Mild explosivity in recent crude oil prices

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This paper provides an analysis of oil prices during and in the aftermath of the Global Financial Crisis, concentrating on the 2007-08 price spike and the 2014-16 price decline. The mildly explosive/multiple bubbles testing strategy by Phillips, Shi and Yu (2015, *International Economic Review* 56(4), 1043-1133) is used to test for price departures from an underlying stochastic trend and to assess whether any such departures can be explained by fundamentals or other proxy variables. The test dates two significant time periods in both Brent and WTI nominal and real front-month futures prices: a mildly explosive episode during the 2007-08 spike, prior to the peak of the Global Financial Crisis; and a significantly shorter, negative such episode during the 2014-16 price decline, whose commencement is dated around a key OPEC meeting in November 2014. Evidence using other commodity prices points to explanatory factors beyond commodity markets. A global economic activity proxy is found to be decisive in the episode in mid-2008; excess speculation is not. U.S. shale oil production, though contributing to the post-June 2014 price decline, is not seen to have been decisive. Against some recent work tying the CBOE Volatility Index (VIX) to oil futures prices, we find no evidence that the VIX decisively affected oil price levels during the sample period. The results are compared and contrasted with those obtained by Baumeister and Kilian (2016, *Journal of the Association of Environmental and Resource Economists* 3, 131-158) via a forecasting approach based on a structural vector autoregressive model without financial variables. Taken altogether, the results herein provide new evidence based on formal statistical testing that help resolve a number of recent controversies in the oil price literature.

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1. Introduction

Crude oil prices over the last decade have exhibited behavior over two notable periods to suggest a standard model of martingale behavior over the whole sample may not appropriately represent their salient features. Towards the end of a sustained rise in crude oil prices from 2003, prices rose from around $50 per barrel at the beginning of 2007 to nearly $150 around the high point of the Global Financial Crisis (GFC) in mid-2008, before collapsing to around $40 towards the year-end. Then, after rising in the aftermath of the GFC, with prices enjoying a period of three or so years of stability at just over $100, there was a steep decline in prices of around 70% from June 2014 to January 2016, prior to a recovery. During this price decline, commodity prices fell by nearly 50% from peaks obtained in the aftermath of the GFC.

While there is now a considerable amount of literature on the oil price spike during the 2007-08 period (e.g. Hamilton, 2009, and the discussion therein), the ramifications of the GFC have continued to sustain controversies relating to identifying its principal cause. A key question is whether a demand fundamental or excess speculation was decisive in the run-up in prices towards their high point in mid-2008 (e.g. Kilian and Murphy, 2014; Singleton, 2014; Pavlidis et al. 2018). In the same vein, there is currently no consensus as to whether the mid-2014 to early-2016 price decline had a principal driver among multiple causes. Azeki and Blanchard (2014) have conjectured the price decline resulted from consequences – actual and expected – of supply increases from the U.S. shale oil revolution. In work more directly sponsored by the International Monetary Fund (IMF), Husein et al. (2015) also pointed to the relevance of supply over demand factors, and suggested that the evidence for excess speculation or financialization was comparatively weaker. In a World Bank Group policy note, Baffes et al. (2015) pointed to weakening global demand, a shift in the policy of the Organization of the Petroleum Exporting Countries (OPEC), and an appreciating U.S. dollar. Baumeister and Kilian (2016) saw the price fall as largely having been based on a negative shift in demand expectations; while a recent World Bank Flagship Report (2018) focussed on the geopolitical risks; the inability of OPEC to regulate global oil supply; and deteriorating global growth prospects. The works just cited reflect a myriad of perspectives and the continuing controversy that surrounds the drivers of oil prices around and in the aftermath of the GFC. The current lack of agreement points towards the need to assess the decisiveness of potential drivers using formal statistical tests. With the echo of the GFC continuing even a decade on, the importance of assessing the role of oil price drivers remains, given the wider bearing oil prices have on the world economy.

The main purpose of this paper is to analyze recent oil prices around and in the aftermath of the GFC, and to assess the role of potential drivers using an approach based on formal statistical testing. We use the mildly explosive test strategy proposed by Phillips, Shi and Yu (2015a; 2105b, PSY),[1] which by design is formulated to address questions based on data sets that embody the non-stationarity seen around or in the aftermath of the GFC. Some authors have used the strategy narrowly as a way of "date-stamping bubbles" but here, as effected in the pioneer paper by Phillips, Wu and Yu (2011, PWY), we provide a direct approach towards testing the role of fundamental or proxy variables in a context where other, potentially rival methods have been justified only under less realistic assumptions. Figuerola-Ferretti et al. (2015) and Figuerola-Ferretti and McCrorie (2016) have shown how the PSY strategy can be tailored to the analysis of the prices of commodities such as oil. Here, we offer a number of results to address recent controversies in the oil price literature. We offer new, clarifying evidence on the extent to which demand and excess speculation were decisive during the 2007-08 price spike, and on the extent to which oil prices and other commodity prices moved cojointly as the GFC unfolded. We assess the potential role of demand and supply shocks in the 2014-16 price fall; and we offer evidence on the decisiveness of the dollar numeraire, above-ground inventories and U.S. shale oil production over the sample period. We also provide a direct statistical test for excess speculation in oil, and assess whether a key financial variable, the Chicago Board Options Exchange Volatility Index (CBOE VIX), played a decisive role in oil prices over the sample period, as has been suggested in some recent work.

In a recent analysis of crude oil prices, the U.S. Energy Information Administration (2016, EIA) discussed seven main, broadly agreed drivers of oil

[1] The use of the acronym "PSY" has become standard for the recursive test proposed by Phillips et al. (2015). All such acronyms introduced in the main text are also displayed alongside the full article listing in the reference section.

prices. These involved the four elements of supply and demand of crude oil by OPEC and non-OPEC countries; the relationship between spot and futures prices; market balance (which depends on inventories); and the nature of trading on financial markets. There was not an attempt, however, to assess how decisive each element had been in determining the recent oil price decline. Baumeister and Kilian (2016) made such an assessment using a forecasting approach based on a structural vector autoregressive (SVAR) model, and showed that more than half the price decline was in principle predictable in real time as of June 2014. Taken at face value, their findings suggest that part of the price decline can be attributed to adverse demand shocks reflecting a slowing global economy in the first half of 2014, and showed the remaining fall could be associated with positive oil supply shocks that occurred prior to July 2014. The strength of their approach, which embodies important methodological advances by Kilian (2009) and the structural model of Kilian and Murphy (2014), lies in its ability to take account of oil price supply and demand shocks through the role it gives to expectations in the formation of oil prices. This means that, realistically, changes in expectations can affect oil prices even when fundamentals are not adjusting. Nevertheless, their approach also has disadvantages. Firstly, the lag structure is fixed *ex ante* as an SVAR model of order 24, chosen simply to reflect two years' worth of monthly data, even although statistical inference in VAR models changes in general if a different lag structure is used.[2] Secondly, while there were attempts to ensure their VAR is stationary through the design of the structural model, this is not tested. Indeed, we show here it is the very aspect of *non-stationarity* in crude oil prices that is salient during two time periods of interest. Thirdly, their structural model is based on strong informational assumptions in which agents directly observe structural shocks, to support an inventory-led strategy to detect speculative effects that is based on the classical theory of storage. Sockin and Xiong (2015) model the informational frictions that agents may face in the global oil market which, if true, challenge the classical theory of storage and render the structural model misspecified. Fourthly, the structural model does not include some financial variables that potentially reflect changes in the oil market that occurred around and in the aftermath of the GFC. For example, Cheng et al. (2015)

[2] For this reason, lag structures in VAR approaches are often selected on the basis of the actual data using statistical procedures based on information criteria.

empirically document recent "convective risk flows" between commodity futures prices and the positions of various trader groups to changes in the VIX.

The above comments on the Baumeister and Kilian (2016) approach do not detract from the essential aspect of their contribution – the provision they make for shocks – but they do motivate considering an alternative, reduced-form approach to reassess or to consolidate their findings. Reduced-form models can provide useful, complementary evidence when there are questions over the specification and properties of a given structural model, or indeed of other, *potential* structural models.[3] This type evidence will be useful, for example, when assessing the potential role played by OPEC in late-November 2014 when, in response to a supply glut arising from increased U.S. shale oil production, it upheld its production ceiling rather than agreeing cuts as was its usual policy.

Until recently, directly testing for trend departures in an explosive direction, of the sort that would be appropriate for the features in the crude oil data described above, represented a considerable challenge because conventional tests based on a model embodying a stochastic trend are very sensitive to explosive departures from the null. The strategy recently proposed by PSY (2015a,b) offers a natural way forward, given its efficacy in testing for departures from an unobservable stochastic trend such as random walk behavior, and departures from fundamental value, in the direction of a positive or negative *mildly explosive process* alternative (to be defined below). The property of mild explosivity is key because it stochastically dominates random walk behavior, and any detected departure from trend in this direction would represent a salient feature in the time series to be explained. PSY (2015b) show their test has desirable asymptotic properties; in particular, it offers a (statistically) consistent basis upon which to date the origination and collapse of such episodes and a statistically justified approach of testing whether individual factors played a decisive role in any departure from an underlying stochastic trend. Other, potentially rival approaches, such as those based on Markov regime switching models, do compute estimates under plausible assumptions but statistical inference and hypothesis testing pertaining to the estimated parameters are not currently justified to

[3] In their introduction, Phillips and Shi (2018) provide a useful discussion of the importance of reduced-form modeling and testing in the context used in this paper.

the same degree under the type of non-stationarity that is characteristic of the data during and in the aftermath of the GFC.

Our methodological contribution is distinguished through its examination of the robustness of the detected date-stamped episodes to a changing dollar numeraire; its unified treatment of both the 2007-08 spike and 2014-16 price decline; and, most cogently, in its full use of the PWY/PSY testing apparatus to assess the decisiveness of potential drivers of recent oil prices.[4] We provide new, decisive evidence on the role of a demand-side fundamental in explaining the rise in oil prices during the 2007-08 spike but provide contrasting evidence on a role for excess speculation. For what seems to be the first time on the basis of a formal statistical test, we associate the high point of nominal prices in 2008 to an oil-specific event: an announcement by U.S. President George W. Bush that ended an executive ban on offshore drilling.[5] The short, negative episode detected in late-2014 is dated for the benchmark prices just after the OPEC meeting in November 2014, and here the demand-side fundamental is *not* seen to be decisive in explaining this departure in trend. Our approach therefore allows us to draw a contrast between the price rise in 2007-08 and fall in 2014-16. No empirical evidence that the VIX or excess speculation decisively affected oil price levels is found during the sample period, counter to some recent work that has proposed transmission mechanisms from the VIX to oil futures prices. The clarifying role of this evidence against the extant literature is described in detail below.

The paper is organized as follows. Section 2 gives some background on the main crude oil price benchmarks and briefly presents their chronology over the last decade. Section 3 summarizes the PSY mildly explosive/bubbles testing methodology. In Section 4, the test is applied to nominal front-month futures prices for the two main crude oil benchmark series, and then to the same two series deflated by the U.S. Consumer Price Index (CPI) and by the currency value of the Special Drawing Rights (SDR) basket to control for a potentially changing dollar numeraire. In Section 5, we provide some interpretation of our results, focussing on the potential drivers of recent

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[4] Our preliminary-stage findings on date-stamping mildly explosive structural breaks connects to and, as we describe later, mildly overlaps with some extant work in the mild explosivity/bubbles literature. None of this work, however, embeds the analysis of fundamentals and speculation into the testing procedure, as is done here.

[5] See http://edition.cnn.com/2008/POLITICS/07/14/bush.offshore/.

crude oil prices. Here, nominal prices are deflated by natural proxies for two traditional fundamental variables, global economic activity and above-ground inventory supply, and then by a financial variable, the VIX, as a means of assessing the extent of the wider role that oil futures now play in portfolio management and in calculations of systemic market risk. We also provide a direct test for excess speculation based on Working's *T*-index. Section 6 provides a point-by-point summary of our results and their role in resolving certain recent controversies in the oil price literature.

2. Crude oil prices over the last decade

There are two principal crude oil benchmarks based on quality and location – Brent Blend and West Texas Intermediate (WTI) – that are used by buyers of crude oil and speculators (who never actually take delivery of it). Around two-thirds of all crude contacts reference Brent Blend,[6] making it the most important marker price by volume. WTI refers to oil extracted from wells in the U.S. that is piped to Cushing, Oklahoma and is the main benchmark for oil consumed in the U.S. WTI crude is lighter and sweeter (i.e. has a lower sulphur content) than Brent Blend which, ceteris paribus, would make it the more expensive crude oil but supplies of the former are landlocked and are relatively expensive to ship to other parts of the World. Some important recent instances of spreads attributed to factors other than quality and location have been reported (e.g. Büyükşahin et al., 2013) and are briefly discussed below. We focus on front-month crude oil futures data, which represent the settlement prices of the contracts that are closest to delivery with the highest open interest, and against which bid/offer prices and deals for physical cargos of crude oil are referenced. Importantly, they are the two benchmark oil contracts, and they are traded on different markets: Brent futures on the Intercontinental Exchange (ICE, into which the International Petroleum Exchange has been incorporated) and WTI contracts principally on the New York Mercantile Exchange (NYMEX). There is a multitude of oil prices including spot prices and futures prices at different maturities, and any true assessment of "oil price explosivity" would confront the aspect of price discovery through extracting information from multiple time series. Different approaches to

[6] Brent Blend originally referred to oil extracted from the Brent oil field, but now refers to oil from four different fields: Brent, Forties, Oseberg and Ekofisk.

price discovery exist: for example, Gibson and Schwartz (1990) and Schwartz (1997) posit different specifications for spot prices and a convenience yield fundamental, implying a specific path for the forward price. See also Cortazar et al. (2015). Figuerola-Ferretti and Gonzalo (2010) offer an alternative view in which spot and futures prices are co-integrated. Recent work that discusses the relationship between oil spot and futures prices includes Wang and Wu (2013); Zhang and Wang (2013); Chen et al. (2014); Shrestha (2014); Balcilar et al. (2015); Chang and Lee (2015); and Nicolau and Palomba (2015). Pavlidis et al. (2017) proffer an approach through which differences between spot and forward (futures) prices are exploitable in a test for periodically collapsing bubbles, which Pavlidis et al. (2018) apply to oil prices. This approach obviates the need for fundamentals under assumptions that speculative bubbles in oil exist and the connection posited between spot and futures prices is true. Their conclusions are tied to an exogenously chosen measure of market expectations.

Here we show, insofar as our focus is on the detection and date-stamping of mildly explosive periods, that the use of spot prices or front-month futures prices is inconsequential in practice and that this conclusion is robust to a potentially changing dollar numeraire. Many oil futures traders follow strategies in which they never make or take delivery of physical oil: some unwind their positions and extract monetary gain or loss by selling the futures contract previously bought; others, in a strategy called rolling, repeatedly roll over their position by selling a current futures contract before expiry, and thereafter purchase the next month's contract. The futures market therefore supports both hedging, where net gains and losses are used to offset fluctuations in operating earnings; and speculation, where actual net gains are counted as profit or loss.[7] Our desire to test the roles of excess speculation and the VIX motivates our focus on oil futures prices above and beyond their being the market reference prices. We shall compare and contrast our results with those obtained by others using spot prices, and those obtained by Tsvetanov et al. (2016) on the shape of the oil futures curve.

[7] The spot price of oil contains forward-looking elements based on expectations that cannot be captured by past data. It is natural that market participants trade on this information: in the oil market, this is done predominantly through the purchase and sale of futures contracts rather than through the purchase, storage and sale of physical oil. Under perfect arbitrage, the two activities are equivalent, with spot and futures prices being jointly determined, and responding to, the same fundamentals. In the sequel, we briefly compare our results with those obtained by Fantazzini (2016) using spot prices, which allows for, in principle, an assessment of how well arbitrage works in the oil market.

Hamilton (2008) and Alquist et al. (2013) discuss whether to employ nominal or real prices in an analysis of oil prices. Having sympathy with an argument in the former paper – that the CPI deflator can affect the ratio as much as the nominal price when influenced by effects seemingly unrelated to oil – we focus primarily on nominal prices. Where relevant, however, we shall also report results for real prices. When considering proxy variables or indices, we first assess their properties against the nominal price series, and then either against the real series or by examining ratios of the nominal prices to each variable and index. Using ratios obviates the need to deflate variables in order to discuss real effects, although some care needs to be applied given the potential for the use of a ratio to distort underlying statistical inference. With the overall approach, we are able naturally to follow the strategy proposed by PWY (2011) and Phillips and Yu (2011) in their treatment of fundamentals based on formal statistical testing. And at the same time, we can make direct comparisons with the results obtained by Baumeister and Kilian (2016) pertaining to real oil spot prices.

Our sample begins in January 2003, at the point from which the CBOE's revised, model-free measure of the VIX has been calculated. This turns out to be just prior to the beginning of the sustained rise seen in oil prices during the last decade. The PSY test relies on a choice of an initial fraction of the data and the various test statistics and critical values are functions of that choice. Our chosen sample end-date is the end of April 2016. This end-date is explicitly chosen to be the same as used by Fantazzini (2016) to ensure there can be a direct comparison of our results, based on front-month futures, with his results based on spot prices. This end-date is just far enough into 2016 to remove potential end-of-sample dating issues, following the recovery in oil prices in early 2016. Given our focus on mild explosivity in the aftermath of the GFC, there is little to be gained in considering an extended sample period; for while oil prices have risen and fallen since then, they have not done so abruptly enough to suggest a departure from random walk or martingale behaviour as is of interest here.

