
Hypothesis Test of the H0: Restriction					
Rank	E-value	Rest. E-value	DF	Chi-Square	Pr > Chi Sq
0	0.0004	0.0004	2	0.31	0.8583
1	0.0000	0.0000	1	0.29	0.5888
ICE Brent Crude Futures Prices: 2-Month vs. 3-Months					
H0: Rank=r	H1: Rank>r	Eigenvalue	Trace	5% Crit Val	
0	0	0.0014	526.253	19.99	
1	1	0.0000	6.4033	9.13	
Hypothesis Test of the H0: Restriction					
Rank	E-value	Rest. E-value	DF	Chi-Square	Pr > Chi Sq
0	0.0014	0.0014	2	0.3	0.8621
1	0.0000	0.0000	1	0.29	0.5886

Table 4. Granger Causality Relationships of ICE Brent Futures Returns with different Maturities [Daily, 30-Minute and 2-Minute Intraday]

Granger causality tests are provided. The last column indicates whether there is Granger causality (GC) or not (No GC).

Panel A. Daily Times Series				
Granger Causality Wald Test (Returns)	DF	Chi-Square	Pr > ChiSq	
Test if 2-Month causes 1-Month	6	10.69	0.0983	No GC
Test if 1-Month causes 2-Month	6	11.14	0.0841	No GC
Granger Causality Wald Test (Returns)	DF	Chi-Square	Pr > ChiSq	
Test if 3-Month causes 1-Month	6	10.62	0.1009	No GC
Test if 1-Month causes 3-Month	6	12.17	0.0583	No GC
Granger Causality Wald Test (Returns)	DF	Chi-Square	Pr > ChiSq	
Test if 3-Month causes 2-Month	6	16.87	0.0098	GC
Test if 2-Month causes 3-Month	6	18.4	0.0053	GC

Panel B. Intraday 30-minute Time Series				
Granger Causality Wald Test (Returns)	DF	Chi-Square	Pr > ChiSq	
Test if 2-Month causes 1-Month	6	4.5	0.609	No GC
Test if 1-Month causes 2-Month	6	49.42	<.0001	GC
Granger Causality Wald Test (Returns)	DF	Chi-Square	Pr > ChiSq	
Test if 3-Month causes 1-Month	6	5.58	0.4721	No GC
Test if 1-Month causes 3-Month	6	117.99	<.0001	GC
Granger Causality Wald Test (Returns)	DF	Chi-Square	Pr > ChiSq	
Test if 3-Month causes 2-Month	6	8.63	0.1955	No GC
Test if 2-Month causes 3-Month	6	83.63	<.0001	GC

Panel C. Intraday 2-Minute Time Series				
Granger Causality Wald Test (Returns)	DF	Chi-Square	Pr > ChiSq	
Test if 2-Month causes 1-Month	6	220.61	<.0001	GC
Test if 1-Month causes 2-Month	6	452.1	<.0001	GC
Granger Causality Wald Test (Returns)	DF	Chi-Square	Pr > ChiSq	
Test if 3-Month causes 1-Month	6	824.66	<.0001	GC
Test if 1-Month causes 3-Month	6	1417.32	<.0001	GC
Granger Causality Wald Test (Returns)	DF	Chi-Square	Pr > ChiSq	
Test if 3-Month causes 2-Month	6	957.1	<.0001	GC
Test if 2-Month causes 3-Month	6	1274.7	<.0001	GC

Table 5. Granger Causality Regressions

The contemporaneous explanatory variable is reported in the table. The lags of the returns are not reported because there is no uniform pattern of significance in the regressions; rather the significance of the lagged explanatory variables are spurious and when significant, they are generally barely borderline significant at 5% significance level.

CO Daily		CO 30-minute		CO 2 Minute	
2-month on 1-Month ICE Futures		2-month on 1-Month ICE Futures		2-month on 1-Month ICE Futures	
Variable	rco1(t)	Variable	rco1(t)	Variable	rco1(t)
Estimate	0.96429	Estimate	0.96174	Estimate	0.93705
StdDev	0.00361	StdDev	0.0013	StdDev	0.00086
t Value	266.89	t Value	742.05	t Value	999
Pr > |t|	0.0001	Pr > |t|	0.0001	Pr > |t|	0.0001
1-month on 2-Month ICE Futures		1-month on 2-Month ICE Futures		1-month on 2-Month ICE Futures	
Variable	rco2(t)	Variable	rco2(t)	Variable	rco2(t)
Estimate	1.02433	Estimate	0.96918	Estimate	0.73703
StdDev	0.00384	StdDev	0.00131	StdDev	0.00057
t Value	266.95	t Value	739.73	t Value	999
Pr > |t|	0.0001	Pr > |t|	0.0001	Pr > |t|	0.0001

3-month on 1-Month ICE Futures		3-month on 1-Month ICE Futures		3-month on 1-Month ICE Futures	
Variable	rco1(t)	Variable	rco1(t)	Variable	rco1(t)
Estimate	0.94412	Estimate	0.94544	Estimate	0.89918
StdDev	0.00486	StdDev	0.00218	StdDev	0.00135
t Value	194.27	t Value	433.19	t Value	667.12
Pr > |t|	0.0001	Pr > |t|	0.0001	Pr > |t|	0.0001
1-month on 3-Month ICE Futures		1-month on 3-Month ICE Futures		1-month on 3-Month ICE Futures	
Variable	rco3(t)	Variable	rco3(t)	Variable	rco3(t)
Estimate	1.03491	Estimate	0.90207	Estimate	0.46786
StdDev	0.00533	StdDev	0.00208	StdDev	0.00103
t Value	194.27	t Value	433.57	t Value	454.33
Pr > |t|	0.0001	Pr > |t|	0.0001	Pr > |t|	0.0001

