BUBBLING OVER ALONG THE OIL FUTURES YIELD CURVE

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Abstract

We employ novel tests to investigate WTI crude oil spot and futures prices along the yield curve for the presence of rational bubbles. The empirical methodology adopted is consistent with periods of multiple bubbles and permits the origination and end dates of each bubble to be identified. The results indicate that all but the spot and nearby series exhibit significant bubble periods ending in late 2008. Moreover, the dating algorithms establish that the bubbles in longer-dated contracts start much earlier and are longer lasting than the bubble in the 3- to 12-month contracts. This information from the oil futures yield curve suggests a period of disconnect between the spot and longer dated futures contracts from 2004 to late 2008 which coincides with a spell of increased institutional investment in oil futures.

JEL code: G10, C15, C22

Keywords: Multiple bubbles; Spot and futures prices; Bubble dating algorithm; Bubble duration.

1 Introduction

The equilibrium price of a security with infinite maturity equals its fundamental value plus a bubble component. When the bubble grows and dominates the fundamental value, it induces explosive behaviour in the price series. Exploiting this property, we apply a battery of tests to examine the null hypothesis that there is no bubble in spot and futures oil prices. We include in our analysis contracts with maturities of up to twenty four months to account for differing investment strategies along the yield curve. To the best of our knowledge, this is the first paper to investigate bubbles in crude oil futures prices across the spectrum of maturities out to two years. We employ the dating strategy introduced by Phillips, Shi, and Yu (2012 to identify the origination and end dates of the bubbles. This strategy can take into account the possibility of multiple bubbles and consistently estimates the origination and collapse dates of each bubble even when they are of different magnitude.

This paper employs monthly data 1995M09-2012M04 to investigate the time series properties of WTI crude oil spot and (3- to 24-month) futures contracts listed on NYMEX. Our empirical analysis produces some novel results. Firstly, while the spot and nearby contracts exhibit no evidence of bubbles according to two of our three dating procedures, all other series exhibited extended periods of bubble behaviour that end in late 2008. This paper is the first to find evidence of this striking disconnect which is difficult to reconcile with rational behaviour using standard models.[1] Secondly, the dating algorithms indicate that the bubble in longer-dated contracts started much earlier and were longer lasting than the bubble in the 6-to 12-month contracts. For instance the results from all three data stamping procedures indicate a continuous bubble for 24-month contract over the 2004-2008 period. Finally, the evidence for contracts 15 through to 24 suggest that the bubbles originated in early 2004.

Our results are consistent with the findings of Buyuksahin, Haigh, Harris, Overdahl, and Robe (2009). They utilise a unique CFTC Large Trader Reporting System (LTRS) position dataset, which allows them to investigate the evolution of futures trading activity by trader type and contract maturity. They argue that the positions of hedge funds and non-registered participants in long-dated futures have increased significantly since early 2004-2005. However, hedge funds are often recognised as sophisticated institutional investors. Their trading activities would correct for any price deviations from fundamental levels and contribute towards market efficiency, preventing the occurrence of bubbles (see Fama, 1965). Contrary to the efficient market prospective, Abreu and Brunnermeier (2003) consider an economy where rational agents would deliberately allow bubbles to persist. Hedge funds may have been aware of the mispricing of long-dated futures but preferred to benefit from it rather than correct it.

Our paper contributes to the financialisation debate. The origination date of bubble periods found in the longer-dated futures contracts coincides with the sharp increase of investor interest in commodity markets. Tang and Xiong (2012)

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[1] Jarrow and Protter (2009) investigate asset price bubbles under arbitrage free pricing theory in incomplete markets. Using a local martingale framework they show that futures prices can possess bubbles that are independent from the underlying asset's price bubble.

argue that from 2004 commodity futures markets entered an era of financialization. Commodities were then viewed as a distinct investment category and began to co-move positively with equity markets. In addition, Sockin and Xiong (2013) show how institutional investors might have contributed towards the commodity boom and bust cycles in 2007-2008. This has caused serious concerns among practitioners and policy makers that excessive speculation might have been the main driver of rising energy and food prices (see, e.g., Masters (2008), Soros (2008), US Senate Permanent Subcommittee on Investigations (2006)). However, our new results do not necessarily imply that excessive speculation in commodity futures markets contributed towards price deviations away from fundamental levels in the physical market. One of the challenges in evaluating this hypothesis is the lack of relevant data on institutional commodity contract positions over a sufficiently long period of time. Further empirical analysis is needed to clarify the potential source of bubble behaviour that we document.

Our results are closely related to those of Shi and Arora (2012) and Phillips and Yu (2011) who explore the crude oil market for bubble behaviour. Shi and Arora (2012) use the convenience yield implied by the nearest and second nearest contracts in three different regime switching models. They find a short-lived bubble in late 2008 and early 2009. Phillips and Yu (2011) apply a recursive right tail unit-root test, originally proposed by Phillips, Wu, and Yu (2009), to the spot price and again find a short bubble episode between March and July 2008. They show a potential transmission mechanism. The bubble behaviour in oil markets appears to have migrated from the housing market. We adopt the same recursive framework but introduce a series of other tests to provide robustness check on our findings.

Unlike these studies, we do not constrain our analysis by focusing on the price behaviour of only the spot or nearby futures contracts. Instead, we test for bubbles in the crude oil market along the spectrum oil futures yield curve from 1 to 24 months. In this sense, our paper also contributes to a strand of literature that investigates the role of futures markets in the process of price discovery. Futures contracts are not redundant securities and they are priced in conjunction with the spot contract. In an economy with risk neutral and rational agents, the contemporaneous futures price for delivery at a specified date should be an unbiased predictor of the future spot price. We show that, under the theory of rational bubbles, the futures price consists of the fundamental value and a bubble component at the maturity date of the contract. If a bubble develops, it should affect the time series properties of the futures contract earlier than the spot. However, while this is consistent with the episodes of bubble behaviour for 2008 in our results, it contradicts the earlier disconnect of longer-dated futures from the spot market.

