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Unit root properties of crude oil spot and futures prices

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ABSTRACT

In this article, we examine whether WTI and Brent crude oil spot and futures prices (at 1, 3 and 6 months to maturity) contain a unit root with one and two structural breaks, employing weekly data over the period 1991–2004. To realise this objective we employ Lagrange multiplier (LM) unit root tests with one and two endogenous structural breaks proposed by Lee and Strazicich [2003. Minimum Lagrange multiplier unit root test with two structural breaks. Review of Economics and Statistics, 85, 1082–1089; 2004. Minimum LM unit root test with one structural break. Working Paper no. 04–17, Department of Economics, Appalachian State University]. We find that each of the oil price series can be characterised as a random walk process and that the endogenous structural breaks are significant and meaningful in terms of events that have impacted on world oil markets.

1. Introduction

There is no uniform view about the trajectory of commodity prices, including crude oil, over time. Some theorists advocate deterministic trend models with either an upward (Simon, 1985) or downward (Singer, 1950; Grilli and Yang, 1988) trend for commodity prices relative to industry prices. In the former, a steady increase in commodity prices can be attributed to economic growth. In the latter a downward trend in commodity prices is due to deterioration in the terms of trade of commodities, higher total factor productivity in agriculture relative to industry prices, or downward (Singer, 1950; Grilli and Yang, 1988) trend for commodity prices relative to industry prices. In the former, a

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proposed by Lee and Strazicich (2003, 2004). Compared with Augmented Dickey-Fuller (ADF) type tests that accommodate endogenous structural breaks, the LM unit root test with structural breaks has the advantage that the breaks are incorporated under the null. The LM unit root test with one and two structural breaks has only been applied to energy prices twice before and that was with annual data over a much longer period of time.

This article is structured as follows. Section 2 discusses the rationale for examining the stationarity of crude oil prices. Section 3 presents a literature review of studies of unit root tests applied to crude oil prices. Section 4 provides a methodological overview of the unit root tests that we apply in this article. Section 5 gives an overview of the data as well as containing a discussion of the potential break points. Section 6 presents the results. Section 7 concludes with a discussion of the implications of the findings, considers some of the limitations of the research and provides suggestions for future research.

2. Why does stationarity of crude oil prices matter?

The stochastic properties of crude oil prices have important implications for forecasting. As Pindyck (1999) pointed out, ideally we would like to be able to explain crude oil prices in structural terms because it is movements in demand and supply, and the factors that determine demand and supply, that cause prices to fluctuate. However, structural models are not very useful for long-run forecasting because it is difficult to come up with forecasts for the explanatory variables in such models, such as investment and production capacity and inventory levels, over long time horizons. As a consequence, industry forecasts of crude oil prices typically assume prices grow in real terms at some fixed rate. One possibility is that prices follow a random walk. Another possibility is that prices revert to a trend line, which implies that shocks to oil prices are temporary. As Pindyck (1999) noted, if oil prices are trend reverting this is consistent with crude oil being sold in a competitive market where price reverts to long-run marginal cost, which changes only slowly.

The stochastic properties of crude oil prices also have important implications for firms making investment decisions. The issue of whether it is preferable to model crude oil prices as a Geometric Brownian Motion (or some other related random walk process) or mean or trend reverting process is important because investments are irreversible and, as such, have option like characteristics. Baker et al. (1998) and Dixit and Pindyck (1994) show that different models of the pricing process carry important implications for investment and valuation decisions. Pindyck (1999, p.2) noted: “Simple net present value [NPV] rules are based only on expected future prices—second moments do not matter for NPV assessments of investment projects. But this is not true when investment decisions involve real options, as is the case when the investment is irreversible. Then second moments matter very much, so that an investment decision based on a mean-reverting process could turn out to be quite different from one based on a random walk”. Research to evaluate oil and gas deposits has developed complex multifactor models. However, as Postali and Picchetti (2006) have stressed, if Geometric Brownian Motion is a reasonable proxy for the behaviour of crude oil prices, it is possible to find closed form solutions to a wide class of problems on real options without complex numerical procedures.

Examining whether crude oil spot and futures prices contain a unit root has important implications for investors. If crude oil spot and futures prices contain a random walk, it follows that the crude oil market is efficient in the weak form, meaning future prices cannot be predicted using historical price data. This implies that an uninformed investor with a diversified portfolio will, on average, obtain a rate of return as good as an expert. If the random walk hypothesis is rejected it follows that it is possible for investors to make profits using technical analysis. Rejection of the random walk null hypothesis, based on a unit root with structural breaks does not necessarily imply that crude oil spot and futures markets are inefficient or that crude oil spot and futures prices are rational assessments of fundamental values. However, such a result would highlight the important role that structural breaks can play in tests for unit roots and raise the important question of whether such trend breaks should be treated like any other, or differently, before crude oil spot and future prices are treated as either trend stationary or difference stationary (Serletis, 1992).

Finally, several studies have tested for a unit root in energy consumption or production (see e.g. Chen and Lee, 2007; Hsu et al., 2008; Narayan et al., 2008; Narayan and Smyth, 2007). These studies emphasise that if energy consumption or production is non-stationary, given the importance of energy to other sectors in the economy, other key macroeconomic variables would inherit that non-stationarity. As Hendry and Juselius (2000) note, “variables related to the level of any variables with a stochastic trend will inherit that non-stationarity, and transmit it to other variables in turn …. Links between variables will then ‘spread’ such non-stationarities throughout the economy”. This issue is just as pertinent for crude oil prices as crude oil consumption or production. Studies have linked shocks to crude oil prices to output and inflation (Hamilton, 1996; Cunado and Perez de Gracia, 2003), the natural rate of unemployment (Caruth et al., 1998), movements in stock market indices (Sadorsky 1999; Papapetrou 2001) and fluctuations in business cycles (Kim and Loungani, 1992). From an economic viewpoint, if these macroeconomic series are non-stationary, business cycle theories, which describe fluctuations in output as temporary deviations from the long-run growth path will lose their empirical support.