We use weekly data to facilitate testing for potentially relevant, shorter periods of mild explosivity than monthly data would permit. This sampling frequency is appropriate for assessing aspects of oil financialization while at the same time is low enough to permit a complementary analysis based on some of the more traditional fundamentals. Our primary data sources are the Bloomberg International and EIA databases. Full details of the data are provided in the supplementary Data-In-Brief file referenced at the end of the paper.

By way of providing a brief market chronology of the benchmark prices over the sample period, we note that both Brent and WTI prices began a steady year-on-year rise from below $30 per barrel at the beginning of the sample, to over $50 in 2005, over $60 in 2005. They reached around $75 in mid-2006 before dropping back to $60 in early-2007. Prices were over $90 by October 2007, around $100 by late-November 2007 and rose sharply to a peak seen in the ICE Brent price of just under $147 in mid-July 2008.

[Figures 1 and 2 around here]

The beginning of the 2008 price collapse coincided with a low point in the U.S. dollar. The price collapsed below $100 in the late summer of 2008, below $70 in mid-October, below $60 in November and below $40 in December, during the time the GFC was unfolding. Two salient features are therefore the 2003-08 run-up in prices, during a period of renewed growth in the Organization for Economic Co-operation and Development (OECD) countries and rapid industrial growth in Asia, particularly in China; and the 2007-08 price spike, where prices in the run-up phase rose significantly faster than before. A similar pattern was found in some other commodity prices in 2007-08. In 2009, prices began to recover, finally exceeding $100 in 2011 and then remaining around this level for two or more years. Figure 1 indicates a divergence between Brent and WTI nominal prices during this time, which can be attributed to U.S. supply bottlenecks at Cushing, Oklahoma (Büyükşahin et al., 2013; Zhang and Zhang, 2015; Robe and Wallen, 2016). The other salient feature in oil prices during the sample period is the mid-June 2014 to early-2016 price decline, which occurred around a time that U.S. shale oil production had increased and China and Europe's demand for oil had decreased. A significant plunge in prices to a four-year low of just over $70 was seen in late-November 2014, around the time of an OPEC meeting which, as noted, did not reinforce the cartel's then established policy of defending prices. Crude oil prices continued to fall in 2015, reaching a price of just over $40 in mid-August not seen since February 2009. In December 2015, the price at below $34 hit an eleven-year low; it then dropped below $30 in January 2016 and reached a low of around $26 in early-February. Prices had recovered to around $45 by the end of the chosen sample period. Oil prices began rising in a relatively sustained manner in 2017 prior to exhibiting a sharper fall towards the end of 2018; however, a standard application of the PSY test indicates that oil prices did not recently exhibit mild explosivity. While the recent price behavior is important in some dimensions, it is not essential to the main argument here.

3. The PSY mildly explosive/bubble-testing strategy

The PSY (2015a,b) strategy represents a breakthrough in the search for a statistically rigorous procedure to test for temporary regime shifts of exuberance and collapse that are embedded in a time series evolving as a stochastic trend, and provides a method of testing whether such shifts are attributable to fundamentals or other proxy variables. The test is underpinned by a rigorous statistical theory that is appropriate for data that pertains to the GFC and its aftermath, when methods justified only under stationarity or unit-root non-stationarity may be insufficient. In this regard, the PSY strategy has efficacy not shared by potentially rival methods such those based on Markov regime switching models. Even just as an algorithm of structural break detection of the type of exuberance and collapse of interest here, Homm and Breitung (2012) showed the prototypical PWY (2011) approach performed well in comparison with other candidates. PSY (2015b) articulated improvements on the PWY (2011) prototype, including robustness to potentially multiple structural breaks. Recently, Phillips and Shi (2019) have discussed its efficacy as a real-time monitoring device for bubbles and financial crises.

The procedure is based upon the notion of a *mildly explosive process* that was introduced by Phillips and Magdalinos (2007): it facilitates constructing appropriate statistical theory in autoregressive (AR) models whose AR parameter is locally above unity. The property of mild explosivity stochastically dominates random walk and martingale behavior in a way that makes its incidence a key feature of a time series to be explained.

The PWY/PSY testing strategy comprises three steps:

- testing the null hypothesis that there are no mildly explosive periods in the sample against the alternative that there is at least one such period;

- if the test rejects, date-stamping the mildly explosive period(s) in the sample;
- assessing whether detected mildly explosive episodes may be due to the behavior of fundamentals or other variables.

As discussed above, most authors have tended to concentrate on using the first two steps as a way of "date-stamping bubbles" but here the reduced-form strategy is fully utilized to generate stylized facts against which the properties of (actual or potential) structural models can be assessed. This evidence can be used to bring clarity to various recent controversies surrounding the behavior of oil prices around and in the aftermath of the GFC. Figuerola-Ferretti et al. (2015) and Figuerola-Ferretti and McCrorie (2016) show how the PWY/PSY strategy can be tailored to commodities such as oil, which do not have a natural, observable fundamental playing the role that dividends play to stocks, and where markets can be in backwardation or contango (e.g. Morana, 2013; Sharma and Escobari, 2018).

Under the null hypothesis of the test, the time series of interest can in general follow a unit root process with an asymptotically negligible drift:

$$x_t = d\,T^{-\eta} + x_{t-1} + \varepsilon_t, \quad \eta > \tfrac{1}{2}, \tag{1}$$

where $x_0 = O_p(1)$, d is a parameter and η is a localizing coefficient that controls the magnitude of the drift as $T \to \infty$. Starting from a fraction r_1 and ending at a fraction r_2 of the total sample, with window size $r_w = r_2 - r_1$, we fit the regression model

$$\Delta x_t = \alpha_{r_1,r_2} + \beta_{r_1,r_2}\, x_{t-1} + \sum_{i=1}^{k} \psi^{i}_{r_1,r_2}\, \Delta x_{t-i} + \varepsilon_t, \tag{2}$$

where k is the lag order chosen on sub-samples using the Schwarz Bayesian Information Criterion (BIC), and $\varepsilon_t \sim$ i.i.d. $(0, \sigma^2_{r_1,r_2})$. The number of observations in the regression is $T_w = \lfloor T\, r_w \rfloor$, where $\lfloor . \rfloor$ is the floor function, and we denote the usual ADF-statistic (t-ratio) of the coefficient of x_{t-1} based on this regression by $ADF_{r_1}^{r_2}$.

PSY (2015a&b) introduce two statistics, the backward sup ADF (BSADF) statistic and the generalized sup ADF (GSADF) test. They are defined as:

$$BSADF_{r_2}(r_0) = \sup_{r_1 \in [0, r_2 - r_0]} \{ADF_{r_1}^{r_2}\}. \tag{3}$$

$$GSADF(r_0) = \sup_{r_2 \in [r_0, 1]} \{BSADF_{r_2}(r_0)\}, \tag{4}$$

where the endpoint of the sample is fixed at r_2 and the window size is allowed to expand from an initial fraction r_0 of the total sample to r_2. PSY (2015a) propose r_0 be chosen according to the rule $r_0 = 0.01 + 1.8/\sqrt{T}$, where T is the sample size, and this choice has become the industry standard. This procedure defines a particular BSADF statistic. The GSADF statistic is then constructed through repeated implementation of the BSADF procedure for each $r_2 \in [r_0, 1]$. Critical values are obtained by simulation. PSY (2015a&b) provide limiting distribution theory and small sample simulation evidence. See also Pavlidis et al. (2017).

The null test of no mildly explosive periods is based on the GSADF statistic. Date-stamping mildly explosive periods is achieved through the BSADF statistic: the origination and termination points of a first mildly explosive period, $r_{1,e}$ and $r_{1,f}$, are estimated, subject to a minimum duration condition, by

$$\hat{r}_{1,e} = \inf_{r_2 \in [r_0,1]} \left\{ r_2 : BSADF_{r_2}(r_0) > scv_{r_2}^{\beta_T} \right\}, \tag{4}$$

$$\hat{r}_{1,f} = \inf_{r_2 \in [\hat{r}_e + \delta \log(T)/T,\, 1]} \left\{ r_2 : BSADF_{r_2}(r_0) > scv_{r_2}^{\beta_T} \right\}, \tag{5}$$

where $scv_{r_2}^{\beta_T}$ is the 100(1 $-\beta_T$)% right-sided critical value of the BSADF statistic based on $\lfloor T r_2 \rfloor$ observations and δ is a tuning parameter that can be chosen on basis of sampling frequency. A tuning parameter of unity, reflecting a standard application of the test, implies a minimum duration condition of log(T) observations. A mildly explosive period is declared if the BSADF statistic is above its critical value for at least $\lfloor T \hat{r}_{1,e} \rfloor + \lfloor \log(T) \rfloor$ observations. Conditional on a first mildly explosive period having been found and estimated to have terminated at $\hat{r}_{1,f}$, the procedure is then repeated in search of a second and possibly subsequent periods. PSY (2015b) show that, subject to rate conditions, the sequential procedure provides consistent estimates of the origination and termination dates of one, two and, in principle, more mildly explosive episodes.

The data generation process (DGP) under the alternative hypothesis embodies structural breaks in the form of K mildly explosive episodes in the sample period, represented in terms of sample fraction intervals $B_i = [\tau_{i,e}, \tau_{i,f}]$ (i = 1, 2 , . . . , K), within periods of prevailing martingale-type behavior in the intervals $N_0 = [1, \tau_{1,e}]$, $N_j = [\tau_{j-1,f}, \tau_{j,e}]$ ($j = 1, 2, \ldots, K-1$) and $N_K = [\tau_{K,f}, T]$, as follows:

$$x_t = (x_{t-1} + \varepsilon_t)\, 1(t \in N_0) + (\delta_T\, x_{t-1} + \varepsilon_t)\, 1(t \in B_i) + \sum_{i=1}^{K} \left(\sum_{l=\tau+1}^{t} \varepsilon_l + x^*_{\tau_{i,f}} \right) 1(t \in N_i) \quad (t = 1, \ldots, T) \tag{6}$$

$$\delta_T = 1 + c/T^{\alpha}, \quad c > 0, \quad \alpha \in (0, 1). \tag{7}$$

Under the given conditions on c and α, the AR parameter δ_T is greater than unity. Phillips and Magdalinos (2007) called this condition *a mildly integrated root on the explosive side of unity*, with the underlying process being a *mildly explosive process*. Because the statistics remain the same if the time series is reversed, such processes can be rising or falling, and for our purpose can therefore be applied to test for a departure in trend in *both* the 2007-08 oil price spike and the mid-2014 to early-2016 price decline. We refer to testing the recent price decline for a departure in trend as being in the (negative) mildly explosive direction rather than being in a mildly implosive direction because "implosion" has typically been used in the literature to refer to a collapse period immediately following a bubble (Phillips and Shi, 2018). Implosion in the PSY test is modelled, for each *i*, by $x^*_{\tau_{i,f}} = x_{\tau_{i,e}} + x^*_i$, where $x^*_i = O_p(1)$. For a positive mildly explosive episode, this entails a collapse to the value of the last pre-bubble observation plus an $O_p(1)$ perturbation, from which the process resumes its trend. Where the implosion of a mildly explosive process may be relevant, e.g. in the collapse phase of the 2007-08 oil price spike, we supplement our application of the PSY test with information obtained from its application to the reverse regression, as proposed by Phillips and Shi (2018).

The PSY test has sometimes been presented as a test for economic or financial bubbles although for two reasons we have avoided this nomenclature here. Firstly, the notion of a "bubble" has a number of different connotations in the literature which, given our focus on the purely statistical property of mild explosivity, we need not address or tie down here. In this sense, our approach differs from, say, the approach by Pavlidis et al. (2018) which is predicated on assumptions about the existence and nature of speculative bubbles. Secondly, results from applying the PWY/PSY testing strategy can been interpreted differently depending on whether or not the third stage of the strategy is implemented. For example, Tsvetanov et al. (2016) and Fantazzini (2016) declare bubble episodes in oil prices mainly on the basis of the second-stage implementation of the test. Gronwald (2016) and Su et al. (2017) relate their results to the wider, economic environment but without using the third stage of the test procedure. This means the fundamentals and proxy variables they correlate with oil are therefore not subjected to a statistical test to assess their decisiveness. The third-stage offers information on the *salience* of any departure from an underlying trend in a mildly explosive direction. PWY (2011) show a mildly explosive departure in the NASDAQ price index was of an order of non-stationarity greater than exhibited by the dividend fundamental, thereby providing evidence for speculative behavior. In contrast, Figuerola-Ferretti et al. (2015) tied detected mildly explosive prices in non-ferrous metals to the behavior of a stock-to-use ratio fundamental, allowing them to conclude that non-ferrous metals, often characterized by fluctuating demand around inelastic supply, showed mildly explosive behavior that did not constitute a bubble, defined in terms of a departure from fundamental value. In both cases, the results of the third-stage materially affect the interpretation of any detected departure from trend. For this reason, an important aim of this paper is to investigate whether any detected mildly explosive episodes in oil prices can be linked to fundamentals or financial variables. Following the general strategy outlined in PWY (2011) and Phillips and Yu (2011), we apply the PSY test to assess whether the degree of non-stationarity in the price series is greater than the degree of non-stationarity in the particular fundamental or proxy variable.

The approach taken here can be contrasted with those based on alternative modeling approaches towards rational or speculative bubbles in oil prices. Markov regime switching models offer an approach where a posited bubble component can be in one of a number of states (or regimes) with certain probabilities. Notable papers are Shi and Arora (2012), Lammerding et al. (2013), Brooks et al. (2015) and Zhang and Wang (2015). Balcombe and Fraser (2017) explicitly ask whether bubbles have an explosive signature in Markov switching models. Such models offer a potentially rival *modeling* approach to the one here but the methods and procedures used currently lack formal statistical justification in the context of the non-stationarity seen during in the aftermath of the GFC as exhibited, say, by the 2007-08 oil price spike.

At its heart, the problem in the context of explosive time series is the lack of a statistical invariance principle to support a distribution theory for test statistics. To our knowledge, this problem has not been formally addressed in the Markov switching literature. The achievement of PWY(2011) and successors, on the back of theoretical work by Phillips and Magdalinos (2007), was to provide a basis for conducting valid statistical inference with data having properties of a type apparently thrown up by the GFC. For this reason, it is natural to use the PSY test in an analysis of possible explosivity in recent oil price series that contain both the 2007-08 spike and 2014-16 decline.

Finally, we mention that there are other aspects to oil prices that could be better analyzed using other approaches. For example, Bencivenga et al. (2012) discussed the GFC from the point of view of oil price volatility set within a macroeconomic framework. D'Ecclesia et al. (2014) considered a model where oil price dynamics are explicitly driven by both macroeconomic and financial shocks. Using a time-varying VAR model, Jelabi et al. (2014) point oil prices in a different direction, in an examination of the transmission mechanism between food, energy and financial markets. Lin et al. (2014) focussed on the issue of dynamic volatility and volatility transmission between oil prices and the stock market. This also necessitated a multivariate approach, where the authors used a Dynamic Conditional Correlation (DCC-) GARCH model.

4. Test results

In this section, we conduct the first two stages of the PSY test using both Brent and WTI benchmark series, and the corresponding spot prices, documenting any detected departures from an underlying stochastic trend in the direction of a mildly explosive alternative. We also examine the robustness of the results to a changing dollar numeraire and to possible non-stationary volatility in the shocks driving the oil prices. In Section 5, we use the third stage of the PSY procedure to provide an interpretation of the salient features we find in the data using specifically chosen proxy variables for traditional fundamentals, a financial variable and a measure for excess speculation. Taken as a whole, this provides an evidence base against which some of the recent controversies in the oil price literature can be assessed.

Formally, the GSADF statistic tests in the direction of at least one episode of mildly explosive behavior in the sample. Tables 1A and 1B give the GSADF statistics corresponding to the Brent and WTI nominal front-month futures prices observed on a weekly basis and the same series deflated by the currency value of the SDR basket, and an interpolated U.S. CPI series given that the raw CPI series is available only at a monthly frequency.[8] Critical values are generated for the given sample size and the rule-based value of r_0.

[Tables 1A – 1D around here]

In every case, for both spot and futures price series, the GSADF statistic rejects the null hypothesis of there being no mildly explosive periods during 2003-2016 at the 1% significance level. With such corroboratory evidence for mild explosivity in the sample, we move to the second, date-stamping stage of the PSY procedure, which uses the BSADF statistic, noting that because of the imposition of a minimum duration condition, it is possible that no mildly explosive period is actually dated here. Figures 2A and 2B show the respective BSADF sequences for the two benchmark series at the 5% significance level. The sequences for the spot price series are similar.