The reminder of the paper is organised as follows. In section 2, we provide some theoretical background on the price-bubble relationship for storable commodities. We outline the motivations behind the used empirical methodology. Sections 3 and 4 describe the econometric approach for the purposes of our analysis. In Section 5, we present the data, provide some descriptive statistics. The empirical results are discussed in Section 6. Finally, Section 7 concludes.

2 The theory of rational bubbles in commodity markets

We follow Diba and Grossman (1988b) and explain the price change of storable commodities by the changes in expected future net payoffs defined as "fundamentals'. The current spot price of a commodity, S_t, is determined by the present value of next period's expected spot price, $E_t[S_{t+1}]$, and marginal convenience yield, C_t:

$$S_t = \frac{E_t[S_{t+1} + C_t]}{(1 + R)}. \tag{1}$$

where $E_t[.]$ denotes the expectation conditional on the information at time t. R is a time invariant interest rate. The net of storage cost marginal convenience yield measures the benefit from holding inventories per unit of commodity over the period t to $t + 1$ and is analogous to the dividend on a stock. Under the theory of storage it should satisfy the standard no arbitrage condition

$$C_t = (1 + \mathrm{R})\mathrm{S}_t - \mathrm{F}_{1,\mathrm{t}} \tag{2}$$

where $F_{1,t}$ denotes the futures price at time t for delivery of a commodity at $t + 1$. If S_t and C_t are both integrated processes, the series are cointegrated with specific cointegrating vector $[1, -1/R]$ (see Campbell and Shiller (1987)). Solving (2) for $F_{1,T}$ and extracting S_t from both sides, it follows that the difference between the futures and spot prices is the interest forgone in storing the commodity over the period t to $t + 1$, less the marginal convenience yield.

Solving the difference equation (1) forward and applying the low of iterated expectations, yields

$$S_t = E_t\left[\sum_{\tau=0}^{\infty}\frac{1}{(1+R)^{\tau+1}}C_{t+\tau}\right] + \lim_{\tau\to\infty} E_t\left[\frac{1}{(1+R)^{\tau}}S_{t+\tau}\right]. \tag{3}$$

Imposing the transversality condition $\lim_{\tau\to\infty} E_t[(1+R)^{-\tau}S_{t+\tau}] = 0$ eliminates the last term in (3). It follows that the price S_t collapses to the discounted sum of expected future payoffs, i.e. the fundamental value which will be denoted by S_t^f. However, if the transversality condition does not hold, there are infinitely many solutions to (3) that take the form:

$$S_t = S_t^f + B_t \tag{4}$$

where B_t is a bubble component that has to satisfy:

$$B_t = (1+R)^{-1}E_t\,[B_{t+1}]. \tag{5}$$

In other words, the bubble has to grow over time at a rate R in order for investors agree to hold the asset (see Blanchard and Watson (1982)). Diba and Grossman (1988a) argued that rational bubbles cannot be negative. If a bubble is negative, then when it erupts, it could make the price of the security negative also. In addition, if $B_t = 0$, (5) implies that $B_{t+1} = 0$ with probability 1. It follows that the existence of bubbles would be consistent with rationality only when $B_t > 0$.

Taken together, equations (1) and (2) imply that the futures price is an unbiased predictor of the future spot price

$$F_{1,t} = E_t[S_{t+1}] \tag{6}$$

Given the decomposition of the spot price in (5), it follows that the contemporaneous futures price with maturity $t+T$ embodies information about the expected value of the bubble component over the period t to $t+T$

$$F_{T,t} = E_t\left[S^f_{t+T}\right] + E_t[B_{t+T}] \quad (7)$$

In line with (5), the bubble is expected to grow exponentially at rate R, i.e. $E_t[B_{t+T}]$ contains the root $(1+R)^T$ that is greater than unity. If the bubble erupts at some future time $t+j$, for $1 < j < T$, it will induce an explosive behaviour in the price series futures contracts with maturity greater than $t+j$.

To test for rational bubbles in the stock market, Diba and Grossman (1988b) motivated the use of stationarity tests. However, Evans (1991) suggested that this approach would not efficiently detect periods of explosive behaviour if bubbles collapse periodically. Consistent with the process in (5), he considers bubbles described by:

$$\begin{aligned} B_{t+1} = {} & [(1+R)B_t I\{B_t \leq \alpha\} \\ & + [\varphi + \pi^{-1}(1+R)\theta_{t+1}(B_{t+1} - (1+R)^{-1}\varphi] I\{B_t > \alpha\}] u_{t+1} \end{aligned} \quad (8)$$

where $0 < \varphi < (1+R)\alpha$, u_{t+1} is a positive *iid* variable with $E_t[u_{t+1}] = 1$, and $I\{\cdot\}$ is an indicator function that assumes a value of 1 when the condition in the braces is true and 0 otherwise. θ_{t+1} is an *iid* Bernoulli process and the probability of $\theta_{t+1} = 0$ is $(1-\pi)$ and $\theta_{t+1} = 1$ is π, where $0 < \pi < 1$. Such a bubble would start to grow at a rate $(1+R)\pi^{-1}$ once it exceeds some threshold level α, but with a probability $(1-\pi)$ the bubble will collapse to an expected mean level φ. Since a bubble never collapses to zero it will start growing again without violating the non-negativity constraint given in Diba and Grossman (1988).

The non-linear bubble process in (8) causes the data series to exhibit characteristics similar to an integrated or even a stationary process. As a result, conventional unit root tests applied to the full sample would fail adequately to test the null hypothesis of no bubbles and could lead to false negatives. Phillips, Wu, and Yu (2011) suggested the application of a unit root test in a recursive window framework to overcome this drawback. Their approach allows the statistics to be time dependent and is able to detect explosive behaviour in time series even when bubbles are periodically collapsing.