3. Existing studies

It is common in the literature to explore the stochastic properties of crude oil prices prior to other econometric analysis. Papers that have applied conventional unit root tests such as the ADF (Dickey and Fuller, 1979) and Phillips and Perron (1988) (PP) tests and the KPSS (Kwiatkowski et al., 1992) stationarity test to WTI and Brent crude oil prices include Sivapulle and Moosa (1999), Serletis and Rangel-Ruiz (2004) and Taback (2003) among others. For example, Sivapulle and Moosa (1999) apply the ADF, PP and KPSS unit root tests to daily WTI spot and 1, 3, and 6 months to maturity WTI futures contracts covering the period 2 January 1985 to 11 July 1996. They found all four variables to be non-stationary based on these traditional tests. Serletis and Rangel-Ruiz (2004) applied ADF and PP tests to daily spot WTI crude oil prices from January 1991 to April 2001. They could not reject the unit root null. Taback (2003) tested whether Brent spot and 1, 2 and 3 months to maturity futures prices contain a unit root for the period January 1990–December 2000 using the ADF test and found that both spot prices and futures prices for 1- and 2-month contracts were non-stationary. Coimbra and Esteves (2004) tested the stationarity of Brent crude oil spot and futures prices by applying the ADF test to oil prices for the period January 1989–December 2003 as well as to a shorter period, which omitted the Gulf war, from January 1992 to December 2003. For both timeframes the null hypothesis of a unit root in crude oil prices could not be rejected.

Studies that have tested for a unit root in the prices of crude oils other than WTI and Brent include Alizadeh and Nomikos (2002) and Ewing and Harter (2000) among others. Alizadeh and
Nomikos (2002) tested for a unit root in weekly closing prices of WTI, Brent and Nigerian Bonny Light from 1 January 1993 to 10 August 2001. They applied ADF, PP and KPSS tests and could not reject the unit root null hypothesis. Using monthly data from 1974 to 1996, Ewing and Harter (2000) studied co-movement of Alaskan and UK Brent crude oil prices. Based on the PP unit root test, they could not reject the null of a unit root in either Alaskan or UK Brent crude oil prices. A recent development in the literature has been to analyse the long-run properties of crude oil prices based on unit root tests applied to long spans of data. Studies of this kind include Pindyck (1999) and Krichene (2002), both of which employ annual aggregated data. Pindyck (1999) studied the long-run evolution of American crude oil prices employing 127 years of annual data, from 1870 to 1996. Krichene (2002) examined the time series properties of natural gas and crude oil production and prices from 1918 to 1999. Both Pindyck (1999) and Krichene (2002) could not reject the unit root null for these time periods with standard ADF tests.

There are not many studies of oil prices that have applied unit root tests that allow for either exogenous or endogenous structural breaks. Gulen (1997) applied Perron’s (1989) ADF-type unit root test with one exogenous structural break to spot and contract prices for US and non-US crudes of different gravity. He selected February 1986 as the exogenous structural break because it corresponded to the largest drop in oil prices over the entire sample period. He found that two of the 15 spot price series and three of the 13 contract price series were stationary at the 5% level of significance. In a second study, Gulen (1998) applied Perron’s (1989) ADF-type unit root test to New York Mercantile Exchange (NYMEX) monthly crude oil futures at 1, 3 and 6 months to maturity from March 1983 to October 1995 and treated February 1986 as the exogenous break point. He was unable to reject the unit root hypothesis for any of the oil price series.

Serletis (1992) published the first study that tested for a unit root in oil prices with a single endogenous structural break. He first applied the ADF and PP tests, then proceeded to apply the Zivot and Andrews (1992) ADF-type unit root test with one endogenous structural break to a sample of daily NYMEX energy futures prices, including crude oil, heating oil and unleaded gasoline, over the period July 1983 to July 1999. Based on the ADF and PP tests he concluded that all series contained a unit root. However, the Zivot and Andrews (1992) test rejected the unit root null for all energy prices. Sadorsky (1999) applied the PP and Zivot and Andrews (1992) tests to US monthly real oil prices measured using the producer price index for fuels. The period studied spanned January 1947–April 1996. Real oil prices were found to have a positive upward trend. The unit root null hypothesis was rejected in favour of trend stationarity by both tests.

Lee et al. (2006) and Postali and Picchetti (2006) are recent studies of the unit root properties of crude oil prices that have allowed for two endogenous structural breaks. Lee et al. (2006) applied the Lee and Strazicich (2003, 2004) LM unit root tests with one and two endogenous structural breaks to 11 real commodity prices, including crude oil, from 1870 to 1990. They tested two specifications: a unit root test with linear trend and a unit root test with a quadratic trend. With a linear trend and two endogenous breaks, they were able to reject the null of a unit root for all 11 natural resource price series including petroleum. The two breaks were found to occur in 1896 and 1971, which corresponded to the end of the economic depression in the US and the termination of the Gold Standard for the American dollar. However, with the quadratic trend in the two-break model, the unit root null could only be rejected for five of the 11 series excluding petroleum. The structural breaks were found to be in 1914 and 1926, which corresponded to the start of the First World War and the General Strike in Great Britain, respectively.