[Figures 2A and 2B around here]

We date mildly explosive episodes by the periods during which the BSADF sequence is above the 5% critical value line such that the minimum duration condition is satisfied. These are reported in Tables 2A and 2B for both front-month futures and spot prices. We find essentially the *same two* mildly explosive episodes dated for *both* benchmark Brent and WTI nominal *and* real (U.S.-CPI-deflated) front-month futures *and* spot prices. These are the central results of this paper: a positive mildly explosive episode is dated between mid-May and mid-July 2008 (when nominal prices are rising) and a negative such episode is dated between late November/early December 2014 and mid-February 2015 (when nominal prices are falling). The only discrepancy is seen in the Brent real spot price series, where no mildly explosive episode is dated at the 10% significance level. Given the weekly sampling frequency, we report dates

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[8] The interpolation method to obtain a weekly U.S. CPI series is described in the supporting Data-In-Brief file. The currency value of the SDR is determined using a basket of major currencies (the U.S. dollar, the euro, Japanese yen and pound sterling) based on market exchange rates. Adjusting nominal oil price series by the U.S. CPI index and the SDR currency value confers some robustness on our approach but is not definitive because the oil price is a *world* price denominated in dollars: prices can rise in one currency and fall in another. Deflating by the U.S. CPI, we follow the convention that has been standard in the literature since the paper by Deaton and Laroque (1996).

identified up to the Friday of a given week. Strong evidence is provided on the end-date of the first episode: in most cases, the estimated end-date is the Friday immediately following the Bush announcement on 14 July 2008 lifting the ban on offshore drilling. In all but two cases, the start-date of the second episode is date-stamped to around a week or so of the OPEC meeting on November 27 and lasts for about a month. Ordinarily, results such as these would provide strong evidence for spot and front-month futures prices being closely attuned. The two exceptions are, however, the Brent real and nominal spot price series, where the start-date is estimated to be earlier, in October 2014. This is potentially crucial because, if true, it would mean the departure from random walk behavior in Brent spot prices occurred *prior* to the OPEC meeting in late-November. Given that Fantazzini (2016) obtained a similar result,[9] we undertake a further robustness assessment below.

[Tables 2A and 2B around here]

The third columns of Tables 2A and 2B show synchroneity between the date-stamping using SDR-adjusted prices on one hand, and nominal and real prices on the other.[10] This indicates the depreciating dollar in mid-2008 or the appreciating dollar

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[9] We briefly compare our date-stamping results with extant work where we see potential overlap, as part of our robustness checks. The results of Tsvetanov et al. (2016) and Gronwald (2016) relate to the first episode. Using WTI weekly data but date-stamping only to the nearest month, Tsvetanov et al. (2016) detect a mildly explosive period in the front-month contract (*ibid*., Figure 5, Contract 1) between April and July 2008, beginning a week or two earlier than ours. Gronwald (2016) demonstrates a similar period of explosivity as one of three detected within a longer data span, but without tying down dates. Su et al. (2017) date-stamped a number of bubbles in spot prices over a thirty-year period, and Sharma and Escobari (2018) and Liu et al. (2018) looked at bubble detection in the energy sector as a whole, although precise date-stamping was of secondary importance to their main arguments. Caspi et al. (2018) report a longer episode in real prices than detected here, from October 2007 to August 2008, right at the end of their study of historical oil prices using monthly data since the nineteenth century. It should be noted (in a way not to detract from their contribution to the historical evidence base) their results were obtained using an earlier version of the PSY test: indeed the data themselves indicate that real oil prices had begun their steep decline before the end of their last detected episode. The overall consistency of our results across spot and futures prices, and for both real and nominal prices, demonstrates robustness in the detection of the first episode

Fantazzini (2016) focusses mainly on the second episode. Using daily data, he reports a (negative) mildly explosive episode between early October 2014 and late February 2015 in Brent nominal and real *spot* prices, and between early December 2014 and late March 2015 in WTI nominal and real spot prices. In robustness checks using weekly data and with a longer data span, an earlier episode from mid-May 2008 to mid-July 2008 is reported, synchronous across Brent and WTI real and nominal spot prices (*ibid*., Table 2, p. 392). The later episode is dated in each case from October 2014 to April 2015, with exact synchronicity reported between Brent real and nominal prices, and between WTI real and nominal prices.

[10] The 2008 episode for SDR-adjusted WTI prices detected at the 5% significance level is slightly longer, beginning in late-April rather than mid-May. This result is not especially significant given that dating identification is to the nearest week.

during 2014 were not decisive in the movements in oil prices that led to the rejection of random walk null behaviour. Evidence from the BSADF sequence relating to both Brent and WTI prices points to the actual appreciation in the dollar numeraire of just under 10% after June 2014 as having mildly contributed to the post-June 2014 oil price decline. This corroborates the conclusion reached by Baumeister and Kilian (2016) on the basis of their structural approach but contradicts the view of Baffes et al. (2015) that it was a decisive factor.

In Section 5, one of our aims will be to examine whether a fundamental can be tied to the run-up in oil prices in 2008. The collapse phase of the 2007-08 oil price is also potentially important. Given the abrupt way the PSY test models price implosion under the alternative, we also report, in Tables 2C-2F, results for Brent and WTI nominal and real prices based on applying the PSY test using the reverse regression method proposed by Phillips and Shi (2018).

[Tables 2C – 2F around here]

The similar end-dates for the first episode demonstrate the robustness of the PSY test in this case. And while the test based on the reverse regression picks up the high point of prices in June 2014 prior to the beginning of the price decline when no minimum duration condition is applied, it detects nothing at all using customary significance levels under the standard duration condition.

Simulation evidence presented by Harvey et al. (2016), applied to the PWY (2011) prototype of the PSY test, suggests the efficacy of the test may be affected by a size distortion arising from changes in the unconditional variance of the shocks across the different regimes. This property, which following early literature they call "non-stationary volatility", can be informally assessed by examining the plot of the first differenced series.

[Figures 3A – 3C around here]

Figures 3A and 3B show that both the Brent and WTI benchmark nominal series do seem to exhibit some increase in volatility during and in the immediate aftermath of the price spike in 2008. Figure 3C suggests the evidence is stronger in Brent spot prices, which is potentially important given the disparity seen between spot and futures prices the second episode was date-stamped. While the evidence is weaker than Figuerola-Ferretti and McCrorie (2016, Figure 2) presented for the precious metals complex over the same period, we follow Harvey et al. (2016) and apply the wild bootstrap resampling scheme to the first differenced data. This procedure controls for the (potential) problem in hand by replicating the pattern of volatility in the resampled data that is present in the original innovations.[11] This makes for an unambiguously more stringent test than is provided by a standard application of the PSY test.

[Figures 4A – 4C around here]

Figures 4A – 4C overlay the Brent nominal spot prices, the Brent real (CPI-deflated) spot prices and WTI front-month nominal prices and their respective BSADF sequences with a number of wild-bootstrap-adjusted critical value lines computed using 5,000 replications.[12] In all cases, there are spikes in the BSADF sequences that either touch or go above the 5% critical value line for a period, around the time of the first episode in mid-2008 detected using standard PSY critical values. Similar spikes go above the 1% critical value line from early December 2014, around the time of the second previously detected episode. As reported in Table 2C, at the 5% significance level with imposed minimum duration condition, there are mildly explosive periods dated only for the second episode, that were shorter than were detected using standard PSY critical values. The mildly explosive period dated for both Brent nominal and real spot prices from 12th December is now *the same* as it is for the front-month futures prices and, crucially, occurs *after* the late-November OPEC meeting. The evidence suggests that the date-stamping of the origination of the second episode using the standard PSY test was *not robust to non-stationary volatility*.

[Table 2G around here]

Evidence using a 10% significance level reveals slightly longer episodes for the three chosen series, whose origination in early-December is closer to the OPEC meeting on November 27th. The first episode in 2008 is detected in Brent and WTI nominal spot and futures prices at the 12% significance level, lasting between mid-June and again the Friday in mid-July immediately after the Bush announcement. As noted, the test incorporating the wild bootstrap is a more stringent test, and it is significant for what

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[11] The wild bootstrap controls for a wide variety of permanent volatility changes, whether single or multiple, abrupt or smooth. A step-by-step algorithm for computing wild bootstrapped critical values in the current context is provided, for example, by Figuerola-Ferretti and McCrorie (2016, p. 724).

[12] This is the same number of replications that PSY (2015a) used in the generation of critical values in the standard case and ensures comparability with their approach.

follows that such an episode is declared, even if it is near the boundary of what would normally be regarded as a conventional significance level.

To summarize the evidence in this section: there is compelling evidence on the basis of a standard application of the PSY test pointing to two significant departures from random walk behavior over the last decade in both nominal and real crude oil prices. The first is detected between the second and third quarters of 2008, in the run-up phase of the 2007-08 spike; and the second beginning in late-2014 and lasting for around a month or more, during the post-June 2014 to early-January 2016 price decline. Insofar as there is overlap with the extant literature, the results broadly corroborate earlier findings and we offer a degree of robustness not hitherto provided. In particular, our results are robust to a potentially changing dollar numeraire. Using the wild bootstrap, we found that the October 2014 episode detected for spot prices by Fantazini (2016) was not robust at conventional significance levels and occurs later, notably *after* the late-November OPEC meeting. A key conclusion is that the use of the benchmark futures prices or spot prices is inconsequential for testing for mild explosivity in oil prices around and in the aftermath of the GFC.

Corroboratory evidence exists outside the PSY framework for the first mildly explosive or similar type of episode during 2008. For example, Shi and Arora (2012) applied a regime-switching model with the oil price decomposed into deterministic and bubble components, and found the estimated probability of being in a bubble-surviving regime rose just prior to a spike in the estimated probability of being a bubble collapsing regime in late-2008. Similar evidence within the regime-switching framework was provided by Lammerding et al. (2013), Brooks et al. (2015) and Zhang and Wang (2015). Zhang and Yao (2016) and Fantazzini (2016) employ a log-periodic power law model.

5. Fundamentals and the role of financial variables

We now apply the third stage of the PSY strategy, which uses the test to assess whether the detected mildly explosive periods can be related to fundamentals or other proxy variables. In so doing, we can formally assess various conjectures and results about the drivers of oil prices that have appeared recently. Even today, economic theory is surprising silent on general principles of choosing or identifying the fundamentals for a given asset or commodity and this means we are forced to follow the convention of choosing fundamental and other proxy variables on an ad hoc basis. Given the reduced-form nature of our approach, we can only provide corroborative evidence: we cannot assert causation between two variables because there is always the possibility that a third variable is acting on both the oil price and the proxy variable. It is also possible that the same evidence can be consistent with two or more competing hypotheses. We can, however, use results from the PSY test to seek evidence *against* causation given that the mild explosivity property dominates other features in the series, and in this way we can build up an evidence base that allows the implications of potentially different structural model specifications to be assessed.

In this section, we firstly view oil through a pure commodity lens and ask whether recent oil price behavior was mirrored in other commodities or commodity indices. Finding evidence pointing to factors specific to oil, we then consider whether the detected mildly explosive episodes pertaining to the 2007-08 oil price spike and the post-2014 price collapse were consistent with their having been driven by oil fundamentals. We use two traditional fundamentals: global economic activity, which we proxy by the Baltic Dry Index; and inventories which, following Phillips and Yu (2011) and others, can be proxied by U.S. crude oil stocks that the EIA conveniently makes available as end-of-week data. We then assess recent conjectures regarding the financialization of oil, where large numbers of financial actors, specifically investment banks, hedge funds and index investors, have become involved in oil and commodity futures markets. Financialization has undeniably changed the composition of oil markets but whether it has been the major driver of oil prices is much more controversial.[13] We consider evidence using the PSY strategy by taking two perspectives: first, to consider whether there was any significant, wider role that might have been played by oil prices as an element in financial portfolios or in calculations of systemic market risk; and second, to consider whether there is evidence of there having been excess speculative activity in oil. The former is assessed using the equity VIX and the latter using Working's (1960) *T*-index computed using U.S. Commodity Futures Trading Commission (CFTC) position data.

[13] See Fattouh et al. (2013) and Cheng and Xiong (2014) for surveys that apply generally to commodity markets.

5.1. Oil and other commodities

We first consider whether commodities other than oil exhibited their own statistically significant departures from a random walk behavior, synchronous with our detected periods in oil. Formally, we test the same for copper and zinc – which Azeki and Blanchard (2014) cited as exemplars – and the Bloomberg Commodity Index (BCI), the preferred index used in the EIA (2016) in its summary of oil price drivers. This represents a sharper approach than simply making an informal appeal to a seemingly apparent observation of a coincident boom and bust in certain commodity markets in 2007-08, such as presented by Sockin and Xiong (2015).

Figuerola-Ferretti et al. (2015) applied the PSY test to weekly data on six London Metals Exchange (LME) three-month futures prices, reflecting the most liquid futures contract traded.

[Table 1C around here]

Table 1C reports new results for the GSADF statistic for copper and zinc, where the parameters (the sample start and end dates, and the initial sample fraction r_0) are now aligned to this paper and thereby include the recent period of commodity price falls. The null of no mildly explosive period is rejected at the 1% significance level. The BSADF sequence dates mildly explosive episodes in copper between March and June 2006 and in zinc between December 2015 and February 2016, and March and June 2006, at the 5% level. Conclusively, they are *not* during the two detected episodes for oil. Results obtained using the Phillips and Shi (2018) reverse regression approach (not reported) offered no additional information. The results for copper and zinc echo those for all six non-ferrous metals in Table IV in Figuerola-Ferretti et al. (2015) obtained on the basis of a different sample.

Comparison of our oil results with those obtained by Figuerola-Ferretti and McCrorie (2016) in their application of the PSY test to precious metals are less clear. Episodes of mild explosivity in gold and platinum front-month futures prices were identified in 2008 in the midst of the GFC, although in the two or three months *prior* to the detected episode in oil. Etienne et al. (2015), using the PSY test with daily data, detected some mildly explosive episodes in grain futures prices in 2007 and 2008 but each lasted only a few days in length. Although there were two such episodes in soybeans in June 2008, there is nothing substantive to tie their results to oil prices.

We also applied the PSY test to the BCI, an index measure of a basket of commodities where the combined weighting of WTI and Brent prices is 15%. Interestingly, the GSADF statistic reported in Table 1C now only rejects the null of there being no mildly explosive episode at the 10% significance level. As reported in Table 3, the second-stage of the test using the BSADF statistic and minimum duration condition again dates the very same two mildly explosive episodes as before, but using a 10% critical value line. This higher significance level can be explained by combining the fact that the BCI dilutes the role of Brent and WTI prices given our lack of strong evidence to reject a random walk null in the other commodities around the same time as in oil.

Our overall conclusion is that factors beyond the recent behavior of commodity prices underlie recent oil prices both in the run-up to the high point in prices during the GFC and during the recent oil price decline. Our work corroborates the conclusions of Azeki and Blanchard (2014) and Baumeister and Kilian (2016) in this regard, but points to commodity-specific differences among the commodities observed using weekly data during the boom and bust cycle in 2007-08 considered recently by Sockin and Xiong (2015).

5.2. Global economic activity

Rather than interpolate one of the traditional proxies for global economic activity, such as an OECD measure of industrial production available as monthly data, we follow the general standpoint of Killian (2009, p. 1005) who constructed a bespoke index for the analysis of oil prices based on dry cargo single ocean freight rates. As a leading rather than a coincident indicator, it can better anticipate and capture demand shifts for industrial commodities in global markets. Here, we use the Baltic Dry Index (BDI) to proxy global economic activity, a similar such index that is available on the Bloomberg International Database.[14] The GSADF statistics of both the BDI reported in Table 1E and the ratio of WTI nominal prices to the BDI reported in Table 1F both reject the null of there being no mildly explosive episode at the 1% significance level.

[Tables 1E and 1F around here]

[14] The BDI is an economic indicator issued daily by the London-based Baltic Exchange, and provides an assessment of the price of moving raw materials by sea. It measures the demand for shipping capacity versus the supply of dry bulk carriers and indirectly measures the global supply and demand for the commodities shipped aboard dry bulk carriers.

Table 4 reports the results of the second-stage of the test. Two mildly explosive periods are seen in the BTI index itself, between mid-April until the end of May 2007 and end-August to end-December 2007.[15] The test based on the WTI/BDI ratio, as reported in Table 5, dates a two-month episode in 2005 and a six-week-or-so episode during October and November 2008 when the BDI is falling.

[Tables 4 and 5 around here]

Evidence obtained on the basis of the PSY test to support global economic activity having been a key driver of the post-June 2014 oil price decline is therefore non-existent; however, the extent to which it might explain the behavior of oil prices during the 2007-08 price spike depends on the extent to which the BDI can be viewed as a leading indicator. The supply of cargo ships is generally tight and inelastic and so marginal increases in the demand for shipping capacity can quickly push up the BDI. Because dry bulk primarily consists of materials that function as raw material inputs to the production of intermediate or final goods, the index is indeed an indicator of future growth and production. The lag time involved is plausibly of a length similar to the time difference between the episodes detected in the BDI and in nominal oil prices, providing support for global economic activity – a traditional oil fundamental – as having been an important driver in the run-up in oil prices during the 2007-08 oil price spike. Our results therefore provide new support for the explanations of the run-up in oil prices in 2007-08 advanced by Hamilton (2009), Kilian (2009) and Kilian and Hicks (2013) as being sourced in the real economy.[16] This question continues to be of relevance more than a decade on: Pavlidis et al. (2018) and Kruse and Wegener (2019) offer similar conclusions on the importance of a demand component in early 2008 prices using different methods to those used here.