3 Testing for explosive behaviour

Suppose we observe the sequence $\{Y_t\}_{t=1}^{T}$ and estimate the following atoregression:

$$Y_\tau = \delta_\tau Y_{\tau-1} + u_\tau \qquad \text{for} \qquad \tau = 1,2,\dots,\lfloor rT \rfloor \quad \text{and} \quad r \in [r_0, 1] \tag{9}$$

where u_τ is white noise, r is a fraction of the total sample and $\lfloor x \rfloor$ denotes the integer part of x. The recursive window of the regression expands by one observation at a time from some initial sample $\lfloor r_0 T \rfloor$. The tests adopted in our empirical analysis are performed under the null that the time series contain a unit root for every τ:

$$H_0\colon \delta_\tau = 1 \qquad \text{for} \qquad \tau = 1,2,\dots,\lfloor rT \rfloor \quad \text{and} \quad r \in [r_0, 1] \tag{10}$$

Under the alternative hypothesis, Phillips, Wu, and Yu (2011) specified a data generating process where the series starts as a unit root but switches to a regime of mildly explosive behaviour (δ is greater than unity but still in its vicinity) at date $\lfloor r_e T \rfloor$ until $\lfloor r_f T \rfloor$. At date $\lfloor r_f T \rfloor$ the series returns to a unit root regime. The model is defined as:

$$Y_\tau = Y_{\tau-1} I\{\tau < \lfloor r_e T \rfloor\} + \delta Y_{\tau-1} I\{\lfloor r_e T \rfloor \le \tau \le \lfloor r_f T \rfloor\} +$$

$$\left(\sum_{j=\lfloor r_f T \rfloor+1}^{\tau} u_j + Y^*_{\lfloor r_f T \rfloor}\right) I\{\tau > \lfloor r_f T \rfloor\} + u_\tau I\{\tau \le \lfloor r_f T \rfloor\}, \tag{11}$$

$$\delta = 1 + \frac{c}{T^a}, \quad c > 0, \quad a \in (0,1)$$

The restriction on parameter c and values of a over the specified open interval yields the mildly explosive process discussed in Phillips and Magdalinos (2007a, 2007b). The boundary as $a \to 1$ includes the local to unity case where defining a bubble period is not possible (see Phillips and Yu (2011)).

Phillips, Wu, and Yu (2011) suggested the application of Dickey-Fuller t-statistics (or the augmented version of Said and Dickey (1984)) to the recursive autoregression in (9) to test the null hypothesis of a unit root or no bubbles. The test statistic is given as

$$SDF_r^\tau = \sup_{r \in [r_0, 1]} \{DF_r^\tau\} \qquad \text{and} \qquad DF_r^\tau = \frac{\hat{\delta}_\tau - 1}{\hat{\sigma}_{\delta_\tau}} \tag{12}$$

where $\hat{\delta}_\tau$ is the least square estimator of δ_τ, and $\hat{\sigma}_{\delta_\tau}$ is the estimator of the standard deviation of $\hat{\delta}_\tau$.

A similar procedure, but under the assumption that observation $\lfloor rT \rfloor$ causes a break in the autoregressive coefficient, is a Chow-type test. The model is written as

$$\Delta Y_\tau = \begin{cases} u_\tau & \text{if } \tau \le \lfloor rT \rfloor \\ \delta Y_{\tau-1} + u_\tau & \text{if } \tau > \lfloor rT \rfloor \end{cases} \tag{13}$$

The null hypothesis $H_0\colon \delta = 0$ is tested against the alternative $H_1\colon \delta > 0$. Homm and Breitung (2012) suggested the following test statistic:

$$SDFC_r^\tau = \sup_{r\in[0,1-r_0]} \{DFC_r^\tau\} \qquad \text{and} \qquad DFC_r^\tau = \frac{\sum_{\tau=\lfloor rT\rfloor+1}^{T} \Delta Y_\tau Y_{\tau-1}}{\hat{\sigma}_\tau \sqrt{\sum_{\tau=\lfloor rT\rfloor+1}^{T} Y_{\tau-1}^2}} \tag{14}$$

where

$$\hat{\sigma}_\tau^2 = (T-2)^{-1} \sum_{\tau=2}^{T} (\Delta Y_t - \hat{\delta}_\tau Y_{t-1} I\{\tau > \lfloor rT\rfloor\})^2$$

$\hat{\delta}_\tau$ is the least squares estimator of δ from Equation (13).

Homm and Breitung (2012) also motivate the use of Busetti-Taylor statistics on the assumption that the series has a unit root up to observation $\lfloor rT\rfloor$ after which they switch to a regime of mildly explosive behaviour. Using a random walk model to forecast the final value Y_T from the periods $Y_{\lfloor rT\rfloor}, Y_{\lfloor rT\rfloor+1}, \dots, Y_{T-1}$should result in a large sum of squared forecast errors. The modified version of the statistic is given by,

$$SBT_r^\tau = \sup_{r\in[r_0,1]} \{BT_r^\tau\} \tag{15}$$

where

$$BT_r^\tau = \frac{T-1}{(T-\lfloor rT\rfloor)^2 \sum_{t=1}^{T} \Delta Y_t^2} \sum_{\tau=\lfloor rT\rfloor+1}^{T} (Y_T - Y_{\tau-1})^2$$

Evidence against the null hypothesis of no bubble in all of the above tests is obtained by comparing the sup statistics with the corresponding right-side critical values from the limit distribution. However, the above procedures do not facilitate the identification of the explosive period. In doing so, it is desirable to set some minimum duration for this bubble period successfully to discriminate between bubbles and short-lived blips.

4 Bubble dating strategies

Techniques that can help identify bubble periods are useful as a real-time monitoring procedures and early warning signals for bubble formation. They also overcome some weaknesses of the suggested tests above. For example, the $SDFC_r^\tau$ and SBT_r^τ procedures assume that the time series switches to mildly explosive behaviour at some date over the interval $[0,1-r_0]$. Homm and Breitung (2012), in extensive Monte Carlo simulations, have found that when there is a one-time change in the time series behaviour, even if this change is random, both tests have an advantage over the SDF_r^τ test in terms of power. But, if there is an additional break signalling a return to a unit root process, this advantage disappears.