Postali and Picchetti (2006) also applied the Lee and Strazicich (2003, 2004) LM unit root tests with one and two endogenous structural breaks to international oil prices. Similar to Pindyck (1999); Postali and Picchetti (2006) found that with annual data the length of the sample period was the most important factor in determining whether the series had at least one unit root. They divided the sample that covered 1861 to 1999 into several subsamples spanning 50–110 years. Traditional ADF and PP tests were only able to reject the unit root null for the entire sample with more than a century of annual data. For the sub-periods, conventional tests and LM unit root tests with two breaks in the intercept could not reject the unit root null. However, allowing for two breaks in the intercept and trend the unit root null hypothesis could be rejected for the period 1861–1999 and the sub-periods.

In summary, stationarity of crude oil prices has not been confirmed by the majority of studies. The failure of many of these studies to find that oil prices are mean-reverting processes might reflect the low power of conventional unit root tests. These tests are typically criticised for their low power in rejecting the alternative hypothesis of stationarity in small samples as noted by Pindyck (1999). In addition, conventional tests give ambiguous results when the data are described by a near unit root process or when the data are of high frequency with fat tails and volatility clustering (Boswijk and Kaasen, 2005), which is a characteristic of crude oil prices. Moreover, results of these tests crucially depend on the choice of lag in the model as well as the data frequency. Studies that have found evidence of stationarity in crude oil prices have typically applied ADF-type or LM unit root tests with structural breaks to annual data spanning 50–140 years.

4. Econometric methodology

4.1. Unit root tests without structural breaks

In order to provide a benchmark for the LM unit root tests with one and two structural breaks, we consider the ADF and PP unit root tests as well as the LM unit root test without a structural break. In the specification of the unit root regressions we include a constant and a time trend for the following reason. Oil is a non-renewable resource, supply of which is finite and limited relative to demand. Since the turn of the century very few giant discoveries have been made. Moreover, in recent times the discoveries that have been made are in deep-water, which require sophisticated technology in terms of exploration and extraction as well as constant risk of environmental hazards, which have to be included in the spot price. Therefore, based on the recent pattern in oil discoveries and production one would expect to see an upward trend in prices, which would reflect supply constraints.

An upward trend in oil prices is consistent with Hotelling’s (1931) theory, which postulates that prices for exhaustible resources should increase at an exponential rate over time. From 1991 (start of our sample) until 2004 prices have almost doubled. If we take into consideration a longer time frame up to 2007, one can see that prices have grown almost five times. Based on Hotelling’s theory one would also expect to see an upward trend in prices for other non-renewable resources such as gold, iron ore, platinum and others.

The ADF unit root test is based on the auxiliary regression

$$\Delta y_t = \kappa + \gamma y_{t-1} + \omega t + \sum_{j=1}^{k} d_j \Delta y_{t-j} + \epsilon_t. \quad (1)$$

The ADF auxiliary regression tests for a unit root in $y_t$, where $y$ refers to crude oil spot and futures prices, $t = 1, \ldots, T$ is an index of
time and $\Delta y_{t-j}$ is the lagged first differences to accommodate serial correlation in the errors. Eq. (1) tests the null hypothesis of a unit root against a trend stationary alternative. In Eq. (1), the null and the alternative hypotheses for a unit root in $y_t$ are: $H_0: \Delta y_t = 0$ and $H_1: y_t < 0$. The PP unit root test is also based on Eq. (1), but without the lagged differences. While the ADF test corrects for higher-order serial correlation by adding lagged difference terms to the right-hand side, the PP unit root test makes a non-parametric correction to account for residual serial correlation. The available evidence from Monte Carlo studies suggests that the PP unit root test generally has greater power than the ADF test (see Banerjee et al., 1993).

Schmidt and Phillips (1992) propose an LM-based unit root test without a structural break

$$y_t = \psi + \xi t + X_t. \quad (2)$$

Here $X_t = \beta X_{t-1} + e_{ij}$ and $e_{ij} \sim iidN(0, \sigma^2)$. $\psi$ and $\xi$ are the nuisance parameters representing level and deterministic trend, respectively. The null hypothesis of a unit root is the same as in the ADF and PP unit root tests, that is $\beta = 1$. LM test statistics are obtained from the following regression:

$$\Delta y_t = c + \phi_1 y_{t-1} + \epsilon,$$  \quad (3)

where $c$ is the constant term, $\epsilon$ is the error, $\phi_1 = y_{t-1} - \psi - \xi(T-1)$ and $\psi = y_1 - \epsilon$. Schmidt and Phillips (1992) proposed two statistics—$\rho$ and $\tau$ to test the null hypothesis of a unit root.

4.2. LM unit root test with one and two structural breaks

A limitation of these tests is that do not take into account potential structural breaks in crude oil prices. Perron (1989) was the first to point out that power to reject the unit root null declines if the data contains a structural break that is ignored. Perron (1989) incorporated an exogenous structural break into an ADF test. The subsequent literature has extended the ADF-type unit root test to incorporate one and two endogenous structural breaks (Zivot and Andrews, 1992; Lumsdaine and Papell, 1997). As an alternative to ADF-type tests, Lee and Strazichic (2003, 2004) extend the LM unit root test proposed by Schmidt and Phillips (1992) to develop LM unit root tests with one and two structural breaks. The Zivot and Andrews (1992) and Lumsdaine and Papell (1997) ADF-type endogenous break unit root tests both have the limitation that the critical values are derived while assuming no break(s) under the null hypothesis. Nunes et al. (1997) showed that this assumption leads to size distortions in the presence of a unit root with structural breaks. As a result, when utilising ADF-type endogenous break unit root tests, one might conclude that a time series is trend stationary, when in fact it is non-stationary with break(s), meaning that spurious rejections might occur. The LM unit root test has the advantage that it is unaffected by breaks under the null (Lee and Strazichic, 2001).