The later, negative mildly explosive episode seen in the ratio of WTI nominal prices to the BDI (when nominal prices are falling) indicates that in the immediate aftermath of the high point of the GFC in mid-September, when the global financial services firm Lehman Brothers Holdings Inc. filed for bankruptcy, WTI oil prices fell

[15] This evidence may be consistent with one, longer mildly explosive episode being detected from mid-April to mid-Dececmber 2007 on the basis of lower frequency data.

[16] Indeed, on the basis of a forecasting approach, Kilian and Hicks (2013) showed that the run-up in real oil prices over the period from mid-2003 to mid-2008 was attributable to repeated demand shocks. As is shown here, however, only during the 2007-08 period was the run-up significant enough for the null of random walk behavior to be rejected and only immediately prior to this one period did the BDI show a similar departure from trend.

faster than can be explained by global economic activity alone. Finally, and not insignificantly, the BSADF sequence of the BDI level series, as shown in Figure 6, indicates that in 2014 the BDI was falling, which is consistent with the evidence provided by Bauermeister and Kilian (2016) in the sense that it conveys that lower global demand played *some* role in the post-June 2014 price decline.

[Figure 6 around here]

The BSADF sequence is, however, always below the 5% critical value line around this time, suggesting it exhibited a lower degree of non-stationarity than crude oil prices. This indicates the BDI did not decisively anticipate the later shift to a (negative) mildly explosive regime, which is a weaker result than Bauermeister and Kilian's. This evidence taken at face value also indicates that the drivers of the two detected mildly explosive episodes over last decade or so were different in character.

5.3. Inventories

Deaton and Laroque (1992) argue that the classical fundamental in a commodity price setting is the stock or inventory variable. Fantazzini (2016) and Caspi et al. (2018) follow Phillips and Yu (2011) in applying the PWY/PSY strategy to crude oil nominal spot prices deflated by the traditional above-ground inventory supply proxy of U.S. WTI stocks. Using the prototype test by PWY (2011), they detected a mildly explosive period in the ratio between March and July 2008 using monthly data. Here, on the basis of weekly data, we apply the PSY test – which PSY (2015b) showed supersedes the PWY (2011) test – to the U.S. stocks themselves and then to the ratio of nominal WTI front-month futures prices to the same. The GSADF statistic for stocks reported in Table 1E shows the null hypothesis of no mildly explosive period is not rejected at the 10% significance level. We do not therefore proceed to the second, date-stamping stage of the PSY test. Consistent with this evidence, the GSADF statistic of the ratio of WTI nominal prices to U.S. stocks as reported in Table 1F is significant at the 1% level and, as can be seen in Figure 7 and is reported in Table 5, a mildly explosive period is dated between mid-May and mid-June 2008 and between mid-November 2014 and mid-March 2015.

[Figure 7 around here]

These are coincident with the same such periods in WTI nominal prices alone, as reported earlier, but begins slightly later than in the detected period by Phillips and Yu (2011) based on monthly spot price data.

For the ratio of monthly data on WTI nominal spot prices to U.S. stocks, Caspi et al. (2018, Table 2) report a longer mildly explosive period at the end of their sample, between July 2007 and September 2008, than Phillips and Yu on the basis of the PWY test.[17] For the same ratio using weekly spot price data, Fantazzini (2016, Table 3) dates a positive episode between October 2007 and September 2008, and a negative episode between mid-December 2014 and mid-March 2015, the first encompassing the first episode and the second coincident with the second episode detected using WTI nominal prices alone.

Taking the evidence altogether, our fundamental proxy does *not* offer prima facie evidence that above-ground inventories drove oil prices either during the run-up in prices in 2008 or the post-2014 price decline. Our results therefore corroborate the conclusion of Kilian and Lee (2014) that above-ground inventories were not decisive in explaining the 2007-08 price spike. Their conclusion was reached using two inventory measures. On the basis of the underlying Kilian and Murphy (2014) structural model, which embodies the theory of storage, the effect of speculation was quantified there as raising the real oil price by between $5 and $14 between March and July 2008. Taken at face value, their estimates provide a counterfactual that would be insufficient to reverse the conclusions of the PSY test.

5.4. U.S. shale oil and the role of OPEC

The traditional argument that U.S. stocks proxy above-ground inventory supply is based on such inventories being in the country in the world economy that has the largest consumption of oil. It neglects other important elements of world supply such as the role played by OPEC producers, notably Saudi Arabia, in holding stocks below-ground. In recent years, this has been affected by the emergence of U.S. hydraulic fracturing (or "fracking"), a technique designed to recover gas and oil from shale rock. Kilian (2017) examines the consequences of the recent emergence of U.S. shale

[17] The samples of PY (2011) and Caspi et al. (2018) do not encompass the post-June 2014 price decline.

oil on Arab crude oil producers and estimates that the price was around $10 lower in mid-2014, falling to about $5 lower in mid-2015. Taken at face value, the estimates provide a counterfactual under which its marginal impact can be assessed using the PSY test by adjusting prices upwards, but this is not enough to prevent the declaration of a mildly explosive episode at the 10% significance level around this time. This suggests that while U.S. shale oil played a role in the falling oil price from June 2014, it was not decisive in contributing to the short rejection of random walk behavior in oil prices in late-2014.

Azeki and Blanchard (2014) and Baffes et al. (2015) have argued strongly that the OPEC meeting in November 2014 represented a watershed moment: with OPEC agreeing to maintain its production ceiling at 30 million barrels per day, it signalled a change in policy from one of targeting an oil price band to maintaining market share.[18] This would represent a *supply shock* where, rather than agreeing on production cuts to maintain prices, OPEC signalled a fundamental change in expectations about future global oil supply and prices (with clear implications for the profitability of emergent and continuing U.S. fracking activity).[19] If the results using the wild bootstrap are taken at face value, *all* of our results, whether spot or futures prices, or real or nominal prices, date a short (negative) mildly explosive episode in the midst of the post-June 2014 to early-2016 price decline as beginning around the immediate aftermath of the OPEC meeting and lasting for up to two months. While our reduced-form approach can never offer prima facie evidence for such a linkage, the consistency of our findings across different series offers strong corroboratory evidence. On the basis of an observed negative forecast error in their proxy for global real activity, Baumeister and Kilian (2016) inferred there was a *negative demand shock* in December 2014, which they attributed to an unexpected weakening of the global economy. As discussed above, we were unable to demonstrate that there were similar, coincident price falls in other commodities around this time.[20] And from

[18] The role of U.S. shale oil is not unimportant here because the decision may have been motivated by predatory pricing considerations that took account of actual and future expectations of supply.

[19] Behar and Ritz (2017) provide a model to explain this behavior.

[20] The discrepancy found by Baumeister and Kilian between their prediction at June 2014 of a $27 decline in oil prices and their attribution of only around $10 to a slowdown in economic activity is consistent, as the authors note, with the disparity later seen in the larger decline in crude oil prices from around then compared with other commodities. The issue here, however, is that if there had been a negative demand shock in December 2014 that was decisive in moving oil prices away from random

today's standpoint, a negative forecast error in global economic activity around December 2014 would not automatically be seen as evidence of a significant, negative demand shock given the weak transmission mechanism from falling and low oil prices to economic activity that was seen in 2015 and 2016. Using a different structural model that explicitly models the "shale oil revolution", Belu Mănescu and Nuño (2015) found the decline in prices was principally a consequence of unanticipated supply shocks. Bataa and Park (2017) employ an SVAR model with structural breaks to estimate that around a quarter of the decline in prices between June 2014 and February 2016 was attributable to global supply shocks. Here, we are concerned with identifying any episode during the price decline in which prices are inconsistent with random walk behavior, and we found the period after the OPEC meeting was salient. While we have exploited the advantages offered by a reduced-form approach and the evidence is strong in this context, the approach does not allow us positively to identify whether the price fall at this time arose from a negative supply or a negative demand shock, or for another reason.

5.5. Financial aspects and the OVX

An interesting element of the Kilian and Murphy (2014) structural model is that it does not contain a futures price as a variable. This does not rule out speculation; for it can be seen as an inventory demand shock in the spot market that follows changes in expected fundamentals. Perfect arbitrage would then imply full pass-through from speculation in the futures market to the spot market via changing inventories.[21] There are plausible reasons that have been offered recently, however, to suggest that perfect arbitrage might not hold in oil or other commodities markets, with the consequence

walk behavior, its impact should have been observed in the same way across other commodities; otherwise it would have to be derived from another source.

[21] Hamilton (2009) also points out that if the short-run price elasticity of gasoline demand is zero, there is scope for speculation to drive up the real price of oil without crude oil inventories being affected. This condition is not testable within the PSY mild explosivity framework. We therefore simply report that in their structural model, Kilian and Murphy (2014) related the gasoline demand elasticity to the short-run elasticity of oil demand and provided a posterior median estimate of the latter of -0.26, and showed there was an 84% probability that this value was below -0.09 (*ibid*., Table II). In a different model, Baumeister and Peersman (2013) reported evidence to suggest the short-run elasticity of oil demand was time varying but that the boundary of their 95% posterior credible set was less than zero throughout their sample (*ibid*., Figure 4). Taken at face value, both sets of results suggest that the case of a zero price elasticity of demand is an unlikely explanation for any run-up in crude oil prices seen before their high point in July 2008.

that inventory data may not be sufficient to capture speculative activity within spot and futures markets. Lombardy and Van Robays (2011) provide a structural model along the lines of the Kilian and Murphy (2014) model but with incomplete pass-through. Acharya et al. (2013) propose a model of commodities in which the interaction of commodity producers averse to price fluctuations and capital-constrained speculators induces a link between a financial friction in the futures market and spot prices. Sockin and Xiong (2015) and Basak and Pavlova (2016) similarly provide models of financialization that impact upon both commodity futures and spot prices. In a significant paper, Singleton (2014) demonstrates that money flows associated with index investors help predict changes in oil futures prices, although recent work by Irwin and Sanders (2014) and Hamilton and Wu (2015) may mollify this conclusion.

The above motivates using the PSY strategy to assess whether the evidence supports there having been financial speculation in the oil futures market during one or both of the detected mildly explosive episodes, either from different sources or in excess of that implied by normal backwardation or the classical theory of storage. As noted earlier, no discrepancy was found when using spot and front-month futures prices as the basis of inference. Recent work by Robe and Wallen (2016) has tied measures of oil price volatility and economy-wide financial conditions as captured by the equity VIX to the oil futures market. Indeed, Cheng et al. (2015) propose a transmission mechanism from financial traders to futures markets whereby a "convective risk flow" from speculators, who sell in response to rises in risk as prices fall, to hedgers, who operate on the other side of the market, reallocates risk from groups less able to bear it to groups that can. Empirical evidence, where in their framework the VIX acts as a proxy for the risk appetite of financial traders and funding constraints, corroborates commodity index traders having an impact on commodity futures prices, thereby implying a role for financialization. Accordingly, we shall assess whether there is evidence that the VIX had a role to play in recent oil price movements, in particular during the two detected mildly explosive episodes. Oil has its own measure of volatility, the CBOE Crude Oil Volatility Index (OVX), which we shall first use to establish a benchmark.

The OVX was launched by CBOE as an oil-related volatility index on 3 June 2008 during the unfolding of the GFC. Data are available at the CBOE official website. It measures oil market uncertainty through options taken on crude oil prices, specifically the market's expectation of the 30-day volatility of WTI nominal prices applying the standard CBOE volatility index methodology (discussed briefly in Section 5.6 below) to options on the United States Oil Fund.[22] Implied volatility indices are generally derived from *option prices*, and reflect market expectations on the *future volatility* over the lifetime of the option. Such measures, therefore, allow us the possibility of incorporating market-based expectations in a way that traditional fundamental variables do not (although this aspect is less important in our approach than it is in a forecasting-based approach). For the interpretation of our results, we need to rely on some linkage between the volatility index and futures prices such as discussed in the papers cited above.

Figure 8A displays WTI benchmark future prices and the OVX.

[Figure 8A about here]

The negative relationship between WTI nominal prices and the OVX seen after the fall in the oil price in 2008 is notable right through to the end of the sample. There are spikes when volatility is high, around or just after the second (negative) mildly explosive episode detected in WTI nominal prices, and for a second time in 2015. To apply the PSY test, given the launch date, we need to alter some of the parameters chosen above. We continue to use the PSY (2015a) recommended rule-based calculation of the initial sample fraction, r_0, but use a sample only from January 2009, beyond the launch date, to ensure the chosen sample is clear of the oil price shock in 2007-08. Table 1D indicates that the GSADF statistic is significant at the 1% significance level, meaning that the null of there being no mildly explosive period is rejected; however, as reported in Table 6, the second-stage of the test does not date a mildly explosive period.

[Table 6 around here]

Figure 8B shows that the BSADF sequence *does* cross the 5% critical value line at almost exactly the point of the OPEC meeting, but the crossing is not of sufficient

[22] The United States Oil Fund (USO) is an exchange-traded security designed to track changes in crude oil prices. By holding near-term futures contracts and cash, the performance of the Fund is intended to reflect, as closely as possible, the spot price of WTI crude oil, less USO trading expenses.

duration for a mildly explosive episode to be declared. This may indicate the OVX, as a forward-looking variable based on expectations, adjusted once-and-for all in the aftermath of the meeting.

[Figure 8B around here]

On the basis of the ratio of WTI nominal prices to the OVX, the null of no mildly explosive episode is not rejected at the 10% significance level, as is reported in Table 1F, and so we do not proceed to the date-stamping stage of the test.

[Table 1F around here]

Taken at face value, this result is not surprising; for we would expect the OVX to act as an omnibus measure that reflects the myriad of influences on the oil price. For precisely this reason, however, the results by themselves are uninformative in terms of identifying specific drivers. We will therefore treat the OVX results as a benchmark case against which to compare results obtained using the VIX.

5.6. VIX

The CBOE Volatility Index (VIX) is the implied volatility of Standard and Poor's S&P 500 equity index over the next 30-day period and is the premier benchmark for U.S. stock market volatility. It is the square root of the risk-neutral expectation of the variance of the S&P 500 index over this period, computed on the basis of a weighted average of prices for a range of options over the index, and is quoted as a percentage. Figure 9A shows that there are two spikes in the VIX during the sample period: the first occurs during the later stages of the 2007-08 oil price spike, *after* the mildly explosive episode detected during the run-up in prices;[23] and in mid-2011 around the time of Standard and Poor's downgrade of U.S. sovereign debt.

[Figure 9A around here]

Little upward or downward movement is seen in the VIX during the recent oil price decline and there is only a small uptick around the detected mildly explosive episode, in marked contrast to the OVX series. The GSADF statistic rejects at the 10% significance level the null of no mildly explosive episode, as reported in Table 1D,

[23] That the spike in the VIX occurred during the *collapse-phase* of the 2007-08 spike is not unexpected but, as Table 6 indicates, no mildly explosive episode was detected in the VIX levels series during this period.

but no such episode is dated in the second stage of the test. Figure 9A shows that the BSADF sequence cuts the 5% critical value line during the 2007-08 oil price spike but not for a sufficient time period for a mildly explosive episode to be declared. It may be, however, that the VIX is more relevant during the collapse phase of the spike. Accordingly, we apply the reverse regression procedure of Phillips and Shi (2018).

[Table 7 and Figure 9B around here]

When the minimum duration condition is not applied, two short mildly explosive episodes are detected, the latter into 2009. This may suggest the VIX had some influence during and after the collapse phase of the oil price spike, reflecting greater uncertainty at this time. There is, however, no such declared episode when the standard condition is applied.

As reported in Table 1F, the ratio of WTI prices to the VIX does not reject the null of no mildly explosive episode at the 10% significance level and so we do not proceed to the date-stamping stage of the test. Inspection of the BSADF sequence in Figure 9C shows that this rejection occurs *without* the sequence cutting the 5% critical value line, which points to the need for further analysis.

[Figure 9C around here]

Because the ratio of the WTI nominal price series to the VIX is the same as the ratio of the WTI real prices to the VIX deflated by U.S. CPI, we consider the BSADF sequence of the ratio of the VIX to the U.S. CPI series, shown in Figure 9D, to try to gain more insight into the first-stage non-rejection. Nothing substantively different emerges compared with the VIX levels case: the BSADF sequence again cuts the 5% critical value line in late 2008 – in the collapse phase of the 2007-08 oil price spike – and there is no spike in late-2014.

[Figure 9D around here]

Running the PSY test on the ratio of WTI nominal prices to the S&P 500 index itself indicates that the null of no mildly explosive episode is rejected at the 1% significance level and, as reported in Table 8, the same mildly explosive episodes are detected as using WTI nominal prices alone even given the evidence reported by Silvennoinen and Thorp (2013) that the two variables have become increasingly correlated under financialization.