The technique described next is robust to multiple breaks in the series. Under the data generating process in (9), the series switches from unit root to mildly explosive behaviour for a period of time and then returns to a unit root. The break dates are defined as $\lfloor r_e T \rfloor$ and $\lfloor r_f T \rfloor$, respectively. Phillips, Wu, and Yu (2011) provided consistent estimators of the break points as the first and last observation at which the SDF_r^τ statistic is significant at some level β_T. Phillips, Shi, and Yu (2012) consider a more general case where the SDF_r^τ statistics is computed backwards for the interval $r \in [r_0, 1]$ but the starting point varies over the feasible range $r^* \in [0, r-r_0]$. They show that this procedure is more efficient when multiple bubbles are present in the data.

The generalized test statistic is

$$GSDF_r^\tau = \sup_{\substack{r\in[r_0,1] \\ r^*\in[0,r-r_0]}} \left\{SDF_r^{r^*}\right\} \tag{16}$$

where SDF_r^τ is the sup Dickey-Fuller statistics given in (12) and calculated backwards from observation $\lfloor r^* T \rfloor$. The fraction points for the origination and collapse points of the bubble are generalized to:

$$\hat{r}_e^{GSDF} = \inf_{s \geq r_0} \left\{ s: SDF_s^{r^*} > cv_{\beta_T}(s) \right\} \quad \text{and}$$
$$\hat{r}_f^{GSDF} = \inf_{s \geq \hat{r}_e^{GSDF} + \gamma \frac{\ln(T)}{T}} \left\{ s: SDF_s^{r^*} < cv_{\beta_T}(s) \right\} \tag{167}$$

where cv_{β_T} are the right-side $100\beta_T\%$ critical values of the SDF_r^τ statistics.

Alternatively, Homm and Breitung (2012) considered two different statistics:

$$\text{CUSUM:} \quad S_{r_0}^r = \frac{1}{\hat{\sigma}_\tau} (Y_\tau - Y_{\lfloor r_0 T \rfloor})^2 \ \text{ for } \tau > \lfloor r_0 T \rfloor \tag{18}$$

$$\text{FLUC:} \quad Z_{r_0}^r = \frac{\hat{\delta}_\tau - 1}{\hat{\sigma}_{\delta_\tau}} = DF_r^\tau \quad \text{for } \tau > \lfloor r_0 T \rfloor \tag{19}$$

The FLUC monitoring procedure is the bubble dating algorithm suggested by Phillips, Wu, and Yu (2011). Both procedures are efficient real time bubble detectors when the monitoring horizon is fixed in advance. In our empirical analysis we apply the procedures to a historical dataset. This is because we are interested in knowing whether there were bubble periods, when they originated and ended, and how long they lasted. We employ a modified version of the CUSUM and FLUC monitoring procedures to estimate the fraction for the origination and collapse points of the bubble as:

$$\hat{r}_e^{CUSUM} = \inf_{s \geq r_0} \left\{ s: S_{r_0}^s > cv_{\beta_T}(s) \right\} \quad \text{and}$$
$$\hat{r}_e^{FLUC} = \inf_{s \geq r_0} \left\{ s: Z_{r_0}^s > cv_{\beta_T}(s) \right\} \tag{17}$$

and

$$\hat{r}_f^{CUSUM} = \inf_{s \geq \hat{r}_e^{CUSUM} + \gamma \frac{\ln(T)}{T}} \left\{ s: S_{r_0}^s < cv_{\beta_T}(s) \right\} \quad \text{and}$$
$$\hat{r}_f^{FLUC} = \inf_{s \geq \hat{r}_e^{FLUC} + \gamma \frac{\ln(T)}{T}} \left\{ s: Z_{r_0}^s < cv_{\beta_T}(s) \right\} \tag{18}$$

where $\gamma \frac{\ln(T)}{T}$ suggested by Phillips and Yu (2011) is the minimum duration necessary for a part of the series to qualify as a bubble period. The parameter is chosen based on the sampling frequency so that periods shorter than $\left\lfloor \gamma \frac{\ln(T)}{T} \right\rfloor$ observations are considered insignificant. The cv_{β_T} are the right-side $100\beta_T\%$ critical values of the corresponding test statistic. To consistently estimate the origination and collapse dates of the explosive periods β_T is allowed to depend on the sample size. For the empirical analysis, we use the boundary functions suggested by Homm and Breitung (2012). The procedures in (18) and (19) are executed with the initial observation as a starting point in contrast with that of Phillips, Shi, and Yu (2012).

5 Data and sample characteristics

Daily WTI crude oil prices for the spot and futures contracts on NYMEX were downloaded from Datastream for the September 1995 to April 2012 period. The starting date of the sample was dictated by the availability of continuous series for contracts 15 to 24. Data were collected for a range of maturities along the yield curve including contracts 1, 3, 6, 9, 12, 15, 18, 21, and 24. NYMEX crude oil futures usually expire on the third business day prior to the 25th calendar day of the month preceding the delivery month. The delivery month for contract 1 is the one that follows its expiration month. Contract 3 is for the third delivery month after contract 1. Contracts 6 to 24 are then analogously defined.

Table 1 summarises the relationship between the price of contract j at $t = 1$, month of expiration, and month during which the delivery takes place.

[Table 1 around here]

The same logic applies as t is varied. For the empirical analysis, a monthly series of 200 observations was constructed using the closing prices on the last business day of each month 1996M09-2012M04. This avoids concerns about roll-over strategy and calendar effects. We denote the price of the j^{th} contract at time t as $F_{j,t}$, so that $F_{1,t}$ represents the price of contract 1 at month t.

Table 2 provides descriptive statistics for two non-overlapping subsamples, one up to the end of 2003 and the other commencing in January 2004.

[Table 2 around here]

The break point was chosen to highlight the effect of increased investment flows in commodities since 2004. The post-2004 standard deviation is almost the same for each series. Short-dated contracts are positively skewed but, as we move towards more distant contracts, the skewness lessens and becomes even negative for contracts 18, 21, and 24. The kurtosis for all contracts stays within the range of a normally distributed variable.The table reveals some interesting patterns.