3-month on 2-Month ICE Futures		3-month on 2-Month ICE Futures		3-month on 2-Month ICE Futures	
Variable	rco2(t)	Variable	rco2(t)	Variable	rco2(t)
Estimate	0.98368	Estimate	0.96985	Estimate	0.90724
StdDev	0.0018	StdDev	0.00191	StdDev	0.00279
t Value	547.43	t Value	506.94	t Value	325.05
Pr > |t|	0.0001	Pr > |t|	0.0001	Pr > |t|	0.0001
2-month on 3-Month ICE Futures		2-month on 3-Month ICE Futures		2-month on 3-Month ICE Futures	
Variable	rco3(t)	Variable	rco3(t)	Variable	rco3(t)
Estimate	1.01353	Estimate	0.91364	Estimate	0.5747
StdDev	0.00185	StdDev	0.0018	StdDev	0.00095
t Value	548.55	t Value	507.14	t Value	604.33
Pr > |t|	0.0001	Pr > |t|	0.0001	Pr > |t|	0.0001

Table 6. Relation between Spot Returns and Futures Returns in Crude Oil

Regression results between spot and futures returns in crude oil are reported in the table. R^2 excludes the explanatory power of the error models. Chi-square statistic tests for the autocorrelation of residuals for the first 6 lags. Panel A reports individual regressions, while Panel B and Panel C report the joint vector autoregression results. In Panel B and Panel C, FPE is the Final Prediction Error Criterion, AIC is the Akeike Information Criterion, SBC is the Schwarz Bayesian Criterion, and the HQC is the Hannan-Quinn Criterion

Panel A. ARIMA Single Equation Regressions							
Brent Index return on Dated Brent return							
Model	Intercept	Slope	t-stat	R^2	Err Model	Chi-sq(6)	p(Chi-sq)
(1)	0.00002	0.782	64.7	71.8%	MA(2)	7.86	0.097
One-Month Brent Futures return on Dated Brent return							
Model	Intercept	Slope	t-stat	R^2	Err Model	Chi-sq(6)	p(Chi-sq)
(2)	-0.00010	0.940	108.2	92.8%	MA(2)	4.76	0.31
One-Month Brent Futures return on Brent Index return							
Model	Intercept	Slope	t-stat	R^2	Err Model	Chi-sq(6)	p(Chi-sq)
(3)	-0.00020	1.020	89.6	78.5%	MA(4)	0.74	0.69
Two-Month Brent Futures return on Dated Brent return							
Model	Intercept	Slope	t-stat	R^2	Err Model	Chi-sq(6)	p(Chi-sq)
(4)	-0.0001	0.915	110.1	93.0%	MA(2)	4.23	0.376
Two-Month Brent Futures return on Brent Index return							
Model	Intercept	Slope	t-stat	R^2	Err Model	Chi-sq(6)	p(Chi-sq)
(5)	-0.0002	0.990	87.6	85.3%	MA(4)	2.75	0.252
Three-Month Brent Futures return on Dated Brent return							
Model	Intercept	Slope	t-stat	R^2	Err Model	Chi-sq(6)	p(Chi-sq)
(6)	-0.0001	0.895	103.8	0.918	MA(2)	3.75	0.441
Three-Month Brent Futures return on Brent Index return							
Model	Intercept	Slope	t-stat	R^2	Err Model	Chi-sq(6)	p(Chi-sq)
(7)	-0.0002	0.977	89.6	0.755	MA(4)	1.71	0.425

Panel B. Joint VAR of Brent Index and 1-, 2-, 3- Month Brent Futures returns on Dated Brent returns				
VARX(2,0)	FPE	AIC	SBC	HQC
	3.90E-22	-49.2952	-49.0776	-49.2126
Brent Index return on Dated Brent return				
Model	Intercept	Slope	t-statistic	
(1)	0.00023	0.714	56.2	
One-Month Brent Futures return on Dated Brent return				
Model	Intercept	Slope	t-statistic	
(2)	-0.00014	0.939	107.58	
Two-Month Brent Futures return on Dated Brent return				
Model	Intercept	Slope	t-statistic	
(3)	-0.00016	0.913	105.5	
Three-Month Brent Futures return on Dated Brent return				
Model	Intercept	Slope	t-statistic	
(4)	-0.00018	0.89305	97.29	

Panel C. Joint VAR of Dated Brent and 1-, 2-, 3-Month Brent Futures returns on Brent Index returns				
VARX(2,0)	FPE	AIC	SBC	HQC
	6.49E-22	-48.7861	-48.5686	-48.7036
Dated Brent return on Brent Index return				
Model	Intercept	Slope	t-statistic	
(5)	-0.00011	1.093	54.23	
One-Month Brent Futures return on Brent Index return				
Model	Intercept	Slope	t-statistic	
(6)	-0.00026	1.098	63.26	
Two-Month Brent Futures return on Brent Index return				
Model	Intercept	Slope	t-statistic	
(7)	-0.00026	1.05826	59.89	
Three-Month Brent Futures return on Brent Index return				
Model	Intercept	Slope	t-statistic	
(8)	-0.00029	1.03559	57.94	

Table 7. Relations between Daily Futures Returns in Crude Oil for Various Maturities

Daily Futures contract return regressions are reported in this table. R^2 excludes the explanatory power of the error models. Chi-square statistic tests for the autocorrelation of residuals for the first 6 lags.