[Table 8 around here]

This offers prima facie evidence to suggest there were factors beyond stock prices driving both departures from random walk behavior. At face value, the failure of the ratio of WTI prices to the VIX to detect the departures seen in the WTI series offers corroborative evidence consistent with Cheng et al. (2015) and Robe and Wallen (2016) who tie WTI futures prices to the VIX. The supporting evidence, however, suggests otherwise. Firstly, the rise in the VIX occurs *after* the high point of crude oil prices in 2008 and therefore after the dated mildly explosive episode; there is no spike in the VIX in late-2014 in contrast to that seen in the oil-specific OVX; and the results are the same for both nominal and real prices. On the basis of the PSY testing strategy, it is therefore difficult to support the VIX having played a role in driving the level of oil prices around 2007-08 or during the post-2014 oil price decline. Inspection of the BSADF sequence in Figure 9C suggests that the VIX series is considerably more volatile than the oil price series, and this volatility translates into the ratio of prices. It may be that the PSY test, which derives its statistical power from its concentration of focus on the autoregressive parameter, and relies on a minimum duration condition in the date-stamping stage, is not conducive towards assessing the actual role of the VIX. Market expectations of oil price volatility should be higher during periods of financial stress and so we would expect the VIX to be a good predictor of the *volatility* in oil prices, but not necessarily their levels as is tested for here.

5.7. Non-commercial positions and speculation

The evidence presented above points to the mildly explosive episode detected in the run-up in oil prices during the 2007-08 spike as having been driven by a real economy fundamental: a mildly explosive episode in the BDI leading indicator proxy for global economic activity preceded the same in both WTI and Brent benchmark oil prices in mid-2008. Alongside this, on the basis of a counterfactual from Kilian and Lee's (2014) approach, which embodied speculation within the classical theory of storage, above-ground inventories were seen not to have been decisive. Sockin and Xiong (2015) argue, however, that the period coinciding with our detected mildly explosive episode was characterized by a global economy whose developed economies had begun to show signs of weakness and that, even if growth in the emerging economies remained strong, a price rise of around 40% between January and July 2008 was not justified by global economic activity alone.

Using the PSY test applied to Commitments of Traders (CoT) position data published by the U.S. Commodity Futures Trading Commission (CFTC), we can assess whether and to what extent there is a contribution from financialization that may have amplified the effects of this rising demand. This data breaks down the overall open interest between the positions of commercials ("hedgers") and non-commericials ("speculators").[24] Büyükşahin and Harris (2011), Büyükşahin and Robe (2014) and others employ Working's *T*-index as a measure of "excess speculation": it calculates the amount of speculation in excess of what is minimally necessary to meet short and long hedging demand. If we write long and short commercial (hedge) positions as H_L and H_S, and long and short non-commercial (speculative) positions as S_L and S_S, Working's *T*-index is defined by

$$T = 1 + \frac{1\left(H_S \geq H_L\right) \cdot S_s + 1\left(H_S < H_L\right) \cdot S_L}{H_L + H_S} \qquad (8)$$

If T = 1, the level of non-commercial activity is just sufficient to be available as counterparties for the commercial imbalance. Any excess over unity implies that speculators are acting as counterparties for each other. Here, we provide a *direct test* for excess speculation by applying the PSY test to a time series of Working's *T*-index.

The GSADF statistic as reported in Table 1G shows that the null of no mildly explosive period is rejected at the 1% significance level.

[Table 1G around here]

The BSADF sequence as shown in Figure 10 indicates than at no point prior to the high point of nominal and real oil prices in 2008 did the sequence cut the 5% critical value line.

[Figure 10 around here]

There is therefore no evidence provided by the PSY test to suggest that excess speculation played a role either in the run-up in oil prices from 2003 or during the 2007-08 spike seen during the GFC. The index rises from late-2014 onward but no

[24] Commercial positions are associated with producers and consumers of the commodity. Non-commercial positions reflect the activities of financial traders for investment purposes.

mildly explosive episode coinciding with the detected periods in nominal and real prices is reported in Table 9.

[Table 9 around here]

Such is the rise in the index that an episode is dated from end-April 2015 to the beginning of January 2016. This may indicate that there have been changes in the oil market that have occurred in response to the recent oil price decline, although any such consideration is outside the scope of the current paper. Our main result corroborates the conclusions of Sanders and Irwin (2014), and Hamilton and Wu (2015), that excess speculation through financialization did not drive either the run-up phase in the 2007-08 price spike or the mid-June 2014 to early 2016 price decline. Recent evidence provided by Yan, Irwin and Sanders (2018) strengthens this conclusion for the 2007-08 period.

6. Conclusion

This paper provides an analysis of crude oil prices around and in the aftermath of the GFC. Many of the recent hypotheses on oil prices and their drivers have been put forward in a way that does not properly subject them to a statistical test and, therefore, to the capability of being rejected on the basis of the data. Here, we have used the PSY testing strategy in all its elements to create an evidence base against which the implications of structural models of the oil market – actual and potential – could be assessed. This approach provided new, and sometimes clarifying, evidence on some of the recent controversies surrounding oil prices during and in the aftermath of the GFC.

Our main conclusions are as follows:

1. Two periods of mild exposivity were detected in oil prices during and in the aftermath of the GFC. A statistically significant rise beyond that consistent with random walk behavior is detected in both Brent and WTI, real and nominal, spot and benchmark crude oil futures prices between mid-May and mid-July 2008, in the midst of the GFC. A similar, shorter episode was detected in the midst of the post-June 2014 to early-2016 price decline, beginning in late-November or early-December 2014 and lasting for up to two months. Insofar as the date-stamping stage of PSY strategy contained some overlap with the extant literature, we provided extensive robustness checks that controlled for potential changes in the

dollar numeraire and for possible non-stationary volatility during the sample period. The depreciating dollar in early-2008 and the appreciating dollar in 2014 were not found to be decisive, corroborating the view of Baumeister and Kilian (2016) but contradicting the view of Baffes et al. (2015). Using spot prices or front-month futures prices was found to be inconsequential; in particular, the recent detection in the literature of an earlier explosive period in Brent spot prices compared with front-month futures prices was found not to be robust.

2. The end of the first mildly explosive period coincided with the end of the run-up in nominal prices in 2008 and, on the basis of a statistical test, was precisely dated to an announcement by U.S. President George W. Bush that ended an executive ban on offshore drilling. This marked, at the same time, a low point of the U.S. dollar.
3. New evidence was provided for the rise in oil prices during the 2007-08 spike as having been driven by a real economy fundamental, global economic activity, corroborating a conclusion on the determinants of oil prices during this period that Hamilton (2009) and Kilian (2009) derived by different means. Our results also corroborate the view of Kilian and Hicks (2013) that the long run-up in oil prices from 2003 was demand-driven. Our evidence from applying the third-stage of the PSY testing strategy shows that the behavior of the fundamental changed in 2008. This offers a new insight into why the oil price behavior in 2008 was different.
4. The date-stamp on a short, second episode during the post-June 2014 price decline, robustly found across all the oil price series considered herein, ties with the immediate aftermath of an OPEC meeting in late-November 2014 where, in the face of a glut, the cartel did not reinforce its longstanding policy of defending prices. Taken at face value, this corroborates the view of Azeki and Blanchard (2014) and Baffes et al. (2015) that the outcome of this meeting constituted a significant supply shock to oil prices and negates the view of Baumeister and Kilian (2016) as to the meeting's lack of decisive importance. We recognize that our reduced-form strategy cannot distinguish between a price fall arising from a supply shock or a demand shock; however, we found that the behavior of other commodities, which would have been similarly exposed to a negative global

demand shock, was not decisive in explaining the detected short shift to a mildly explosive regime.

5. On the basis of counterfactuals provided by structural models, neither above-ground inventories nor the supply of U.S. shale oil was found to have been decisive in driving the departures from random walk behavior during the 2007-08 spike or the 2014-16 price decline. This does not mean such variables are unimportant in determining prices. For example, actual and potential increases in the U.S. shale oil supply may have driven the outcome of the OPEC meeting in November 2014.
6. In spite of recent work by Cheng et al. (2015) and Robe and Wallen (2016) tying crude oil futures to the equity VIX, we find no hard evidence to suggest that the VIX decisively influenced oil price levels during the sample period. On the basis of a direct test using Working's *T*-index constructed with CFTC position data, there was no evidence found to suggest that excess speculation was a contributory factor to either the 2007-08 oil price spike or the 2014-16 oil price decline. This corroborates the view of Irwin and Sanders (2014) and Hamilton and Wu (2015) and contradicts the conclusion of Singleton (2014).

From the point of view of the extant oil price literature, the new evidence provided on the role of a real economic variable in the run-up in oil prices in 2008 and the lack of evidence of a role for financialization or speculation are probably the most important. Because of the continuing ramifications of the GFC and ongoing questions concerning post-GFC regulation, they continue to be relevant issues for academics and policymakers more than a decade on. Recent work by Pavlidis et al. (2018) and Kruse and Wegener (2019) attests to this, and interestingly they too find evidence in favour of a decisive role for an economic fundamental in 2008, obtained by very different methods from those used herein.

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Appendix A: Tables

Table 1A GSADF Test Statistics ICE Brent Crude nominal front-month futures and spot 2003 - 2016 (weekly data)			
	Brent	**Brent/CPI**	**Brent/SDR**
Futures	4.382	4.349	4.377
Spot	5.313	5.378	5.142

This table reports the GSADF statistic for ICE Brent Crude nominal front-month futures prices and the GSADF statistics for this series deflated by a U.S. CPI series interpolated weekly by and an SDR factor to control for the changing dollar numeraire. The initial window for recursive estimation is 47 weeks. The ADF lag is chosen to minimize the BIC over every subsample with maximum lag length set at 5 weeks. Standard PSY Critical values: 2.069 (10%), 2.282 (5%) and 2.664 (1%).

Table 1B GSADF Test Statistics NYMEX WTI Crude nominal front-month futures 2003-2016 (weekly data)			
	WTI	**WTI/CPI**	**WTI/SDR**
Futures	4.935	4.898	4.848
Spot	4.541	4.515	4.624

This table reports the GSADF statistics for NYMEX WTI Crude nominal front-month futures month prices and the GSADF statistics for this series adjusted by U.S. CPI and by an SDR factor to control for the changing dollar numeraire. Standard PSY Critical values: 2.069 (10%), 2.282 (5%) and 2.664 (1%).

Table 1C GSADF Test Statistics LME Copper and Zinc nominal three-month futures & Bloomberg Commodity Index 2003-2016 (weekly data)			
	Cu	**Zn**	**BCI**
GSADF	7.963	6.528	2.187

This table reports GSADF statistics for LME copper and zinc nominal three-month futures prices and the Bloomberg Commodity Index. Standard PSY Critical values: 2.069 (10%), 2.282 (5%) and 2.664 (1%).

Table 1D
GSADF Test Statistic
Fundamental measures (in levels)
2003-2016 (weekly data)

	BDI	Inventories	VIX	OVX *
GSADF	4.315	1.882	3.238	3.056

This table reports GSADF statistics for the Baltic Dry Index (BDI); U.S. end-of-week stocks (EIA data); and the VIX and OVX volatility index measures. Standard PSY Critical values: 2.069 (10%), 2.282 (5%) and 2.664 (1%).

*Note that for the OVX measure, the sample runs from 2009 to 2016 and the initial value window, also chosen using PSY's rule, is 35 weeks.

Table 1E
GSADF Test Statistics
WTI Crude Nominal Front-Month Prices deflated by fundamental proxy variables and financial variables
2003-2016 (weekly data)

	WTI/Baltic Dry Index	WTI/inventories	WTI/S&P500
GSADF	4.850	4.930	4.703

This table reports GSADF statistics for WTI front month NYMEX futures weighted by (a) the Baltic Dry Index; (b) U.S. end-of-week (WTI) crude oil stocks (Source: EIA); (c) S&P 500 index. Standard PSY Critical values: 2.069 (10%), 2.282 (5%) and 2.664 (1%).

Table 1F
GSADF Test Statistics
Nominal Crude Oil Prices deflated by Volatility Measures
2003-2016 VIX deflated (weekly data)
2007-2016 OVX deflated (weekly data)

	WTI/OVX	WTI/VIX	Brent/VIX
Futures	0.992	0.525	1.072
Spot	1.023	1.169	2.524

This table reports GSADF statistics for WTI Crude nominal front-month and spot prices deflated by the OVX index and GSADF statistics for both WTI Crude and Brent Crude nominal front-month futures prices deflated by the CBOE VIX index. Standard PSY Critical values: 2.069 (10%), 2.282 (5%) and 2.664 (1%).

Table 1G **GSADF Test Statistic** **Working's *T* index** **2003-2016 (CFTC weekly data, reported Tuesdays)**	
	CFTC
GSADF	2.823

This table reports the GSADF statistic for Working's *T*-index calculated using data on Commercial Long, Commercial Short, Non-Commerical Long and Non-Commercial Short positions. The initial window for recursive estimation is 47 weeks. The ADF lag is chosen to minimize the BIC over every subsample with the maximum lag length set at 5 weeks. Standard PSY Critical values: 2.069 (10%), 2.282 (5%) and 2.664 (1%).

Table 2A: ICE Brent Crude nominal prices
2003-2016 (weekly data)

Estimated start and end dates for periods of mildly explosive price behavior

Front-Month Futures Prices					
Nominal		**CPI deflated**		**SDR deflated**	
Start	**End**	**Start**	**End**	**Start**	**End**
16-5-2008	18-7-2008	16-5-2008	18-7-2008	16-05-2008	25-07-2008*
05-12-2014	06-02-2015	05-12-2014	13-02-2015	5-12-2014	06-02-2015
Spot Prices					
23-05-2008	25-07-2008	No mild	explosivity	16-05-08	25-07-2008
24-10-2014	06-02-2015	17-10-2014	06-02-2015	5-12-2014	06-02-2015

This table reports detected mildly explosive periods in ICE Brent crude weekly nominal front-month futures and the same deflated by an interpolated U.S. CPI series and by the currency value of the SDR basket using the PSY procedure with 5% size.
*Only detected at the 10% significance level.

Table 2B: NYMEX WTI Crude nominal prices
2003-2016 (weekly data)

Estimated start and end dates for periods of mildly explosive price behavior

Nominal		CPI deflated		SDR deflated	
Front-Month Futures Prices					
Start	**End**	**Start**	**End**	**Start**	**End**
16-5-2008	18-7-2008	16-5-2008	18-7-2008	23-04-08	18-07-2008
05-12-2014	06-02-2015	21-11-2014	06-02-2015	21-11-14	06-02-2015
Spot Prices					
16-05-08	25-07-08	16-05-08	18-07-2008	16-05-08	25-07-2008
05-12-2014	06-02-2015	05-12-2014	06-02-2015	5-12-2014	06-02-2014

This table reports detected mildly explosive periods in NYMEX WTI crude oil weekly nominal front-month futures and spot prices and the same deflated by an interpolated U.S. CPI series and by the currency value of the SDR basket using the PSY procedure with 5% size.

Table 2C: ICE Brent Crude nominal front-month futures prices
2003-2016 (weekly data)

Estimated start and end dates for periods of mildly explosive price behaviour (reverse regression case)

Standard minimum duration condition ($\log(T) = 7$)		No minimum duration condition applied	
GSADF statistic: 2.019			
Start	**End**	**Start**	**End**
No mildly explosive episode	No mildly explosive episode	27-6-2008	4-7-2008
9-5-2014	11-7-2014*	6-6-2014	11-7-2014

This table reports detected mildly explosive periods in Brent crude nominal front-month weekly futures prices using the PSY procedure applied to a reverse regression with and without the standard minimum duration condition. The test size is 5%. *Only detected at the 10% significance level.

Table 2D: ICE Brent Crude real front-month futures prices 2003-2016 (weekly data)

Estimated start and end dates for periods of mildly explosive price behavior (reverse regression case)

Standard minimum duration condition ($\log(T) = 7$)		**No minimum duration condition applied**	
GSADF statistic: 1.910			
Start	**End**	**Start**	**End**
No mildly explosive episode	No mildly explosive episode	2-6-2008	25-7-2008
9-5-2014	11-7-2014*	6-6-2014	11-7-2014

This table reports detected mildly explosive periods in Brent crude real (i.e. U.S.-CPI-deflated) front-month weekly futures prices using the PSY procedure applied to a reverse regression with and without the standard minimum duration condition. The test size is 5%. *Only detected at the 10% significance level.

Table 2E: NYMEX WTI Crude nominal front-month futures prices 2003-2016 (weekly data)

Estimated start and end dates for periods of mildly explosive price behaviour (reverse regression case)

Standard minimum duration condition ($\log(T) = 7$)		**No minimum duration condition applied**	
GSADF statistic: 1.987			
Start	**End**	**Start**	**End**
1-6-2008	1-8-2008*	2-6-2008	25-7-2008
		15-8-2008	22-8-2008
No mildly explosive episode	No mildly explosive episode	13-6-2014	11-7-2014

This table reports detected mildly explosive periods in WTI crude nominal front-month weekly futures prices using the PSY procedure applied to a reverse regression with and without the standard minimum duration condition. The test size is 5%. *Only detected at the 10% significance level.

Table 2F: NYMEX WTI Crude real front-month futures prices 2003-2016 (weekly data) **Estimated start and end dates for periods of mildly explosive price behavior (reverse regression case)**			
Standard minimum duration condition (log(T) = 7)		**No minimum duration condition applied**	
GSADF statistic: 1.904			
Start	**End**	**Start**	**End**
No mildly explosive episode	No mildly explosive episode	27-6-2008	11-7-2008
No mildly explosive episode	No mildly explosive episode	20-6-2014	27-6-2014

This table reports detected mildly explosive periods in WTI crude real (i.e. U.S.-CPI deflated) front-month weekly futures prices using the PSY procedure applied to a reverse regression with and without the standard minimum duration condition. The test size is 5%. *Only detected at the 10% significance level.