Lee and Strazichic (2004) developed two versions of the Schmidt and Phillips (1992) LM unit root test with one structural break. Using the nomenclature of Perron (1989), Model A is known as the “crash” model and allows for a one-time change in the intercept under the alternative hypothesis. Model A can be described by $Z_t = [1,t,D_t]$, where $D_t = 1$ for $t > T_b + 1$ and zero otherwise, $T_b$ is the date of the structural break, and $\delta' = (\delta_0, \delta_2, \delta_3)$. Model C, the “crash-cum-growth” model, allows for a shift in the intercept and a change in the trend slope under the alternative hypothesis and can be described by $Z_t = [1,t,D_t]$, where $D_t = 1 - T_b$ for $t > T_b + 1$ and zero otherwise.

Lee and Strazichic (2003) developed a version of the LM unit root test to accommodate two structural breaks. The endogenous two-break LM unit root test can be considered as follows. Model AA, as an extension of Model A, allows for two shifts in the intercept and is described by $Z_t = [1,t,D_t,D_{23}]$, where $D_{23} = 1$ for $t > T_b + 1$, $j = 1$ and 0 otherwise. $T_b$ denotes the date when the breaks occur. Note that the DGP includes breaks under the null ($\beta = 1$) and alternative ($\beta < 1$) hypothesis in a consistent manner. In Model AA, depending on the value of $\beta$, we have the following null and alternative hypotheses:

$$H_0: \gamma_1 = \mu_0 + d_1 B_{1t} + d_2 B_{2t} + \gamma_{y_{t-1}} + v_{t1},$$

$$H_A: \gamma_1 = \mu_1 + \gamma_t + d_1 D_{1t} + d_2 D_{2t} + v_{t2},$$

where $v_{t1}$ and $v_{t2}$ are stationary error terms; $B_{jt} = 1$ for $t = T_b + 1$, $j = 1$ and 0 otherwise. Model CC, as an extension of Model C, includes two changes in the intercept and the slope and is described by $Z_t = [1,t,D_{1t},D_{23},D_{123}]$, where $D_{123} = 1 - T_b$, $j = 1, 2$ and 0 otherwise. For Model CC we have the following hypotheses:

$$H_0: \gamma_1 = \mu_0 + d_1 B_{1t} + d_2 B_{2t} + d_3 B_{3t} + d_4 D_{23} + d_5 D_{123} + \gamma_{y_{t-1}} + v_{t1},$$

$$H_A: \gamma_1 = \mu_1 + \gamma_t + d_1 D_{1t} + d_2 D_{2t} + d_3 D_{12t} + d_4 D_{23t} + d_5 D_{123t} + v_{t2},$$

where $v_{t1}$ and $v_{t2}$ are stationary error terms; $B_{jt} = 1$ for $t = T_b + 1$, $j = 1, 2$ and 0 otherwise. The LM unit root test statistic is obtained from the following regression:

$$\Delta y_t = \delta' Z_t + \phi_1 y_{t-1} + \mu_0,$$

where $\delta' = \delta Z_t$, $\phi_1 = y_{t-1} - \psi - \xi(T-1)$ and $\mu_0$ is the constant term. The $t$-statistic for testing the null hypothesis is $t = t$-statistic for testing the unit root null hypothesis that $\delta = 0$. The location of the structural break ($T_b$) is determined by selecting all possible break points for the minimum $t$-statistic as follows:

$$\min_{\lambda} t(\lambda) = \max_{\lambda} t(\lambda)$$

where $\lambda = T_b/T$.

The search is carried out over the trimming region (0.15$T$, 0.85$T$), where $T$ is the sample size. We determined the breaks where the endogenous two-break LM $t$-statistic is at a minimum. Critical values for the one-break case are tabulated in Lee and Strazichic (2004), while critical values for the two-break case are from Lee and Strazichic (2003).

5. Data and potential structural breaks

We use weekly spot and futures prices at 1, 3 and 6 months to maturity for the two benchmark crude oils over the period spanning January 1991–December 2004. We use US WTI and the UK Brent as the representative crudes for this analysis since these two crudes have well-established spot and futures markets. WTI futures are traded on the NYMEX and Brent futures are traded on the Intercontinental Exchange (ICE). Wednesday prices were chosen to extrapolate the day of the week effect. If the market was closed on Wednesday, the price of the previous trading day was used. The source for the spot prices is the Energy Information Administration (EIA), while futures prices were taken from NYMEX and ICE. Notice that for all of the series WTI was priced higher than Brent.

Inspection of Figs. 1–4 for spot prices and futures prices at 1, 3 and 6 months to maturity suggest oil prices can be characterised by a small number of structural breaks and a large number of jumps. But over the whole sample period, both the duration and the length of jumps changed. From January 1991 to November 1998 there were small shocks that affected the mean value of prices, but prices returned to the mean value with different speeds.
of adjustment. Over the period, November 1998–December 2004, the behaviour of oil prices drastically changed and became more volatile. During this timeframe, oil prices were governed by cycles of local upward and downward trends initiated by a particular shock. The duration of these cycles substantially differs from time to time and is dependent on the nature of the shock. More adverse shocks caused longer cycles. Moreover, the downward shocks were generally more abrupt than the upward shocks, which in turn were more cumulative. An example of the abrupt downward movement in both spot and futures was a big drop in price on 17 September 2001 when the New York Stock Exchange and the NYMEX reopened after 11 September 2001 for the first time. An example of a series of cumulative upward movements was an increase in prices from May 2003 until prices reached a peak in December 2003. This implies that in the oil market it is possible to have one large shock (such as the first or second Gulf war) as well as a series of combined smaller shocks that change the trajectory of prices.