Overall, oil spot and futures price dynamics changed significantly after 2004. Prices remained in a very narrow range during 1995-2003 in comparison to the 2004-2012 period when the maximum price for all contracts was close to $140 per barrel or virtually double the mean prices. The latter reached an all-time high in 2008 followed by a sharp collapse. The post-2004 mean prices and standard deviations increased three to four times in comparison with their corresponding figures for pre-2004 period. The above factors point to distinct investor behaviour in the post-2004 period. For example, Büyükşahin et al. (2009) show that the growth of large net positions in long-dated contracts by hedge funds and other investors dates from 2004 and 2005.

Prior to 2004 the mean price and mean standard deviation decrease as we move towards longer dated contracts. At the same time the mass of the distribution shifts from right to the left and becomes more platykurtic. After 2004 we observe that the mean price increases up to contract 9 and then flattens out or decreases marginally. This can be seen more clearly in Figure 1 which plots the average return of all contracts at different maturities over the two periods.

[Figure 1 around here]

Figure 1 can be viewed as an average term structure or yield curve for futures prices over the two periods. Interestingly the 2004 break coincides with that identified in Büyükşahin et al. (2009) for the nearby contract basis. The downward sloping futures yield curve in panel A implies that the crude oil futures market was backwardated prior to 2004. A trader with a long futures position on average would realize a positive return from rolling her position forward into the cheaper (next) nearby contract. By contrast, panel B show that that the futures yield curve switched to contango with a positive slope in the period from 2004. Now contracts further out the curve cost more and so rolling a nearby position to the next contract would on average be more costly. Moreover a contangoed market may encourage investors to buy longer maturity contracts to avoid rollover risk.

6 Empirical results

The power of the $SDFC_r^\tau$ and SBT_r^τ tests deteriorates if the bubble bursts within the sample period. Homm and Breitung (2012) suggested that successive observations following the explosive period are excluded from the sample to overcome this problem. The spectacular downturn in the price of oil since June

2008 bears a close resemblance to a collapsing bubble. Therefore, the $SDFC_r^\tau$ and SBT_r^τ statistics are estimated over the period 1995M09:2008M06. The SDF_r^τ and $GSDF_r^\tau$ statistics are obtained from the whole sample.

The recursive regressions were run with an initial window size of 36 observations (18% of the total sample) due to the small sample size. The test results are given in Panel A of Table 3 while Panel B provides various right-side critical values.

[Table 3 around here]

An analysis of the results in the Table 3 leads to several conclusions. First, all statistics for the spot price series readily reject the null hypothesis of no bubbles at the 1% level. Second, all statistics for all of the futures price series also provide evidence against the null hypothesis of no bubble the 1% level. This result is novel and is one of the original findings of this study. Finally, the evidence supporting bubbles becomes stronger as the maturity of futures contracts increases.

While Table 3 provides strong evidence of bubbles, we next need to date stamp them. Table 4 present the results from the Phillips, Shi, and Yu (2012) GSDF procedure on bubble origination and collapse dates. The GSDF results are presented first as this is the most general dating procedure in the presence of multiple bubbles. We follow the literature in imposing a minimum six month bubble duration period. Shorter episodes are regarded as blips.

[Table 4 around here]

There are some striking patterns in the results. First, they indicate no bubble in spot prices and the nearby futures (contract 1) at the 5% significance level. The identical results for the spot and nearby contracts are no surprise as otherwise there would have been arbitrage opportunities. They are in line with long standing results that the spot and nearby prices are cointegrated.

By contrast, the results point to a minimum six-month bubble period for contacts 3 through to 24 with a collapse date of September 2008. The latter coincides with that found in Phillips and Yu (2011), and Shi and Arora (2012). Second, the bubble duration increases along the yield curve. For example, it ranges from just 6 months (February to August 2008) for contract 3 to some four and a half years for contract 24 at the 5% level. Contracts 6 through to 18 exhibit evidence of multiple bubbles but there is a continuous bubble for contracts 21 and 24 from March 2004 to August/September 2008 at the 5% level.

The contrasting results between the spot (and nearby) and longer dated futures contracts at the 5% level points to a fundamental disconnect in the crude oil market. This in turn suggests a violation of market efficiency in the 2004-08 period. Market efficiency would imply cointegration between spot and longer dated futures contracts which require both series to have a similar order of integration. Our results contrast with those of Büyükşahin et al. (2009). Their ADF test results for the period from July 2000 to August 2008 showed that nearby, 1- and 2-year futures prices were all I(1) and their cointegration results indicated the prices were cointegrated with one cointegrating vector. One possible explanation is the following. A well-known limitation of Dickey-Fuller type tests is that when the data are described by the generating process in Equation (9) with a coefficient close to but different from one, the unit root null hypothesis cannot be properly assessed.

Finally, there is strong evidence of the bubble commencing in early 2004 for longer maturity contracts. Contracts 15, 18, 21 and 24 show evidence of multiple and continuous bubbles at the 5% level starting in early 2004 while, at the 10%

level, contracts 12 to 24 show evidence of a continuous bubble starting in early 2004. Interestingly, the year 2004 marks the increase of investment flows into commodity derivatives market that many researchers believe changed oil futures price behaviour (see, e.g., Sockin and Xiong (2013), Tang and Xiong (2012), and Singleton (2012)). In that sense, the bubble duration evidence from the GSDF detector for the longer maturity contracts is consistent with the financialisation of commodities hypothesis.

Table 5 present the results from the FLUC procedure on bubble origination and collapse dates.