Table 2G: ICE Brent Crude nominal spot prices 2003-2016 (weekly data) **Estimated start and end dates for periods of mildly explosive price behavior under wild bootstrapped critical values**	
Start	**End**
20-06-08	11-07-08 *
12-12-2014	06-02-2015 **

This table reports detected mildly explosive periods in Brent crude nominal spot weekly futures prices using the PSY procedure. The wild bootstrap is applied to generate automatic critical values to control for non-stationary volatility in the data, *12% test size. ** 5% test size

Table 2H: NYMEX WTI Crude front-month futures 2003-2016 (weekly data)

Estimated start and end dates for periods of mildly explosive price behavior under wild bootstrapped critical values

WTI nominal		WTI nominal/CPI	
Start	**End**	**Start**	**End**
13-06-2008	18-07-2008	No explosive period	
05-12-2014	03-01-2015	12-12-2014	6-2-2015
12-12-2014	03-01-2015*	19-12-2014	6-2-2015*

This table reports detected mildly explosive periods in NYMEX WTI crude weekly nominal front-month futures prices and the same deflated by an interpolated U.S. CPI series using the wild-bootstrapped-adjusted PSY procedure with 10% size.

*as detected at the 5% level.

Table 2H: ICE Brent Crude front-month futures 2003-2016 (weekly data)

Estimated start and end dates for periods of mildly explosive price behavior under wild bootstrapped critical values

Brent nominal		Brent nominal/CPI	
Start	**End**	**Start**	**End**
13-06-2008	18-07-2008	No explosive period	
05-12-2014	03-01-2015	12-12-2014	30-1-2015

This table reports detected mildly explosive periods in ICE Brent crude weekly nominal front-month futures prices and the same deflated by an interpolated U.S. CPI series using the wild-bootstrapped-adjusted PSY procedure with 10% size.

Table 3: Other Commodities and Commodity Indices
LME Copper and Zinc three-month futures prices & Bloomberg Commodity Index
2003-2016 (weekly data)

Estimated start and end dates for periods of mildly explosive price behavior

Copper		Zinc		BCI	
Start	**End**	**Start**	**End**	**Start**	**End**
24-03-2006	16-06-2006	09-12-2005	17-02-2006	23-04-2008	18-7-2008*
		03-03-2006	16-06-2006	21-11-14	06-02-2015*

This table reports mildly explosive periods in the LME copper and zinc three-month futures prices and the Bloomberg Commodity Index (BCI) using the PSY procedure with 5% size. *Only detected at the 10% level.

Table 4: Levels of fundamental proxy variables:
Baltic Dry Index and U.S. end-of-week Stocks
2003-2016 (weekly data)

Estimated start and end dates for periods of mildly explosive price behavior

BDI		U.S. stocks	
Start	**End**	**Start**	**End**
13-04-2007	01-06-2007	01-04-2005	17-06-2005*
24-08-2007	21-12-2007		

This table reports detected mildly explosive periods for the levels of a demand-side fundamental (Baltic Dry Index, BDI) and a supply-side fundamental (U.S. EIA end-of-week stocks) using the PSY test with a 5% significance level. *This period is only detected at the 10% level.

Table 5: Ratios of WTI nominal front-month futures prices to fundamental proxy variables: Baltic Dry Index and U.S. EIA Stocks 2003-2016 (weekly data)

Estimated start and end dates for periods of mildly explosive price behavior

Futures Prices			
Nominal WTI/BDI		**Nominal WTI/stocks**	
Start	**End**	**Start**	**End**
10-06-2005	19-08-2005	16-05-2008	25-07-2008
03-10-2008	21-11-2008	14-11-2014	06-02-2015

This table reports detected mildly explosive periods for the ratios of WTI front-month futures and prices to a demand-side fundamental (the BDI) and a supply-side fundamental (U.S. EIA end-of-week stocks) using the PSY test with a 5% significance level.

Table 6: Levels of fundamental proxy and financial variables OVX and VIX

VIX levels: Jan 2003- Apr 2016 (weekly data)
OVX levels: Jan 2009 – Apr 2016 (weekly data)

Estimated start and end dates for periods of mildly explosive price behavior

VIX	OVX
No mildly explosive period	No mildly explosive period

This table reports detected mildly explosive periods for the levels of the OVX and VIX measures using the PSY test with a 5% significance level.

Table 7: VIX levels
2003-2016 (weekly data)

Estimated start and end dates for periods of mildly explosive price behavior (reverse regression case)

Standard minimum duration condition (log(*T*) = 7)		No duration condition applied	
GSADF statistic: 2.630		**GSADF statistic: 2.63**	
Start	**End**	**Start**	**End**
No mildly explosive period		03-10-2008	07-11-2008
		06-02-2009	06-03-2009

This table reports mildly explosive periods in VIX weekly nominal prices using reverse regressions for the PSY procedure with 5% size.

Table 8: Ratios of WTI nominal prices to financial variables: S&P500 index
2003-2016 (weekly data)

Estimated start and end dates for periods of mildly explosive price behavior

WTI nominal/S&P500	
Start	**End**
23-04-2008	18-07-2008
21-11-2014	06-02-2015

This table reports detected mildly explosive periods for the ratios of WTI front-month futures prices to the S&P500 index using the PSY test with a 5% significance level.

Table 9: Levels of fundamental proxy variables:
CFTC 2003-2016 (weekly data, collected Tuesdays)

Estimated start and end dates for periods of mildly explosive price behavior

CFTC	
Start	**End**
21-04-2015	05-01-2016

This table reports detected mildly explosive periods for the levels of a demand-side fundamental (Baltic Dry Index, BDI) and a supply-side fundamental (U.S. EIA end-of-week stocks) using the PSY test with a 5% significance level.

Figure 1A: ICE Brent and NYMEX WTI crude nominal front-month futures prices: weekly data 2003-2016

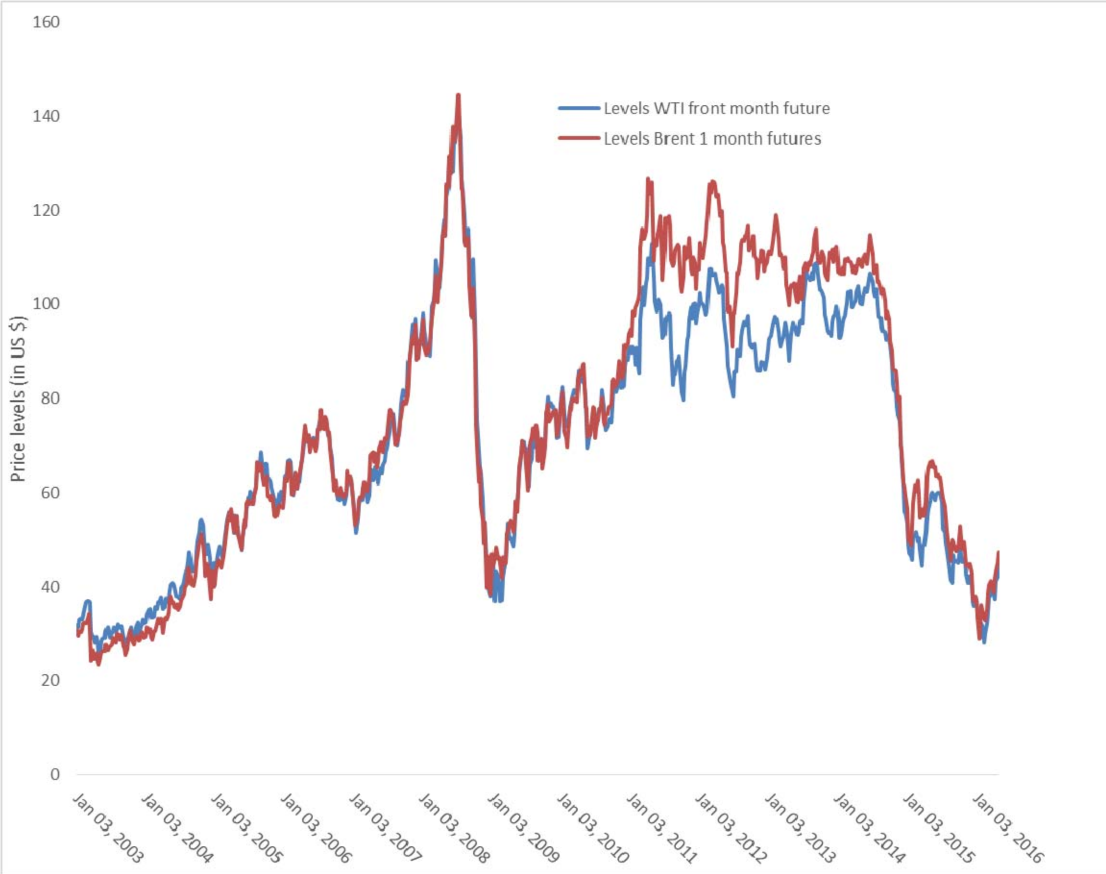

Figure 1B: ICE Brent and NYMEX WTI crude nominal spot prices: weekly data 2003-2016

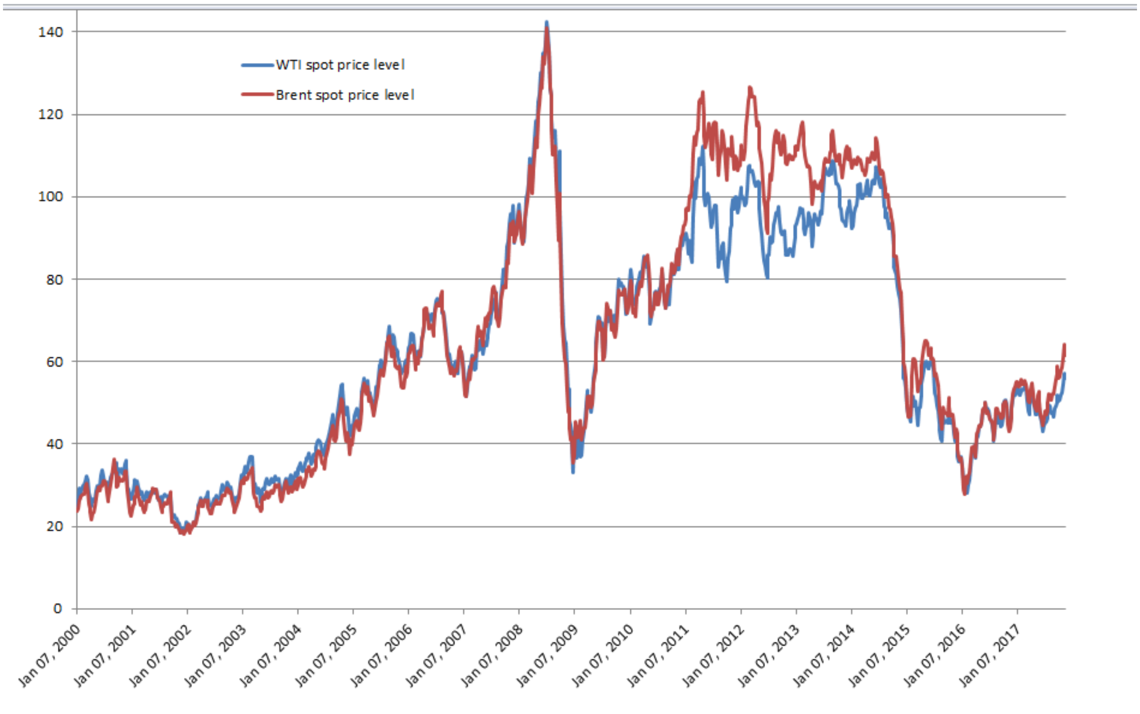

Figure 2A: Brent crude oil front-month futures nominal weekly series: BSADF sequence

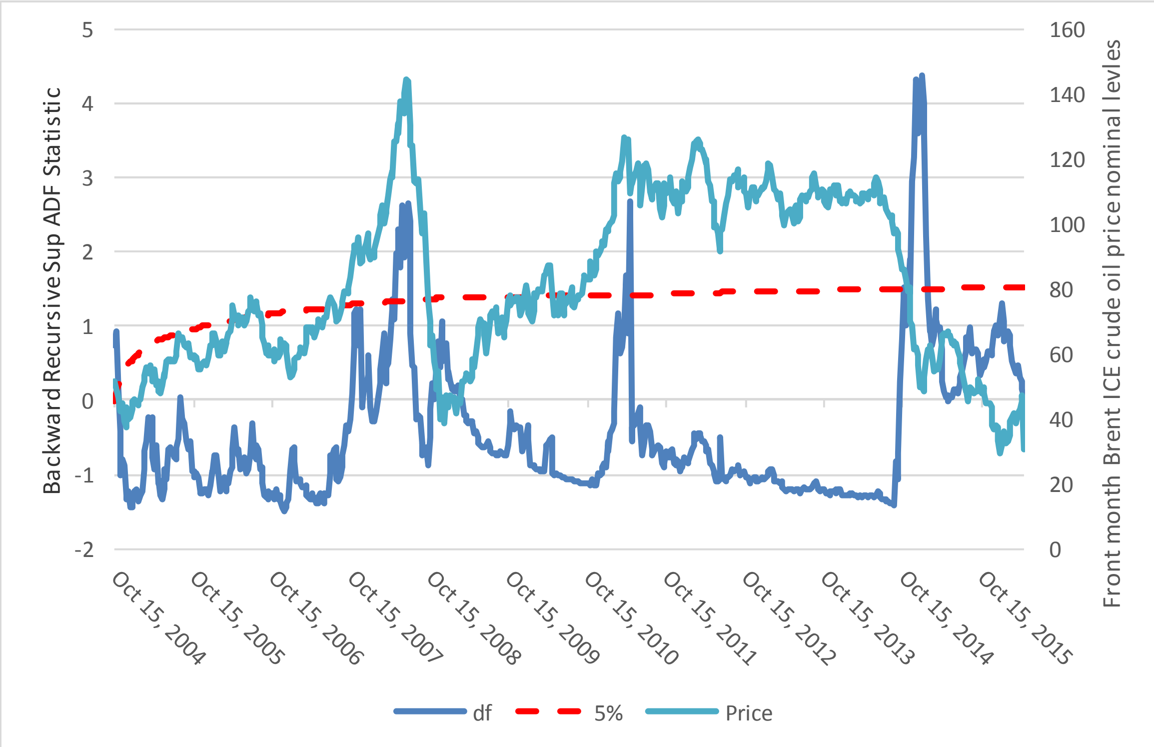

Figure 2B: WTI crude oil front-month futures nominal weekly prices: BSADF sequence

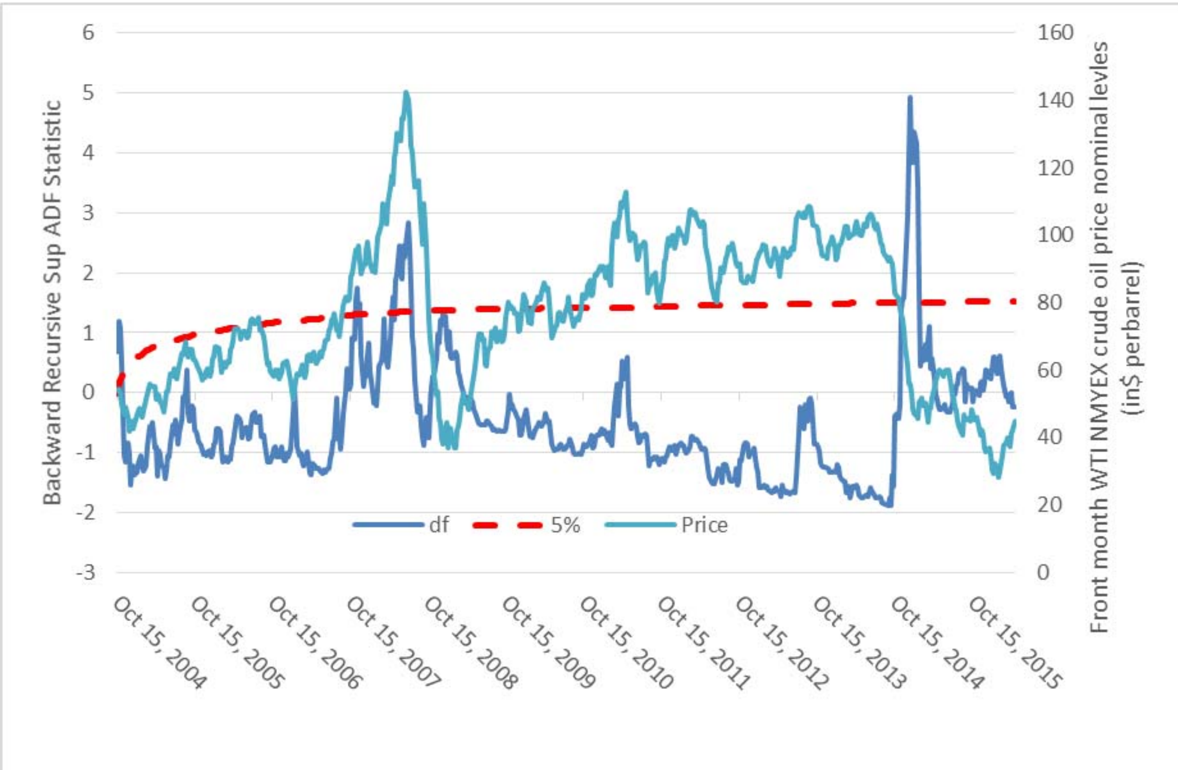

Figure 3A. WTI crude oil front-month futures nominal weekly prices: first differenced series