Panel A. Longer Maturities regressed on Shorter Maturities

Two-Month ICE Brent Futures on One-Month Ice Brent Futures

Model	Intercept	Slope	t-statistic	R^2	Error Model	Chi-sq(6)	p(Chi-sq)
(1)	0.0000008	0.963	749.5	93.2%	MA(2)	6.37	0.173

Three-Month ICE Brent Futures on One-Month Ice Brent Futures

Model	Intercept	Slope	t-statistic	R^2	Error Model	Chi-sq(6)	p(Chi-sq)
(2)	0.000002	0.947	439.3	85.4%	MA(2)	3.82	0.431

Three-Month ICE Brent Futures on Two-Month Ice Brent Futures

Model	Intercept	Slope	t-statistic	R^2	Error Model	Chi-sq(6)	p(Chi-sq)
(3)	0.000003	0.971	514.3	88.9%	MA(2)	3.38	0.496

Panel B. Shorter Maturities regressed on Longer Maturities

One-Month ICE Brent Futures returns on Two-Month Ice Brent Futures returns

Model	Intercept	Slope	t-statistic	R^2	Error Model	Chi-sq(6)	p(Chi-sq)
(1)	0.0000002	0.97	750.6	93.1%	MA(2)	7.15	0.128

One-Month ICE Brent Futures returns on Three-Month Ice Brent Futures returns

Model	Intercept	Slope	t-statistic	R^2	Error Model	Chi-sq(6)	p(Chi-sq)
(2)	0.0000003	0.903	437.2	85.0%	MA(2)	4.5	0.343

Two-Month ICE Brent Futures returns on Three-Month Ice Brent Futures returns

Model	Intercept	Slope	t-statistic	R^2	Error Model	Chi-sq(6)	p(Chi-sq)
(3)	0.0000	0.916	511.6	88.3%	MA(2)	6.31	0.177

Table 8. Relations between Intraday 30-Minute Futures Returns in Crude Oil for Various Maturities

Intraday 30-minute Daily Futures contract return regressions are reported in this table. R^2 excludes the explanatory power of the error models. Chi-square statistic tests for the autocorrelation of residuals for the first 6 lags.

Panel A. Longer Maturities regressed on Shorter Maturities

Two-Month ICE Brent Futures on One-Month Ice Brent Futures

Model	Intercept	Slope	t-statistic	R^2	Error Model	Chi-sq(6)	p(Chi-sq)
(1)	0.0000006	0.9629	751.7	93.2%	MA(2)	6.37	0.1729

Three-Month ICE Brent Futures on One-Month Ice Brent Futures

Model	Intercept	Slope	t-statistic	R^2	Error Model	Chi-sq(6)	p(Chi-sq)
(2)	0.000001	0.9472	439.3	85.4%	MA(2)	8.19	0.224

Three-Month ICE Brent Futures on Two-Month Ice Brent Futures

Model	Intercept	Slope	t-statistic	R^2	Error Model	Chi-sq(6)	p(Chi-sq)
(3)	0.000003	0.9713	514.92	88.8%	MA(2)	3.38	0.4958

Panel B. Shorter Maturities regressed on Longer Maturities

One-Month ICE Brent Futures returns on Two-Month Ice Brent Futures returns

Model	Intercept	Slope	t-statistic	R^2	Error Model	Chi-sq(6)	p(Chi-sq)
(1)	0.0000002	0.97	750.6	93.1%	MA(2)	7.15	0.128

One-Month ICE Brent Futures returns on Three-Month Ice Brent Futures returns

Model	Intercept	Slope	t-statistic	R^2	Error Model	Chi-sq(6)	p(Chi-sq)
(2)	0.0000003	0.903	437.2	85.0%	MA(2)	4.5	0.343

Two-Month ICE Brent Futures returns on Three-Month Ice Brent Futures returns

Model	Intercept	Slope	t-statistic	R^2	Error Model	Chi-sq(6)	p(Chi-sq)
(3)	0.0000	0.916	511.6	88.3%	MA(2)	6.31	0.177

Table 9. Relations between Intraday 2-Minute Futures Returns in Crude Oil for Various Maturities

Intraday 2-minute Daily Futures contract returns are reported in this table. R^2 excludes the explanatory power of the error models. Chi-square statistic tests for the autocorrelation of residuals for the first 6 lags.

Panel A. Longer Maturities regressed on Shorter Maturities

Two-Month ICE Brent Futures on One-Month Ice Brent Futures

Model	Intercept	Slope	t-statistic	R^2	Error Model	Chi-sq(6)	p(Chi-sq)
(1)	0.0000008	0.938	1066.0	69.1%	ARMA(1,3)	4.29	0.117

Three-Month ICE Brent Futures on One-Month Ice Brent Futures

Model	Intercept	Slope	t-statistic	R^2	Error Model	Chi-sq(6)	p(Chi-sq)
(2)	0.000002	0.902	524.1	42.4%	ARMA(1, 4)	7.61	0.058

Three-Month ICE Brent Futures on Two-Month Ice Brent Futures

Model	Intercept	Slope	t-statistic	R^2	Error Model	Chi-sq(6)	p(Chi-sq)
(3)	0.000003	0.913	645.6	52.5%	AR(4)	4.41	0.110