Similar conclusions can be drawn from an examination of futures prices at all maturities. That is, futures prices for the two different crudes and different months to maturity respond to shocks in the same manner. Moreover, futures respond to the same shocks as spot prices. Based on Figs. 1–4 it can be seen that both spot and futures prices are very volatile and are characterised by large jumps, particularly in the later time period of the sample. If there was a large jump in the spot market, this immediately translated into a jump in the futures market. There are no separate jumps that occur in one market only. According to theories of price determination for storable commodities (see, e.g. Working, 1948, 1949; Telser 1958), such jump behaviour in crude oil prices can be largely attributed to shocks in demand and supply and resulting demand/supply disequilibrium.

Fig. 5 presents a crude oil market chronology, highlighting events that have impacted on oil prices. The most drastic events in terms of their impact on oil prices have been the Asian financial
crisis and Russian default, which caused a large decrease in the price of oil, which combined with increased OPEC production in 1998 “sent prices into a downward spiral” (Williams, 2005).

Another important event was the 11 September 2001, terrorist attack, which caused a sudden sharp decline in both spot and futures oil prices. Political unrest in Venezuela in the first 6 months of 2002 caused an increase in oil prices. This was not a separate event, but a series of events in Venezuela that kept oil markets in a perpetual state of unrest. The second Gulf War in March 2003—caused an immediate drop in oil prices. In the few months prior to the war, WTI and Brent futures prices increased due to fears of market participants that Iraq’s oil pipelines and oil fields would be destroyed in the first days of the war. However, this did not happen. The first Gulf War, on the contrary, caused a long sharp upward swing in oil prices. Consistent with efficient market theory, there is either no time lag or only a very small time lag in the market reaction to news. Thus, the oil market is very sensitive not only to news, but also to the expectation of news. For example, prices started increasing at the beginning of March 1999, several days before a meeting of oil-producing countries. On 23 March 1999, OPEC and non-OPEC countries agreed to decrease the combined production of crude oil, which increased prices even further. Events that were connected to oil-producing countries or the largest consumers of oil such as the US have had a greater impact on oil prices than events unrelated to the oil market. For example, the strike in Venezuela affected oil prices more than the outbreak of severe acute respiratory syndrome (SARS) in 2002.

6. Results

The results for the ADF and PP tests are reported in Table 1. We tested two specifications of the ADF and PP tests. The first specification included a constant only and the second specification included a constant and a time trend. Since the constant and time trend combination was significant in each specification, this appears to be a better fit for the data. On the basis of the modified Akaike information criterion, the maximum lag was selected to be eight. For both the ADF and PP tests and for each of the series the null hypothesis of a unit root cannot be rejected at the 5% level. The results of the Schmidt and Phillips (1992) LM unit root test without a structural break are reported in Table 2. The results are consistent with those of the ADF and PP unit root tests. The null hypothesis of a unit root cannot be rejected. These results, however, could be biased because of the failure to account for structural change in the data. Tables 3 and 4 present the results for the LM unit root test with a break in the intercept and a break

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**Fig. 5.** Crude oil market chronology (based on WTI): January 1991–December 2004. Source: Based on the EIA (2006) Annual Oil Market Chronology.

**Table 1**

ADF and Phillips-Perron unit root tests for oil spot and futures prices

| Variable   | ADF unit root test | Phillips-Perron unit root test |
|------------|--------------------|-------------------------------|
|            | With constant | With constant and trend | With constant | With constant and trend |
| Brent Spot | –1.7103 (0.4256) | –3.2992 (0.0671) | –1.3644 (0.6007) | –3.1090 (0.1049) |
| Brent 1-month | –1.4217 (0.5727) | –3.0595 (0.117) | –1.2847 (0.6384) | –3.0468 (0.1203) |
| Brent 3-month | –0.8063 (0.8163) | –2.4741 (0.3411) | –0.7728 (0.8256) | –2.4748 (0.3407) |
| Brent 6-month | –0.2444 (0.9301) | –1.8765 (0.6657) | –0.2465 (0.9298) | –1.8835 (0.6621) |
| WTI Spot | –1.3719 (0.5971) | –2.9221 (0.156) | –0.9812 (0.7615) | –2.6747 (0.2476) |
| WTI 1-month | –1.3292 (0.6175) | –2.8818 (0.3691) | –0.9410 (0.7751) | –2.6093 (0.2762) |
| WTI 3-month | –0.6975 (0.8452) | –2.3089 (0.4281) | –0.5731 (0.8737) | –2.2856 (0.4408) |
| WTI 6-month | 0.0057 (0.9578) | –1.5724 (0.8031) | 0.0572 (0.9622) | –1.5457 (0.813) |

Note: p-Values for the ADF and Phillips-Perron statistics are given in parentheses.
in the intercept and trend. We could not reject the unit root null for either model with any of the series.