[Table 5 around here]

The results exhibit the same broad patterns found using the GSDF procedure. The only difference between the results in Tables 4 and 5 that the GSDF test results indicate the bubble origination date to be earlier than the FLUC date for contacts 15 to 24 at the 5% level. Such differences in results may emerge for several reasons. First, when there are multiple episodes of mildly explosive behaviour in the data series (as in contracts 15 through to 18 at the 5% level), the GSDF procedure consistently estimates the origination and end dates for each of them (see Theorems 3, 4 and 5 in Phillips, Shi, and Yu (2012)). Second, the FLUC detector uses a critical boundary that expands with each observation over the range $[\lfloor r_0 T \rfloor, T]$. In the case of a single period of mildly explosive behaviour, FLUC may be considered a more conservative procedure so that stronger evidence would be required to reject the null hypothesis.

The bubble periods detected by the CUSUM procedure are presented in Table 6.

[Table 6 around here]

In contrast to the GSDF and FLUC procedures, the CUSUM test provides evidence at the 5% level of bubbles in the spot and nearby contracts. The results similarly show evidence of continuous bubbles from early 2004 to August/ September 2008 in contracts 15 to 24. These results are interesting since Phillips, Shi, and Yu (2012) argued that CUSUM is a conservative procedure in comparison to their strategy. In our application it identified more extensive periods of explosiveness than the GSDF algorithm.

To sum up, both the GSADF and FLUC data stamping results indicate a disconnect between the spot and nearby contracts on one hand and the longer dated futures contracts on the other hand. The date stamping strategies identified that the bubble origination date for more distant futures contracts is significantly earlier than that for spot prices and contracts with shorter maturity. The upshot is that there is a clear indication that futures contracts with maturity above six months have been traded at prices considerably higher than their fundamental level since early 2004. This sparks the question of what caused the bubble.

One of the most significant changes in the commodity market behaviour during the bubble that we document is the growth of institutional investors. More details on the exact type of investor and their changing investment patterns are provided in Büyükşahin and Robe (2013) and Büyükşahin et al. (2009). Figure 2 shows that the bubble period coincides with a sharp increase of trading in the crude oil futures market. A large body of empirical work indicate that financial institutions have a sizable effect on asset prices. In an asymmetric information setting, Allen and Gorton (1993) provide a model in which a bubble arises in rational expectation equilibrium because of institutional investors' agency problem. The portfolio manager's payoff has the form of a call option, which will induce them to speculate on the future asset price path.

6 Conclusions

This paper investigates the time-series properties of spot and futures crude oil prices for the presence of mildly explosive bubbles. In particular, we have applied a battery of novel tests of the unit root null against a mildly explosive alternative to monthly data over the sample period September 1995 to April 2012. The procedures employed allow for consistent identification of bubble origination and collapse dates. It has examined time-series properties of the range of futures price from the nearby contract right out to the 24-month contract.

The results are novel. Both the Phillips et al. (2012) GSADF and the Phillips et al. (2011) FLUC data stamping results indicate a disconnect between the spot and nearby contracts on one hand and the longer dated futures contracts on the other hand. The former exhibit no evidence of bubbles while the latter provide significant evidence of extensive bubble periods. They indicate that the prices for 6-month series and beyond series were above their intrinsic values and thus exhibited bubble behaviour in the period up until late 2008. Strikingly, the bubble period starts significantly earlier for longer dated contracts than in shorter-dated contracts. Specifically, there is strong evidence of a prolonged bubble in both the 21- and 24-month futures prices from 2004 to 2008. The latter coincides with the period of increased participation of financial investors including index trackers and hedge funds in commodity derivative markets. Although a necessary condition, our new results do not necessarily infer that excessive speculation in commodity futures markets contributed towards price deviations away from fundamental levels in the physical market. Further empirical analysis is needed to clarify the potential source of bubble behaviour.

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Table 1: Description of futures contracts

Contract	Price month	Expiration month	Delivery month
$F_{1,1}$	September, 1995	October, 1995	November, 1995
$F_{3,1}$	November, 1995	December, 1995	January, 1996
$F_{6,1}$	February, 1996	March, 1996	April, 1996
$F_{9,1}$	May, 1996	June, 1996	July, 1996
$F_{12,1}$	August, 1996	September, 1996	October, 1996
$F_{15,1}$	November, 1996	December, 1996	January, 1997
$F_{18,1}$	February, 1997	March, 1997	April, 1997
$F_{21,1}$	May, 1997	June, 1997	July, 1997
$F_{24,1}$	August, 1997	September, 1998	October, 1998

A description of the relationship between the last business day of the month at which we observe the price for our data series (*price month*), the month in which the futures contract expires (*expiration month*), and the month in which delivery takes place (*delivery month*). NYMEX crude oil futures usually expire on the third business day prior to 25th calendar day of the month proceeding the delivery month. $F_{j,t}$ denotes the j^{th} contract at time t. For illustrative purposes we choose $t = 1$, which represents the price on September 29, 1995.

Table 2: Descriptive statistics

	Spot	Contract 1	Contract 3	Contract 6	Contract 9	Contract 12	Contract 15	Contract 18	Contract 21	Contract 24
Panel A: Period 1995M09 to 2003M12 (100 observations)										
Mean	23.389	23.368	22.866	22.208	21.681	21.269	20.941	20.703	20.537	20.422
Median	23.345	23.390	22.830	21.660	20.710	20.535	20.215	20.205	20.035	19.915
Maximum	36.760	36.600	33.280	30.300	29.160	28.450	27.900	27.470	27.130	26.920
Minimum	11.370	11.220	12.140	12.830	13.140	13.410	13.620	13.860	14.070	14.260
Std. Dev.	5.862	5.872	5.335	4.693	4.214	3.842	3.536	3.291	3.100	2.957
Skewness	2.148	2.149	2.009	1.916	1.878	1.842	1.822	1.823	1.834	1.864
Kurtosis	-0.019	-0.026	-0.053	-0.045	-0.019	0.011	0.034	0.056	0.088	0.131
Panel B: Period 2004M01 to 2012M04 (100 observations)										
Mean	73.715	73.768	74.822	75.485	75.761	75.865	75.826	75.734	75.608	75.465
Median	70.945	70.985	72.430	74.050	74.545	75.275	75.595	75.240	74.740	74.270
Maximum	139.960	140.000	140.950	141.560	141.460	140.870	140.200	139.480	138.930	138.420
Minimum	33.160	33.050	31.490	30.080	29.300	28.700	28.210	27.770	27.430	27.220
Std. Dev.	22.706	22.715	22.534	22.588	22.646	22.669	22.630	22.612	22.608	22.593
Skewness	2.764	2.758	2.849	2.908	2.933	2.942	2.962	2.973	2.982	2.987
Kurtosis	0.416	0.415	0.357	0.266	0.183	0.107	0.043	-0.010	-0.054	-0.090