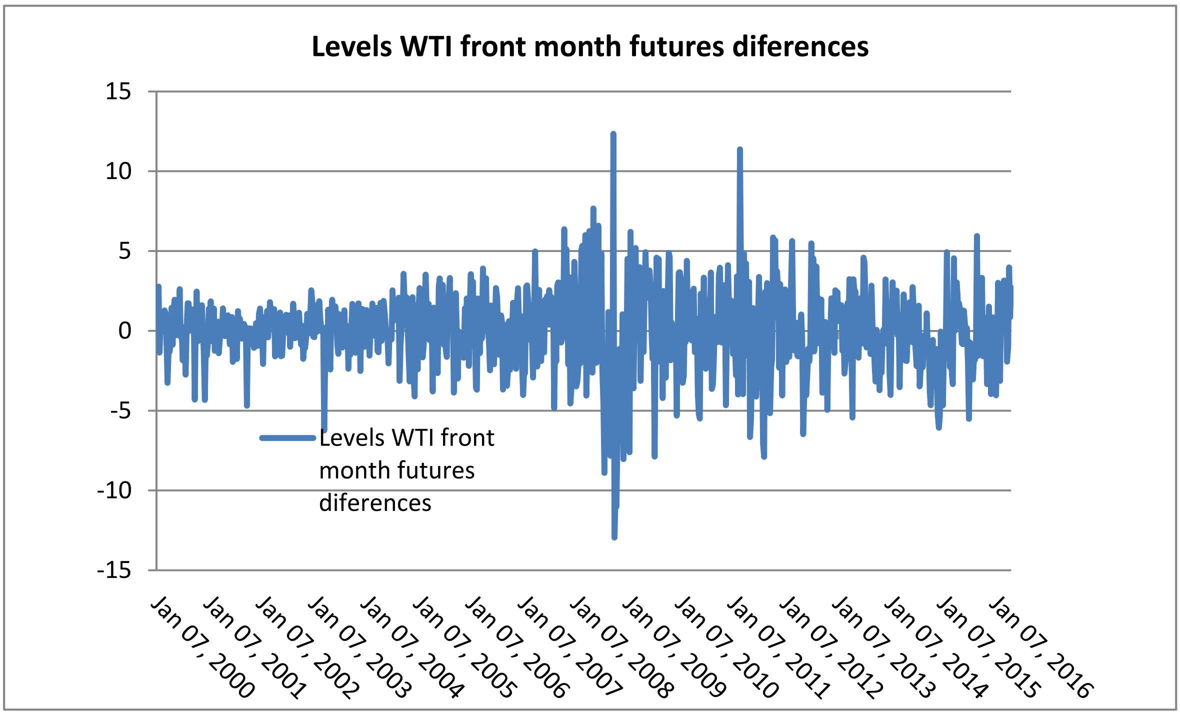

Figure 3B. Brent crude oil front-month futures nominal weekly prices: first differenced series

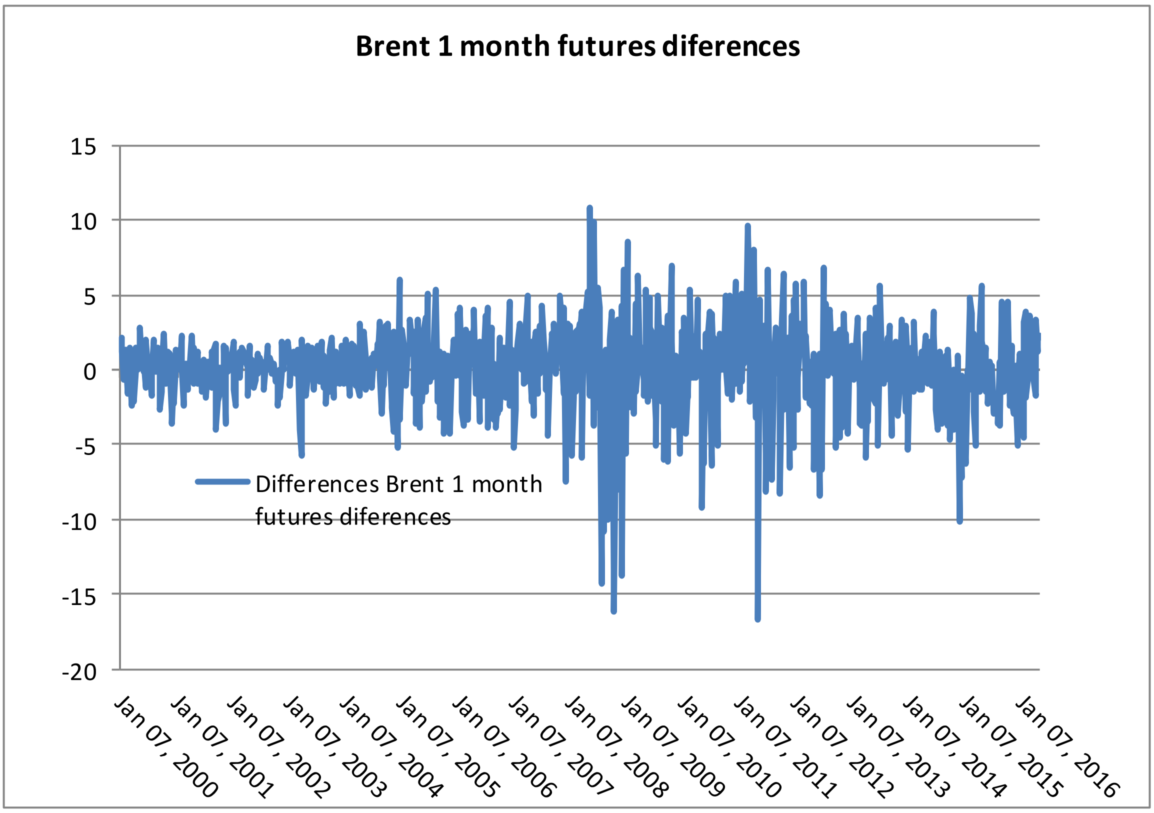

Figure 3C. Brent crude oil nominal weekly spot prices: first differenced series

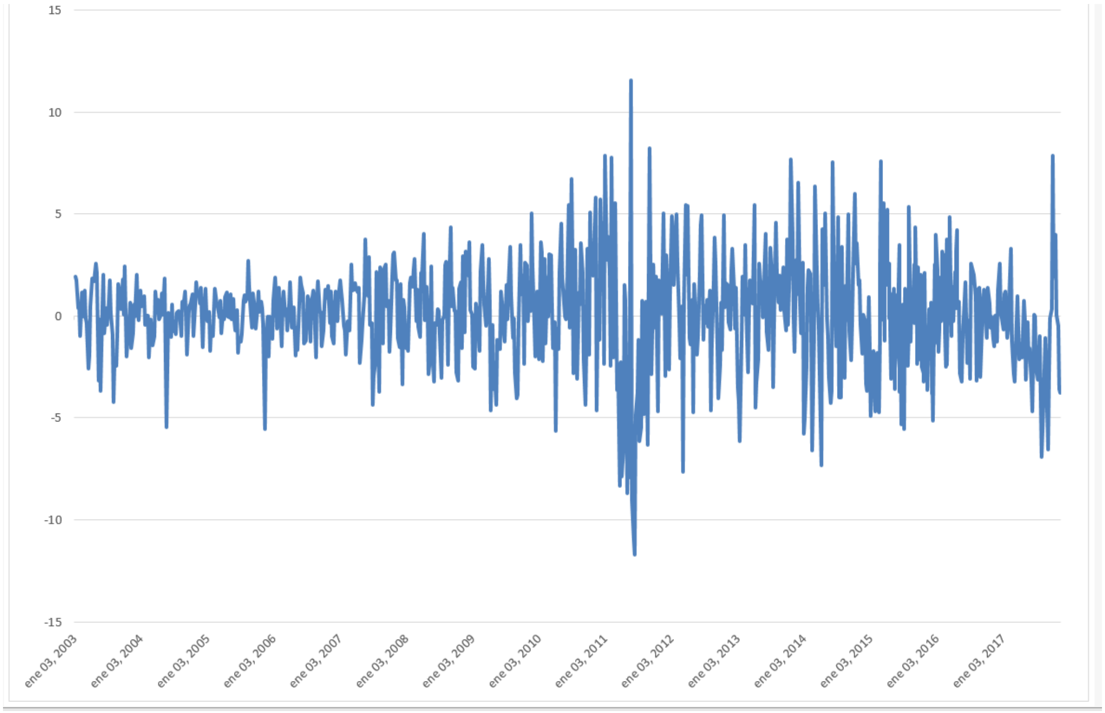

Figure 4A. BSADF sequence: Brent nominal spot prices with wild bootstrapped critical values

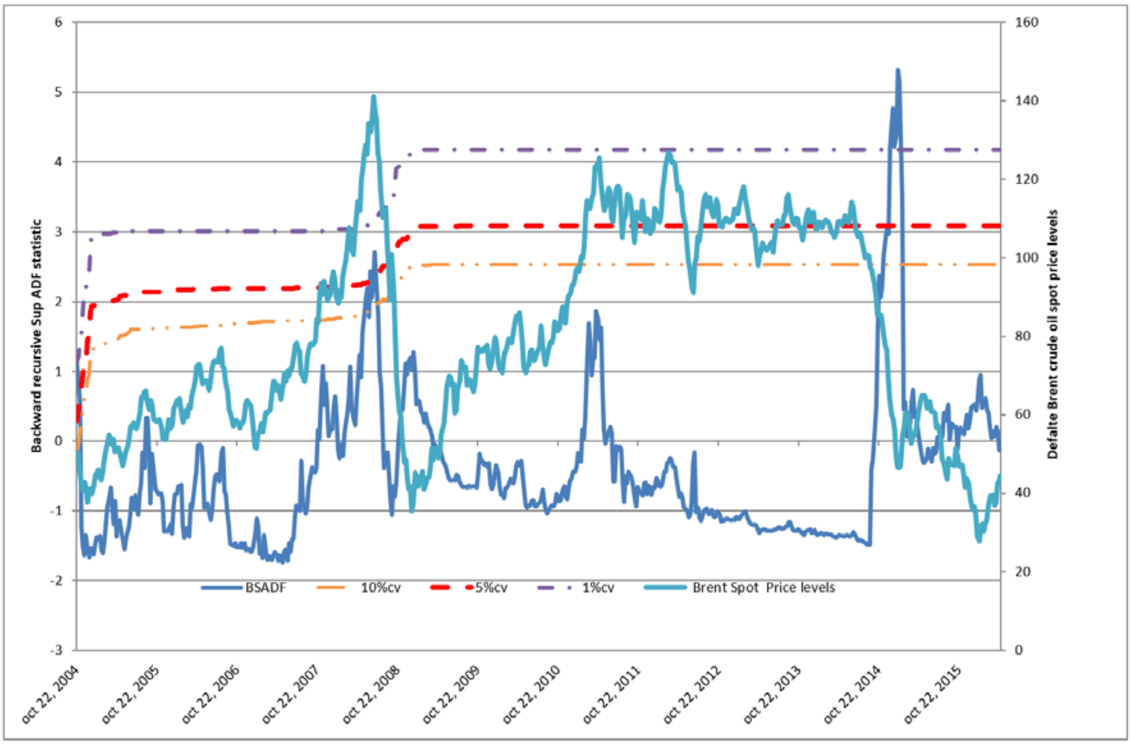

Figure 4B. BSADF sequence: Brent CPI-deflated spot prices with wild bootstrapped critical values

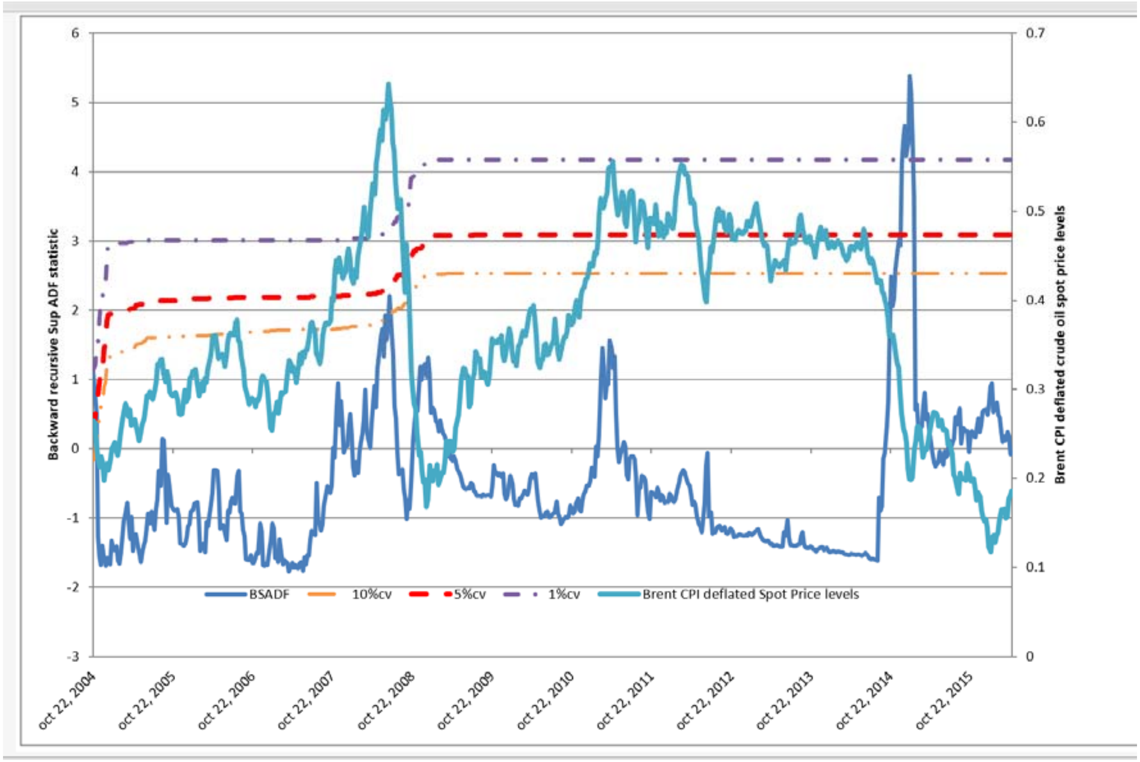

Figure 4C. BSADF sequence: WTI front-month futures nominal prices with wild bootstrapped critical values

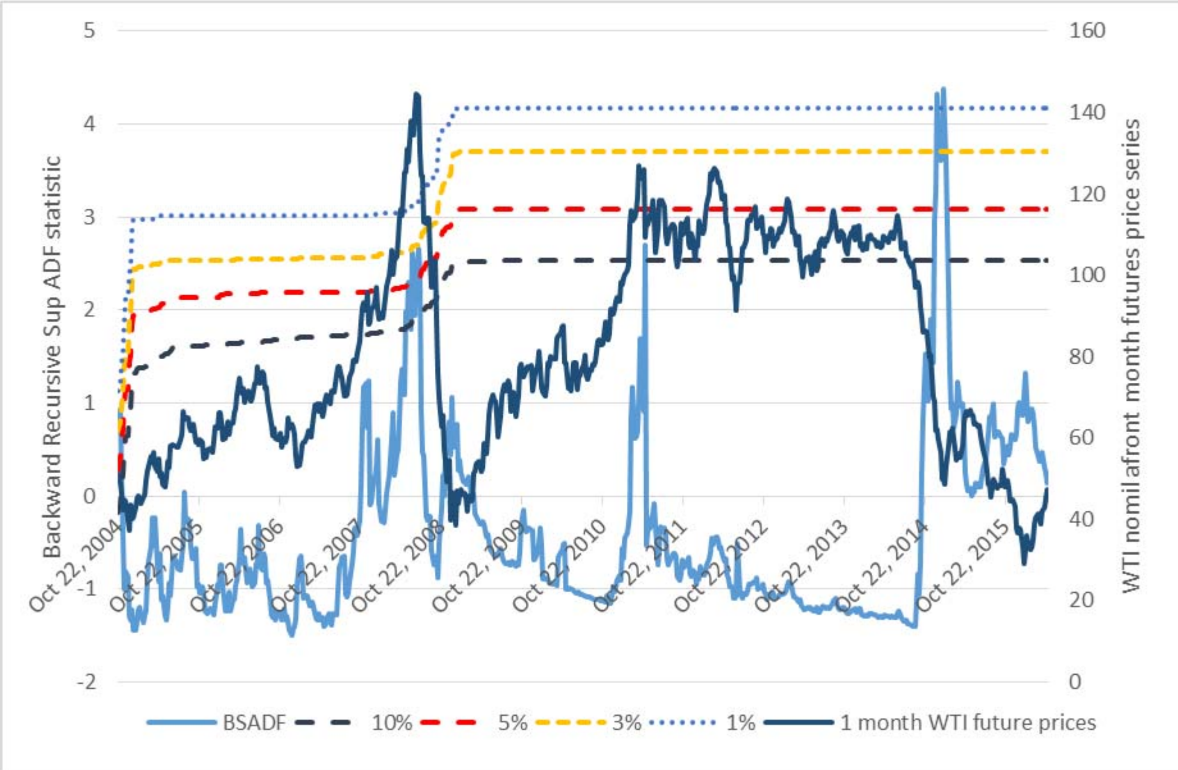

Figure 5. BSADF sequence: Bloomberg Commodity Index

Figure 6. BSADF sequence: Baltic Dry Index

Figure 7. BSADF sequence: Ratio of WTI crude nominal prices to U.S. above-ground inventory supply data