We now turn to examining the location of the break points. It is important to note that estimation of an endogenous break point will not be precise and will not match a particular event date by date (Christiano, 1992; Lee and Straizic, 2001; Sen, 2003). Therefore, it is not possible to analyse the speed of the reaction to the news in different markets based on the estimated break points. Moreover, because the breakpoints are determined endogenously, it is possible that the breakpoints will differ across Models A, C, AA and CC. This is consistent with previous studies that have employed either the LM unit root test with structural breaks or ADF-type unit root tests with structural breaks (see Lee & Stazicz, 2003; Lumsdaine & Papell, 1997). In Model A, each of the break points are statistically significant at the 10% level or better and for seven of the eight series the breakpoint is statistically significant at the 1% level. In Model C, the break in the intercept is not statistically significant, while the break in the trend is statistically significant for Brent spot, 1-month Brent and 6-month WTI at the 10% level or better. Models A and C suggest different break dates. While the breakpoint results may differ across methods we would expect that the break point would be the same for a particular model across the series due to interconnection between spot and futures markets. While the choice of a break point does not coincide within the series, oil prices respond to the same shocks, although with different time lags. For Model A the breakpoint is the same for Brent spot, Brent 1-month and Brent 3-month (8 November 2000) and WTI spot, WTI 1-month and WTI 3-month (7 May 2003). The breakpoint for Brent 6-month and WTI 6-month lag their respective spot prices and shorter maturities by 1–2 months. The breakpoints for Brent spot, Brent 1-month, Brent 3-month and Brent 6-month, follow a period between January 1999 and September 2000 during which oil prices tripled due to a cumulative effect of high world oil demand, OPEC oil production cutbacks, a cold winter in the US and low oil stock levels. The breakpoint for WTI spot, WTI 1-month, WTI 3-month and WTI 6-month coincided with the second Gulf war, a decision by the European Parliament to introduce an emissions trading scheme as well as Hurricane Claudette, which adversely affected Texan oil production in July 2003.

In Model C, each of the break points occurred between November 1997 and September 1999. The breaks at the end of 1997 and in 1998 could be a reflection of the Asian financial crisis and consequent reduced demand for oil from Asia. The break in Brent spot, Brent 1-month, WTI spot and WTI 1-month follow several relevant events in 1999. For example, in May 1999, the US adopted a plan to reduce nitrogen oxides (NO\textsubscript{x}) emission levels from cars and light-duty trucks, which also required refineries to reduce gasoline sulphur content and which affected standards for refined oil imported to the US. In addition, in June 1999, Sudan started operating a pipeline linking its Heglig oil field to Port Sudan on the Red Sea. The location of these break points also reflected activity of the oil majors on the stock market. For instance, BP announced its plan to finalise a merger with Amoco on 16 and 18 July, Elf Aquitaine attempted a takeover of Total Fin.

**Tables 5 and 6 present the results for the LM unit root tests with two breaks in the intercept (Model AA) and two breaks in the intercept and trend (Model CC). In both Models AA and CC, the null hypothesis of a unit root with two structural breaks could not be rejected. In Model AA, at least one of the breaks in the intercept is statistically significant. In Model CC, the breaks in the intercept are statistically insignificant, but the breaks in trend are statistically significant. In Model AA, the first break for each of the series except 1- and 6-month Brent and 6-month WTI futures occurred in 2000 and the second break occurred in 2003. The first break in the series could be due to a terrorist attack on the US warship, Cole, in Yemen in October 2000. The second break could be a reaction to the Gulf war in Iraq, which started in March 2003. For 1-month Brent the first break occurred in 2001 and the second break occurred in 2003. This can be seen as a reaction to what occurred in the Brent spot market, where the difference between the second break in the spot market and the first break in the 1-month futures market is 2 weeks. Both breaks could be a reaction to December and January events, which involved problems with the natural gas market in the US. For 6-month Brent, both breaks occurred in 2001 and for 6-month WTI both breaks occurred in 2003. For 3-month Brent only the first break was significant. In Model CC, the first break for each series occurs in 1999 and is associated with the same events as the one-break case, while the second break occurs at the time of the terrorist attack on the World Trade Centre in New York.**

### Table 2

| Variable | Intercept | Trend | $\tau$ | $\rho$ |
|----------|-----------|-------|--------|-------|
| Brent Spot | 0.3017** (2.091) | 0.0008*** (1.061) | -2.1104 | -8.8352 |
| Brent 1-month | 0.2534* (1.900) | 0.0008*** (3.009) | -2.3617 | -11.0818 |
| Brent 3-month | 0.1629 (1.434) | 0.0006*** (2.794) | -2.5694 | -13.1481 |
| Brent 6-month | 0.0995 (0.995) | 0.0004** (2.532) | -2.3852 | -9.5283 |
| WTI Spot | 0.2759* (-1.851) | 0.0008*** (-2.863) | -1.4787 | -4.3396 |
| WTI 1-month | 0.2669* (1.815) | 0.0008*** (-2.853) | -1.5493 | -4.7448 |
| WTI 3-month | 0.1665 (1.335) | 0.0006*** (2.683) | -1.9782 | -7.7917 |
| WTI 6-month | 0.0801 (0.762) | 0.0004** (2.374) | -1.9128 | -7.3055 |

**Note:** 1-Statistics for dummy coefficients are given in parentheses.
**Significant at 10%.
**Significant at 5% level.
**Significant at 1% level.

### Levels of significance for $p$-statistic

| 1%  | 5%  | 10% |
|-----|-----|-----|
| -25.2 | -18.1 | -15 |

### Levels of significance for $\tau$-statistic

| 1%  | 5%  | 10% |
|-----|-----|-----|
| -3.58 | -3.02 | -2.75 |
used the LM unit root test with one and two breaks in the intercept (Models A and AA) and intercept and trend (Models C and CC). The LM unit root test with structural breaks has the advantage over ADF-type unit root tests with structural breaks that it is unaffected by breaks under the null. We find that each of the oil price series can be characterised as a random walk process and that the evidence of mean reversion over very long periods of time, although even in these cases the rate of mean reversion is so slow as to create large errors in the optimal investment rule''. Our results suggest that for the purposes of making investment decisions one could just as equally treat the crude oil price as a Geometric Brownian Motion or related random walk process. As Pindyck (1999, p. 25) concludes, based on analysis of data spanning more than a century: "These numbers suggest that for irreversible investment decisions for which energy prices are the key stochastic variable, centuries are sufficient."