Panel B. Shorter Maturities regressed on Longer Maturities

One-Month ICE Brent Futures returns on Two-Month Ice Brent Futures returns

Model	Intercept	Slope	t-statistic	R^2	Error Model	Chi-sq(6)	p(Chi-sq)
(1)	-0.0000003	0.737	750.6	69.1%	MA(2)	6.62	0.157

One-Month ICE Brent Futures returns on Three-Month Ice Brent Futures returns

Model	Intercept	Slope	t-statistic	R^2	Error Model	Chi-sq(6)	p(Chi-sq)
(2)	-0.000002	0.468	437.2	42.2%	MA(2)	2.5	0.644

Two-Month ICE Brent Futures returns on Three-Month Ice Brent Futures returns

Model	Intercept	Slope	t-statistic	R^2	Error Model	Chi-sq(6)	p(Chi-sq)
(3)	-0.000002	0.576	642.3	52.3%	MA(2)	8.64	0.071

Table 10. Relationship between Dated Brent Returns and Returns to ICE Brent Futures during pre-MOC and MOC Periods

Daily regression results are reported in the table. R2 excludes the explanatory power of the error models. DW denotes Durbin-Watson statistic for first-order serial correlation. Pre-MOC corresponds to 4:30PM day t-1 to 4PM on day t. MOC corresponds to 4PM to 4:30PM on day t.

Dated Brent Returns on One-Month ICE Brent Futures returns pre-MOC and MOC periods

Model	Intercept	t-stat	Pre-MOC Ret	t-stat	MOC Ret	t-stat	R^2	Err.Model	DW
(1)	0.000137	1.22	0.9906	116.11	1.0161	30.4	93.0%	AR(1)	2.03

Dated Brent Returns on Two-Month ICE Brent Futures returns pre-MOC and MOC periods

Model	Intercept	t-stat	Pre-MOC Ret	t-stat	MOC Ret	t-stat	R^2	Err.Model	DW
(2)	0.000158	1.27	1.0162	113.88	1.031	29.9	92.9%	AR(1)	2.03

Dated Brent Returns on Three-Month ICE Brent Futures returns pre-MOC and MOC periods

Model	Intercept	t-stat	Pre-MOC Ret	t-stat	MOC Ret	t-stat	R^2	Err.Model	DW
(3)	0.000226	1.51	1.0049	94.98	1.0218	24.7	90.2%	AR(1)	1.98

Table 11. Relation between Brent Index Returns and Returns to ICE Brent Futures during pre-MOC and MOC Periods

Daily Brent Index return regressions are reported in the table. R2 excludes the explanatory power of the error models. Chi-square statistic tests for the autocorrelation of residuals for the first 6 lags. p(Chi-sq) indicates the p-value or the significance level of the Chi-square statistic. Pre-MOC corresponds to 4:30PM day t-1 to 4PM on day t. MOC corresponds to 4PM to 4:30PM on day t.

Brent Index Returns on One-Month ICE Brent Futures returns pre-MOC and MOC periods										
Model	Intercept	t-stat	Pre-MOC Ret	t-stat	MOC Ret	t-stat	R^2	Error Model	Chi-sq(6)	p(Chi-sq)
(1)	-0.0000146	-1.01	0.96818	203	0.95885	69.2	78.3%	MA(1)	5.26	0.385

Brent Index Returns on Two-Month ICE Brent Futures returns pre-MOC and MOC periods										
Model	Intercept	t-stat	Pre-MOC Ret	t-stat	MOC Ret	t-stat	R^2	Error Model	Chi-sq(6)	p(Chi-sq)
(2)	-9.63E-06	-0.26	0.95554	128	0.89041	35.5	76.6%	MA(1)	6.02	0.304

Brent Index Returns on Three-Month ICE Brent Futures returns pre-MOC and MOC periods										
Model	Intercept	t-stat	Pre-MOC Ret	t-stat	MOC Ret	t-stat	R^2	Error Model	Chi-sq(6)	p(Chi-sq)
(3)	0.00001873	0.23	0.90121	84.1	0.77039	19.7	75.4%	MA(1)	8.00	0.156

Table 12. Lead-Lag Relations between Dated Brent returns and ICE Brent Futures returns

Lead-Lag regression results are reported in the table. R2 excludes the explanatory power of the error models. DW denotes Durbin-Watson statistic for first-order serial correlation

R(One Month Brent Futures)$_t$ = R(One-Month Brent Futures)$_{t-1}$ + R(Dated Brent) $_t$ + R(Dated Brent) $_{t-1}$

Model	Intercept	t-stat	R(One Month Brent Futures)$_{t-1}$	t-stat	R(Dated Brent) $_t$	t-stat	R(Dated Brent) $_{t-1}$	t-stat	R^2	DW
(1)	-0.00013	-1.09	-0.0917	-2.99	0.9381	119.0	0.0837	2.8	93.1%	2.01

R(Dated Brent)t = R(One-Month Brent Futures)$_t$ + R(One-Month Brent Futures) t-1 + R(Dated Brent) $_{t-1}$

Model	Intercept	t-stat	R(One Month Brent Futures)$_t$	t-stat	R(One Month Brent Futures)$_{t-1}$	t-stat	R(Dated Brent) $_{t-1}$	t-stat	R^2	DW
(2)	0.00015	1.27	0.9921	118.98	0.0895	2.84	-0.0788	-2.570	93.1%	2.01