The main characteristics of monthly spot and futures price series are reported for two non-overlapping periods. Series are constructed using the closing WTI crude oil prices on the last business day of the month. The delivery month for contract 1 is the month that follows after the expiration of the contract. Contracts 3 to 24 are the successive delivery months following contract 1. NYMEX crude oil futures expire on the third business day prior to 25th calendar day of the month proceeding the delivery month. If 25th happens to be a non-business day, the expiration day is the third business day prior to the business day proceeding 25th.

Table 3: Testing for explosive behaviour in WTI crude oil spot and futures price series

	SDF_r^{τ}	SDFC_r^{τ}	SBT_r^{τ}	GSDF_r^{τ}
		Panel A: Test statistics		
Spot	4.233	4.734	8.727	4.233
Contract 1	4.203	4.705	8.636	4.203
Contract 3	4.664	5.147	9.723	4.664
Contract 6	5.182	5.659	10.988	5.182
Contract 9	5.537	6.019	11.836	5.537
Contract 12	5.770	6.258	12.373	5.770
Contract 15	5.924	6.414	12.720	5.924
Contract 18	6.034	6.530	12.977	6.034
Contract 21	6.131	6.634	13.231	6.131
Contract 24	6.195	6.704	13.418	6.195
		Panel B: Critical values		
90%	2.223	1.395	1.755	2.869
95%	2.587	1.749	2.284	3.196
99%	3.314	2.490	3.492	3.893

The $SDFC_r^{\tau}$ and SBT_r^{τ} test statistics are estimated over the horizon September 1995 to June 2008 (154 monthly observations) to enhance the power of the tests. The SDF_r^{τ} and $GSDF_r^{\tau}$ test statistics are estimated over the horizon September 1995 to April 2012 (200 monthly observations). They are calculated recursively with a fraction of the total sample $r_0 = 18\%$ (36 observations) for initial window size. The right-side critical values in Panel B are approximated using Monte Carlo simulations with 10,000 replications.

Table 4: Bubble origination and collapse dates: GSDF results

	Level of significance	
	10%	5%
Spot	2008M02 : 2008M08	-
Contract 1	2008M02 : 2008M08	-
Contract 3	2007M12 : 2008M08	2008M02 : 2008M07
Contract 6	2005M02 : 2006M08	2006M03 : 2006M08
	2007M09 : 2008M08	2007M12 : 2008M08
Contract 9	2005M01 : 2006M11	2005M02 : 2006M08
	2007M09 : 2008M08	2007M10 : 2008M08
Contract 12	2004M05 : 2008M08	2005M02 : 2006M08
		2007M10 : 2008M08
Contract 15	2004M03 : 2008M08	2004M05 : 2006M11
		2007M09 : 2008M08
Contract 18	2004M02 : 2008M08	2004M04 : 2006M12
		2007M09 : 2008M08
Contract 21	2004M02 : 2008M09	2004M04 : 2008M08
Contract 24	2004M02 : 2008M09	2004M03 : 2008M09

The dating of the bubble periods are defined according to Equations (21). The initial sample for the GSDF procedure is chosen to be around 18% of the total sample (36 observations). The estimations are done over the horizon 1995M09:2012M04.

Table 5: Bubble origination and collapse dates: FLUC results

	Level of significance	
	10%	5%
Spot	2008M02 : 2008M07	-
Contract 1	2008M02 : 2008M07	-
Contract 3	2008M02 : 2008M08	2008M02 : 2008M07
Contract 6	2005M12 : 2006M08	2006M03 : 2006M08
	2007M10 : 2008M08	2007M12 : 2008M08
Contract 9	2005M02 : 2006M08	2005M02 : 2006M08
	2007M09 : 2008M08	2007M10 : 2008M08
Contract 12	2004M07 : 2006M11	2005M02 : 2006M08
	2007M09 : 2008M08	2007M10 : 2008M08
Contract 15	2004M07 : 2008M08	2004M07 : 2006M11
		2007M10 : 2008M08
Contract 18	2004M05 : 2008M08	2004M07 : 2006M12
		2007M10 : 2008M08
Contract 21	2004M05 : 2008M08	2004M07 : 2008M08
Contract 24	2004M05 : 2008M09	2004M07 : 2008M08

The dating of the bubble periods are defined according to Equations (18) and (19). The initial sample for the FLUC procedure is chosen to be around 18% of the total sample (36 observations). The estimations are done over the horizon 1995M09:2012M04.

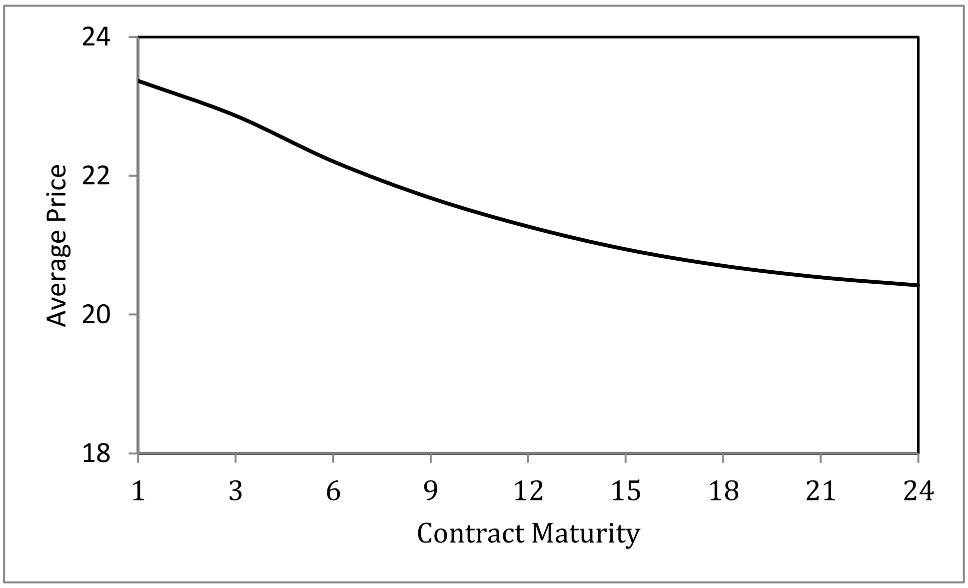
Table 6: Bubble origination and collapse dates: CUSUM results