Some important policy implications emerge from our findings. First, for forecasting purposes, the fact crude oil prices exhibit a random walk means that it is not possible to forecast future movements in crude oil prices based on past behaviour, at least for the timeframe considered in this study. The proviso is that studies such as Pindyck (1999) and Postali and Picchetti (2006) find evidence of mean reversion over very long periods of time, although even in these cases the rate of mean reversion is so slow that for the purposes of making investment decisions one could just as equally treat the crude oil price as a Geometric Brownian Motion or related random walk process. As Pindyck (1999, p. 25) concluded, based on analysis of data spanning more than a century: "These numbers suggest that for irreversible investment decisions for which energy prices are the key stochastic variable, the Geometric Brownian Motion assumption is unlikely to lead to large errors in the optimal investment rule". Our results suggest this is particularly true for shorter periods of time, even after allowing for structural breaks in crude oil prices.

Table 3
LM unit root test results for Model A

| Variable     | Lag order | TB            | B(t)       | LM test statistic |
|--------------|-----------|---------------|------------|------------------|
| Brent Spot   | 7         | 8 November 2000 | 2.4073** (2.1951) | −1.8959          |
| Brent 1-month| 7         | 8 November 2000 | 2.2698** (2.762)  | −1.924           |
| Brent 3-month| 7         | 8 November 2000 | 1.7886** (2.1651) | −1.763           |
| Brent 6-month| 7         | 31 January 2001 | 2.2906*** (3.2881) | −1.5882         |
| WTI Spot     | 7         | 7 May 2003     | 2.6236*** (2.3244) | −1.8851         |
| WTI 1-month   | 7         | 7 May 2003     | 2.7899*** (2.5212) | −1.8619         |
| WTI 3-month   | 7         | 7 May 2003     | 1.9549** (2.1659)  | −1.5657         |
| WTI 6-month   | 6         | 11 June 2003   | 1.3865** (1.8179)  | −2.4359         |

Note: TB is the date of the structural break; B(t) is the dummy variable for the structural break in the intercept. Figures in parentheses are t-values. Critical values for the LM test statistic from Lee and Strazicich (2004) at the 10%, 5% and 1% significance levels are −3.211, −3.566, −4.239. Critical values for the dummy variables follow the standard normal distribution. *, ** and *** denote statistical significance at the 10%, 5% and 1% levels, respectively.

Table 4
LM unit root test results for Model C

| Variable     | Lag order | TB            | B(t)       | D(t)     | LM test statistic |
|--------------|-----------|---------------|------------|----------|------------------|
| Brent Spot   | 7         | 11 August 1999 | 0.2978 (0.2739) | 0.2310*** (2.3242) | −2.9267          |
| Brent 1-month| 7         | 1 September 1999 | 1.2228 (1.2359) | 0.1815* (2.0943)  | −2.8382         |
| Brent 3-month| 7         | 17 December 1997 | −0.0001 (−0.0012) | 0.0333 (0.5425)  | −2.9244         |
| Brent 6-month| 7         | 17 December 1997 | 0.0689 (0.0993) | −0.0039 (−0.0703) | −2.9149         |
| WTI Spot     | 7         | 8 September 1999 | 1.0925 (1.5019) | 0.1428 (1.5939)  | −2.7890         |
| WTI 1-month   | 7         | 8 September 1999 | 1.6459 (1.5115) | 0.1390 (1.6078)  | −2.7563         |
| WTI 3-month   | 7         | 12 November 1997 | −0.0538 (−0.0597) | 0.0009 (0.0127)  | −2.6929         |
| WTI 6-month   | 5         | 19 August 1998  | 0.9389 (1.2344) | −0.1461 (−1.8732) | −3.9825         |

Note: TB is the date of the structural break; B(t) is the dummy variable for the structural break in the intercept; D(t) is the dummy variable for the structural break in the slope. Figures in parentheses are t-values. The critical values for the LM test statistic depend on the location of the break and are as follows:

| Location of break, l | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 |
|-----------------------|-----|-----|-----|-----|-----|
| 1% significance level | −5.11 | −5.07 | −5.15 | −5.05 | −5.11 |
| 5% significance level | −4.50 | −4.47 | −4.45 | −4.50 | −4.51 |
| 10% significance level | −4.21 | −4.20 | −4.18 | −4.18 | −4.17 |

Critical values for the dummy variables follow the standard normal distribution. *, ** and *** denote statistical significance at the 10%, 5% and 1% levels, respectively.