R(Two-Month Brent Futures)$_t$ = R(Two-Month Brent Futures)$_{t-1}$ + R(Dated Brent) $_t$ + R(Dated Brent) $_{t-1}$

Model	Intercept	t-stat	R(Two Month Brent Futures)$_{t-1}$	t-stat	R(Dated Brent) $_t$	t-stat	R(Dated Brent) $_{t-1}$	t-stat	R^2	DW
(3)	-0.00012	-1.08	0.000081	0	0.912	116.9	0.003321	0.1	92.9%	2.00

R(Dated Brent)t = R(Two-Month Brent Futures)$_t$ + R(Two-Month Brent Futures) $_{t-1}$ + R(Dated Brent) $_{t-1}$

Model	Intercept	t-stat	R(Two Month Brent Futures)$_t$	t-stat	R(Two Month Brent Futures)$_{t-1}$	t-stat	R(Dated Brent) $_{t-1}$	t-stat	R^2	DW
(4)	0.00015	1.26	1.0179	116.94	-0.00846	-0.3	0.007508	0.2	92.9%	2.00

R(Three-Month Brent Futures)$_t$ = R(Three-Month Brent Futures)$_{t-1}$ + R(Dated Brent) $_t$ + R(Dated Brent) $_{t-1}$

Model	Intercept	t-stat	R(Three Month Brent Futures)$_{t-1}$	t-stat	R(Dated Brent) $_t$	t-stat	R(Dated Brent) $_{t-1}$	t-stat	R^2	DW
(5)	-0.00016	-1.22	0.0347	1.12	0.8962	97.6	-0.0304	-1.0	90.2%	2.00

R(Dated Brent)$_t$ = R(Three-Month Brent Futures)$_t$ + R(Three-Month Brent Futures) $_{t-1}$ + R(Dated Brent) $_{t-1}$

Model	Intercept	t-stat	R(Three Month Brent Futures)$_t$	t-stat	R(Three Month Brent Futures)$_{t-1}$	t-stat	R(Dated Brent) $_{t-1}$	t-stat	R^2	DW
(6)	0.00021	1.44	1.0062	97.57	-0.0509	-1.55	0.0489	1.57	90.2%	2.00

Table 13. Lead-Lag Relations between Brent Index returns and ICE Brent Futures returns

Lead-Lag regression results with Brent Index returns are reported in the table. R2 excludes the explanatory power of the error models. Chi-square statistic tests for the autocorrelation of residuals for the first 6 lags. p(Chi-sq) indicates the p-value or the significance level of the Chi-square statistic.

R(One Month Brent Futures)$_t$ = R(One-Month Brent Futures)$_{t-1}$ + R(Brent Index)$_t$ + R(Brent Index)$_{t-1}$

Model	Intercept	t-stat	R(One Month Brent Futures)$_{t-1}$	t-stat	R(Brent Index)$_t$	t-stat	R(Brent Index)$_{t-1}$	t-stat	R^2	Error Model	Chi-sq(6)	p(Chi-sq)
(1)	0.00002802	1.69	-0.12055	-3.69	1.13313	92.1	-0.0062464	-0.2	84.7%	MA(1)	4.19	0.522

R(Brent Index)t = R(One-Month Brent Futures)t + R(One-Month Brent Futures) t-1 + R(Brent Index) t-1

Model	Intercept	t-stat	R(One Month Brent Futures)$_t$	t-stat	R(One Month Brent Futures)$_{t-1}$	t-stat	R(Brent Index) t-1	t-stat	R^2	Error Model	Chi-sq(6)	p(Chi-sq)
(2)	-0.0000201	-1.38	0.78328	92.07	0.16819	6.34	0.03208	1.180	85.5%	MA(1)	3.57	0.613

R(Two-Month Brent Futures)t = R(Two-Month Brent Futures)t-1 + R(Brent Index) t + R(Brent Index) t-1

Model	Intercept	t-stat	R(Two Month Brent Futures)$_{t-1}$	t-stat	R(Brent Index) t	t-stat	R(Brent Index) t-1	t-stat	R^2	Error Model	Chi-sq(6)	p(Chi-sq)
(3)	0.00001983	0.68	-0.07091	-1.96	1.07465	81.3	-0.02464	-0.7	82.9%	MA(1)	8.29	0.141

R(Brent Index)t = R(Two-Month Brent Futures)t + R(Two-Month Brent Futures) t-1 + R(Brent Index) t-1

Model	Intercept	t-stat	R(Two Month Brent Futures)$_t$	t-stat	R(Two Month Brent Futures)$_{t-1}$	t-stat	R(Brent Index) t-1	t-stat	R^2	Error Model	Chi-sq(6)	p(Chi-sq)
(4)	-9.84E-06	-0.33	0.79943	81.13	0.15156	5.0	0.04378	1.4	83.8%	MA(1)	7.66	0.176

R(Three-Month Brent Futures)t = R(Three-Month Brent Futures)t-1 + R(Brent Index) t + R(Brent Index) t-1

Model	Intercept	t-stat	R(Three Month Brent Futures)$_{t-1}$	t-stat	R(Brent Index) t	t-stat	R(Brent Index) t-1	t-stat	R^2	Error Model	Chi-sq(6)	p(Chi-sq)
(5)	-0.0000309	-0.35	-0.32448	-5.66	1.03859	68.7	0.23979	4.2	81.0%	ARMA(1,1)	7.13	0.129