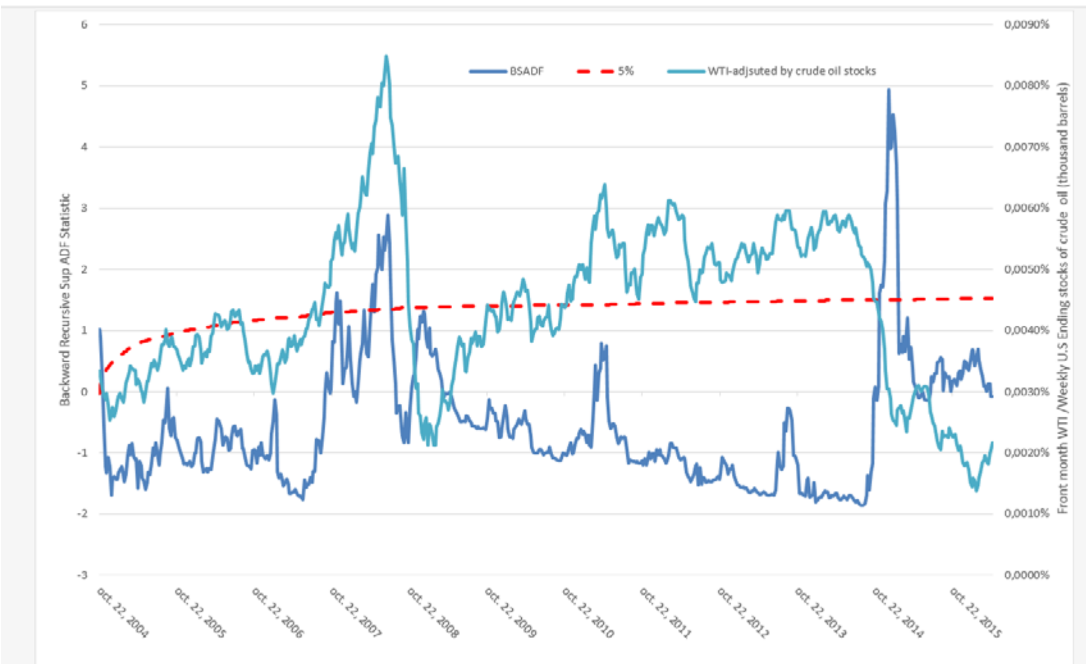

Figure 8A. WTI crude oil front month futures and the CBOE Oil Volatility (OVX) index: 2009-2016 weekly data

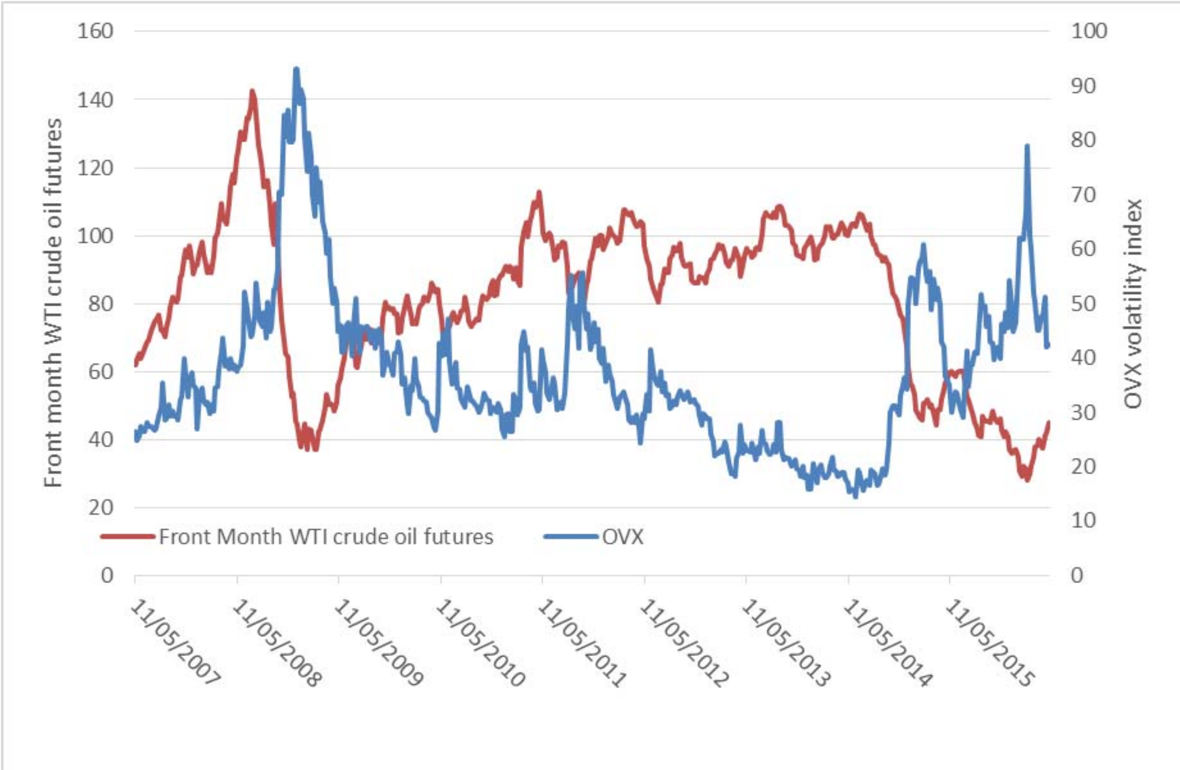

Figure 8B: BSADF sequence: OVX levels

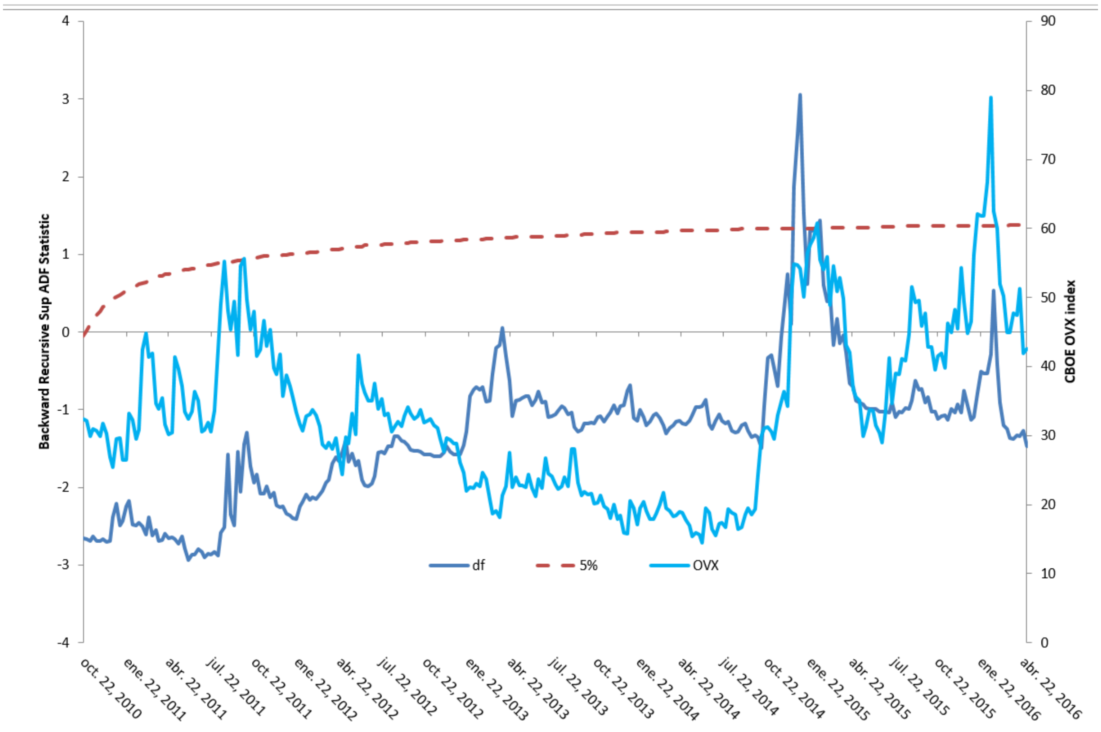

Figure 9A: BSADF sequence: VIX levels

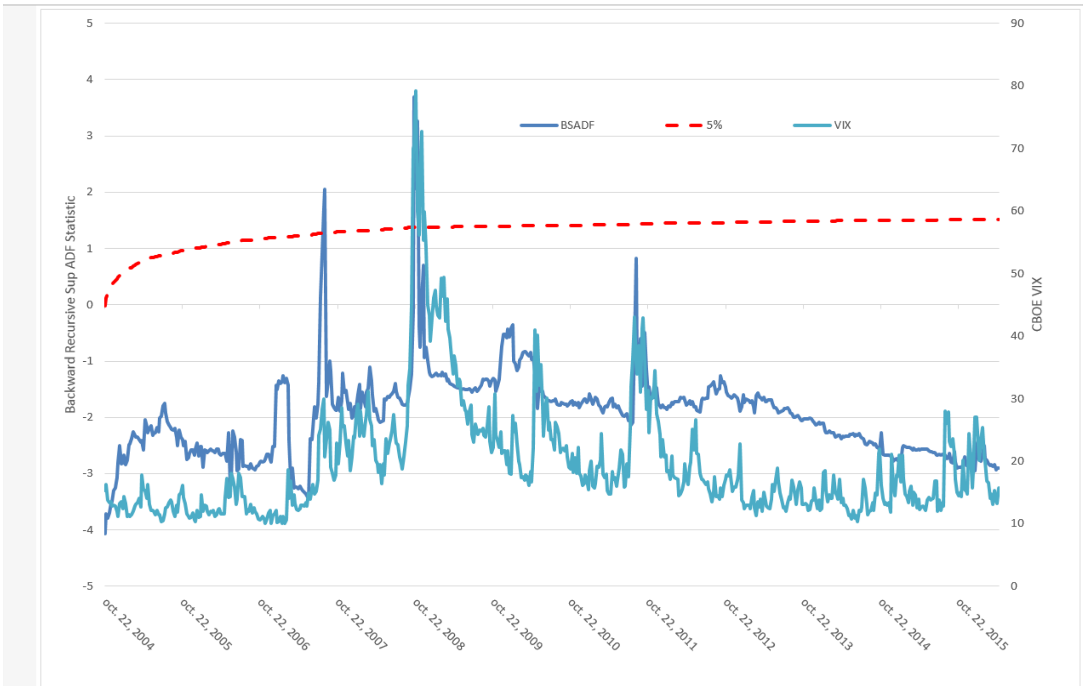

Figure 9B: BSADF sequence: VIX levels (reverse regression)

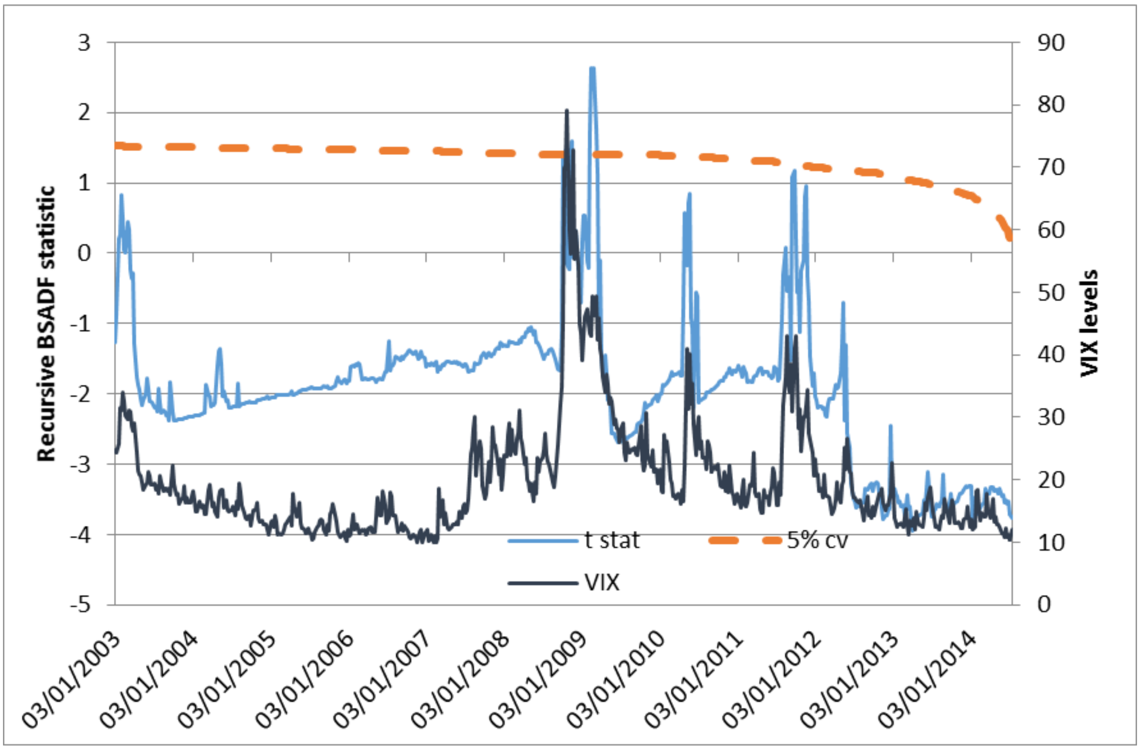

Figure 9C: BSADF sequence: Ratio of WTI front-month futures nominal price to VIX

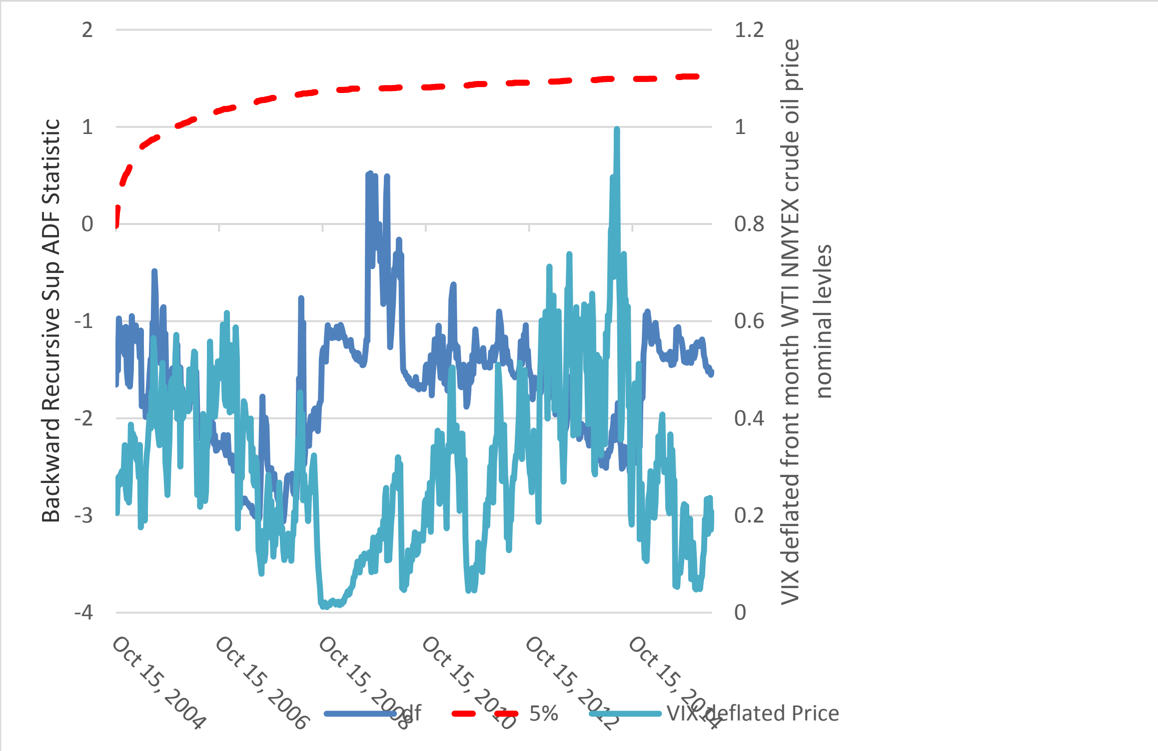

Figure 9D: BSADF sequence: VIX levels deflated by U.S. CPI

Figure 10. BSADF sequence: Working *T*-index (WTI CFTC position data)