Table 5
LM unit root test results for Model AA

| Variable     | Lag order | TB1, TB2   | B1(t)       | B2(t)       | LM test statistic |
|--------------|-----------|------------|------------|------------|------------------|
| Brent Spot   | 6         | 11 August 2000, 17 January 2001 | 2.7868*** (2.5406) | 2.2902** (2.0739) | −2.3594          |
| Brent 1-month| 8         | 31 January 2001, 7 May 2003    | 3.3134*** (3.3241) | 2.9272 (2.8599)  | −2.1822         |
| Brent 3-month| 7         | 8 November 2000, 5 March 2003  | 1.7986** (2.1640) | 1.4258 (1.7328)  | −1.9010         |
| Brent 6-month| 3         | 31 January 2001, 1 August 2001 | 2.5141*** (1.4517) | 0.8011 (1.0989)  | −2.5974         |
| WTI Spot     | 7         | 7 June 2000, 7 May 2003       | 3.2294*** (2.8400) | 2.6347*** (2.3282) | −2.6065         |
| WTI 1-month   | 7         | 12 January 2000, 7 May 2003   | 3.1693*** (2.9004) | 2.7283*** (2.4996) | −2.0182         |
| WTI 3-month   | 7         | 7 November 2000, 7 May 2003   | 2.0606** (2.2611) | 1.9785** (2.1885) | −1.7203         |
| WTI 6-month   | 7         | 7 May 2003, 4 April 2003      | 1.2168* (1.6772)  | 1.2897* (1.7841)  | −1.4620         |

Note: TB1 and TB2 are the dates of the structural breaks; B1(t) and B2(t) are the dummy variables for the structural breaks in the intercept. Figures in parentheses are t-values. The critical values for the LM test at 10%, 5% and 1% significance levels are −3.564, −3.842, −4.545. *, ** and *** denote statistical significance at the 10%, 5% and 1% levels, respectively.
Table 6

| Variable          | Lag order | B1(t) | B2(t) | D1(t) | D2(t) |
|-------------------|-----------|-------|-------|-------|-------|
| Brent Spot        | 7         | -1.3955 (2.3882) | 1.0786** (1.0652) | -0.9322 (1.3606) | -0.4311 (1.3757) |
| Brent 1-month     | 7         | 0.5614 (0.3053)  | 0.4597** (0.4022)  | 0.3589 (0.3070)  | -0.4562 (0.5396)  |
| Brent 6-month     | 7         | -0.1385 (1.0686) | 0.4812 (0.4950)    | 0.3269** (0.3620) | 0.3753 (0.4692)   |
| WTI Spot          | 7         | -1.2690 (2.0693) | 0.5689** (1.3817)  | 0.3578** (1.1371) | -0.8585 (0.6193)  |
| WTI 1-month       | 7         | -1.2495 (1.8711) | 0.5626 (0.6596)    | 0.3476 (0.6860)  | -0.8653 (0.6596)  |
| WTI 6-month       | 7         | -0.6523 (0.9006) | 0.3591 (0.2957)    | 0.2174 (0.2957)  | -0.4311 (1.3757)  |

Note: B1(t) and B2(t) are the dummy variables for the structural breaks in the trend. Figures in parentheses are t-values. For model CC, critical values depend on the location of the breaks and are as follows:

| r | 0.1 | 0.05 | 0.01 |
|---|-----|------|------|
| 1 | 6.16 | 6.25 | 6.33 |
| 2 | 5.27 | 5.33 | 5.37 |
| 3 | 5.32 | 5.37 | 5.40 |

Second, our findings provide support for the integrity of much of the literature on real options, which assumes that input costs, output prices and other pertinent stochastic state variables follow a Geometric Brownian Motion (Pindyck, 1999). Our results, together with studies employing data over long periods that find at best slow mean reversion, suggest that Geometric Brownian Motion assumption will not lead to meaningful undervaluation or overvaluation. If Geometric Brownian Motion is a good proxy for movements in crude oil prices, modellers can take advantage of its operational friendliness, effectively sidestepping the complexities of complex structural models (Postali and Picchetti, 2006).

Third, our findings that oil spot markets and oil futures markets are efficient in the weak form mean that future spot and futures prices cannot be predicted based on past prices. If futures markets are efficient and participants have full information, the futures market will allocate the investment to the most efficient outcome and individual investors with a diversified portfolio can invest with confidence. This, in turn, suggests that institutional and regulatory mechanisms will not be as important, compared with the situation where price movements could be exploited to make profits using technical analysis.

Fourth, the fact that oil prices exhibit a random walk suggests that other macroeconomic variables that are linked to oil prices via flow-on effects such as income and output will potentially inherit that non-stationarity and transmit it to major economic variables such as employment. If non-stationarity in oil prices spread to the real economy, this questions empirical support for business cycle theories and a range of macro theories. As Cochrane (1994, p. 241) notes, lack of mean reversion in real output “challenges a broad spectrum of macroeconomic theories designed to produce and understand transitory fluctuations”.

A limitation on the results here is, as Lumdsdaine and Papell (1997, p. 218) note, “we have little reason to expect that there have been exactly two structural breaks [in the series considered]. In addition, our results do not address the possibility that even higher-order models are more appropriate. This begs the question of where to go next—to a model with three breaks?” There are at least two possibilities, which future research on the stochastic properties of oil prices could follow. One avenue of enquiry would be to apply unit root tests with more than two breaks. Ohara (1999) has developed an ADF-type unit root test with multiple structural breaks, while Westerlund (2006) has developed an LM unit root test with multiple structural breaks. We note, though, the more breaks which are added to the model, the closer the crude oil price series will be to a random walk and the less relevant are unit roots with structural breaks (see Mehl, 2000, p. 376).

If regime-wise stationarity could be established, allowing for further structural breaks or using data over much longer periods, for which previous studies have found mean reversion, a second avenue of research would be to test for the presence of multiple structural breaks using the method proposed by Bai and Perron (1998). The Bai and Perron (1998) method can be applied to test for, and estimate, multiple structural changes once regime-wise stationarity has been established. This could be extended, using the approach pioneered by Caporale and Grier (2000) to examine political influences on interest rates, to investigate the factors that explain oil price shocks. This could contribute to the recent literature modelling oil price shocks (see e.g. Kilian, 2005, 2007, 2008).

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