R(Brent Index)t = R(Three-Month Brent Futures)t + R(Three-Month Brent Futures) t-1 + R(Brent Index) t-1

Model	Intercept	t-stat	R(Three Month Brent Futures)$_t$	t-stat	R(Three Month Brent Futures)$_{t-1}$	t-stat	R(Brent Index) t-1	t-stat	R^2	Error Model	Chi-sq(6)	p(Chi-sq)
(6)	0.00005714	0.7	0.78653	68.61	0.29173	6.52	-0.12404	-2.43	81.7%	ARMA(1,1)	4.70	0.32

Table 14. Sensitivity Tests: Contango vs. Backwardation Periods

Causality evidence, causality regressions, and the joint VAR estimation results are reported for the contango and backwardation periods. From 1/1/2010 to 3/14/2011 is predominantly contango. From 3/15/2011 to end of the sample is predominantly backwardation period. In Panel E, AIC is the Akeike Information Criterion, SBC is the Schwarz Bayesian Criterion, and the HQC is the Hannan-Quinn Criterion.

Panel A. Contango Period				
Granger Causality Wald Test (Returns)	DF	Chi-Square	Pr > ChiSq	
Test if 2-Month causes 1-Month	6	8.78	0.1866	No GC
Test if 1-Month causes 2-Month	6	8.57	0.1991	No GC
Granger Causality Wald Test (Returns)	DF	Chi-Square	Pr > ChiSq	
Test if 3-Month causes 1-Month	6	9.69	0.1385	No GC
Test if 1-Month causes 3-Month	6	9.17	0.1645	No GC
Granger Causality Wald Test (Returns)	DF	Chi-Square	Pr > ChiSq	
Test if 3-Month causes 2-Month	6	7.59	0.2699	No GC
Test if 2-Month causes 3-Month	6	8.85	0.1823	No GC

Panel B. Backwardation Period				
Granger Causality Wald Test (Returns)	DF	Chi-Square	Pr > ChiSq	
Test if 2-Month causes 1-Month	6	6.13	0.4084	No GC
Test if 1-Month causes 2-Month	6	5.91	0.4331	No GC
Granger Causality Wald Test (Returns)	DF	Chi-Square	Pr > ChiSq	
Test if 3-Month causes 1-Month	6	5.64	0.4646	No GC
Test if 1-Month causes 3-Month	6	6.16	0.4051	No GC
Granger Causality Wald Test (Returns)	DF	Chi-Square	Pr > ChiSq	
Test if 3-Month causes 2-Month	6	13.48	0.036	GC
Test if 2-Month causes 3-Month	6	14.19	0.0276	GC

Panel C. Contango Granger Causality Regressions					
2-month on 1-Month ICE Futures		3-month on 1-Month ICE Futures		3-month on 2-Month ICE Futures	
Variable	Rco1(t)	Variable	Rco1(t)	Variable	Rco2(t)
Estimate	0.96805	Estimate	0.95459	Estimate	0.98546
StdDev	0.00614	StdDev	0.00832	StdDev	0.00308
t Value	157.67	t Value	114.75	t Value	320.35
Pr > |t|	0.0001	Pr > |t|	0.0001	Pr > |t|	0.0001
1-month on 2-Month ICE Futures		1-month on 3-Month ICE Futures		2-month on 3-Month ICE Futures	
Variable	Rco2(t)	Variable	Rco3(t)	Variable	Rco3(t)
Estimate	1.02268	Estimate	1.02767	Estimate	1.01209
StdDev	0.00649	StdDev	0.00896	StdDev	0.00316
t Value	157.62	t Value	114.75	t Value	320.45
Pr > |t|	0.0001	Pr > |t|	0.0001	Pr > |t|	0.0001

Panel D. Backwardation Granger Causality Regressions					
2-month on 1-Month ICE Futures		3-month on 1-Month ICE Futures		3-month on 2-Month ICE Futures	
Variable	Rco1(t)	Variable	Rco1(t)	Variable	Rco2(t)
Estimate	0.96221	Estimate	0.93835	Estimate	0.98182
StdDev	0.0045	StdDev	0.00603	StdDev	0.00219
t Value	213.81	t Value	155.54	t Value	447.35
Pr > |t|	0.0001	Pr > |t|	0.0001	Pr > |t|	0.0001
1-month on 2-Month ICE Futures		1-month on 3-Month ICE Futures		2-month on 3-Month ICE Futures	
Variable	Rco2(t)	Variable	Rco3(t)	Variable	Rco3(t)
Estimate	1.02509	Estimate	1.03868	Estimate	1.01522
StdDev	0.00479	StdDev	0.00668	StdDev	0.00227
t Value	213.81	t Value	155.46	t Value	447.08
Pr > |t|	0.0001	Pr > |t|	0.0001	Pr > |t|	0.0001

Panel E. Joint VAR of 1-, 2-, 3- Month Brent Futures returns on Dated Brent returns							
Contango				Backwardation			
VARX(1,0)	AIC	SBC	HQC	VARX(2,0)	AIC	SBC	HQC
	-38.019	-37.810	-37.937		-39.001	-38.837	-38.942
One-Month Brent Futures return on Dated Brent return							
Model	Intercept	Slope	t-statistic	Model	Intercept	Slope	t-statistic
	-0.00047	0.950	56.1		-0.00002	0.935	93.7
Two-Month Brent Futures return on Dated Brent return							
Model	Intercept	Slope	t-statistic	Model	Intercept	Slope	t-statistic
	-0.00051	0.926	54.2		-0.00001	0.908	92.5
Three-Month Brent Futures return on Dated Brent return							
Model	Intercept	Slope	t-statistic	Model	Intercept	Slope	t-statistic
	-0.00053	0.910	51.1		-0.00003	0.887	84.1