	Level of significance	
	10%	5%
Spot	2007M10 : 2008M08	2008M02 : 2008M07
Contract 1	2007M10 : 2008M08	2008M02 : 2008M07
Contract 3	2006M03 : 2006M08	2007M12 : 2008M08
	2007M09 : 2008M08	
Contract 6	2005M01 : 2008M08	2005M12 : 2006M08
		2007M10 : 2008M08
Contract 9	2004M07 : 2008M09	2005M02 : 2006M11
		2007M09 : 2008M08
Contract 12	2004M05 : 2008M09	2005M01 : 2008M08
Contract 15	2004M04 : 2008M09	2004M05 : 2008M08
Contract 18	2004M03 : 2008M09	2004M05 : 2008M08
Contract 21	2004M03 : 2008M09	2004M05 : 2008M08
Contract 24	2004M03 : 2008M09	2004M05 : 2008M09

The dating of the bubble periods are defined according to Equations (18) and (19). The initial sample for the CUSUM procedure is chosen to be around 18% of the total sample (36 observations). The estimations are done over the horizon 1995M09:2012M04.

Figure 1: Futures curve

Panel A. Period 1995M09 to 2003M12



Panel B. Period 2004M01 to 2012M04

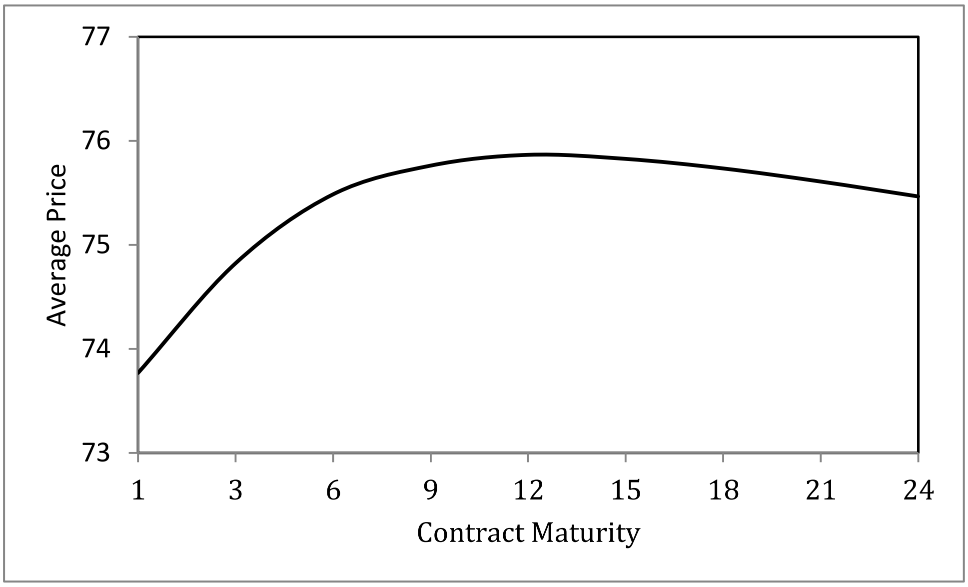
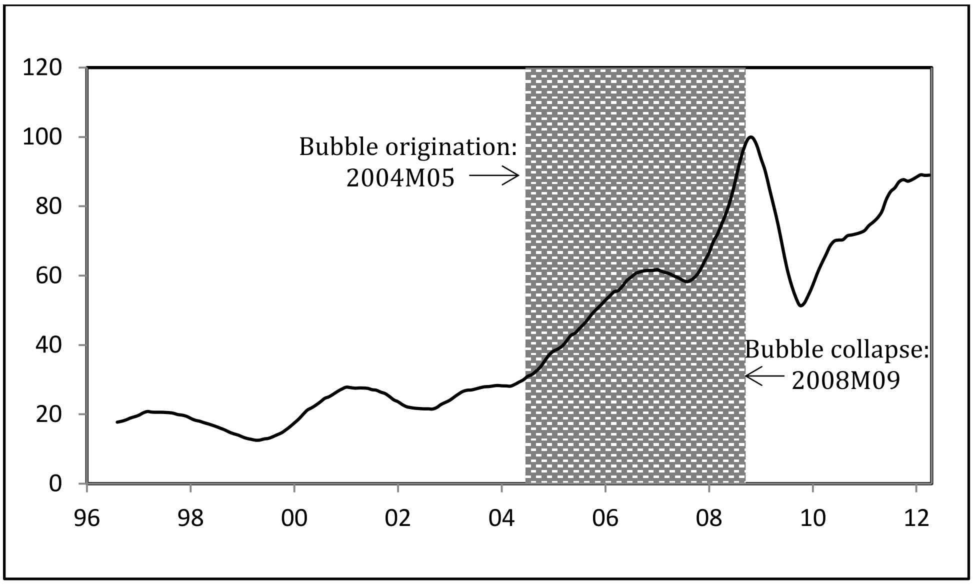


Figure 2: Trading volume



Time series (*solid line*) are the 12 month moving average of WTI futures volume. The volume is the number of all trading contracts. The shaded area is the bubble period defined by the date-stamping strategies for the long maturity contracts.