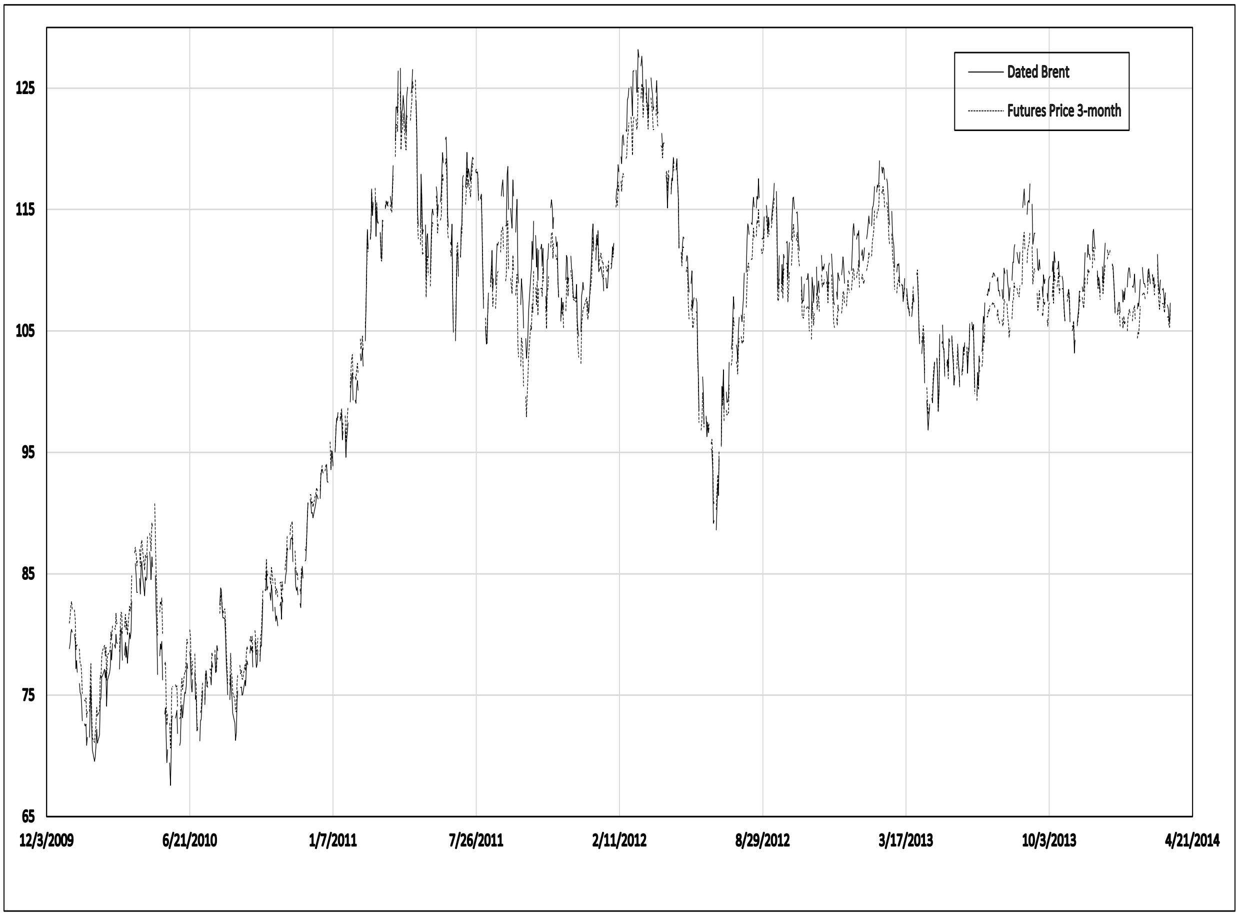

Figure 1. Spot vs. 3-Month Futures Oil Prices

Dated Brent Spot Price and 3-Month ICE Brent Crude Oil Futures prices are plotted.

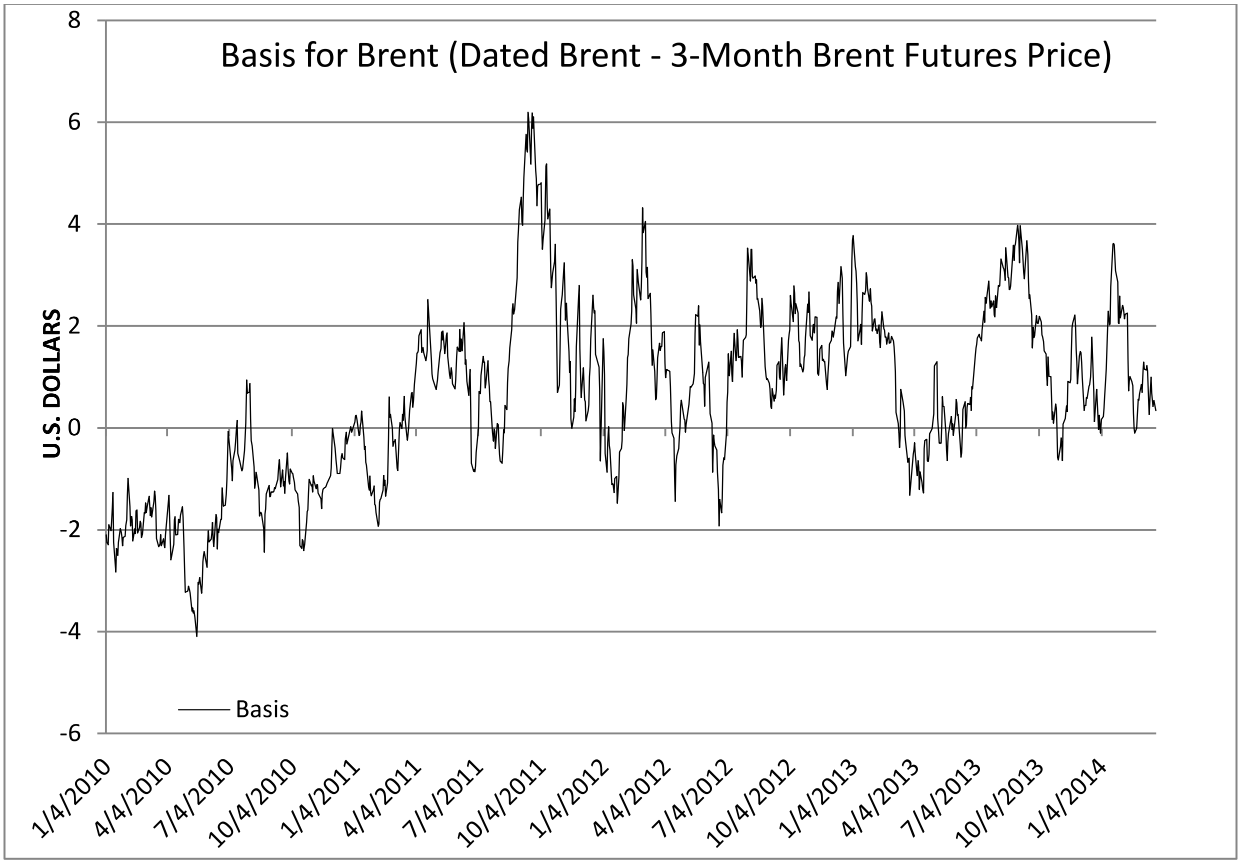

Figure 2. Basis for ICE Brent Futures

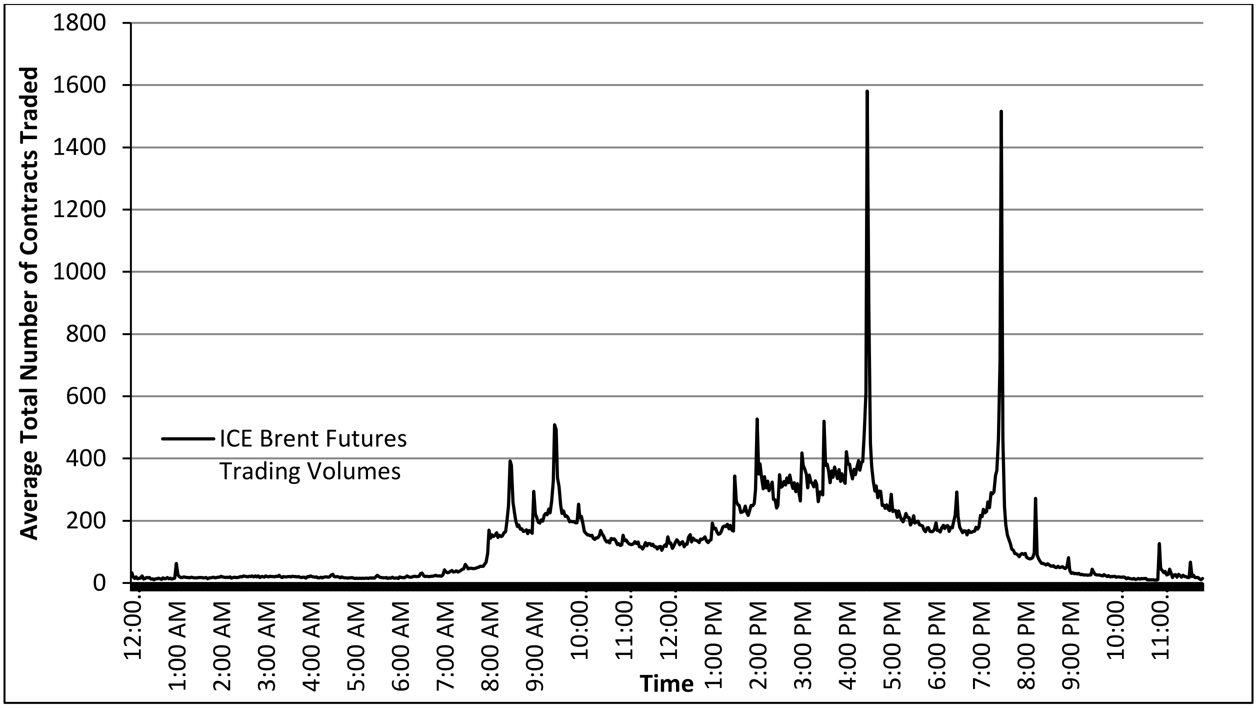

Figure 3. ICE Brent Futures Trading Volumes