First Draft: April 14, 2014
This Draft: June 11, 2014

Fundamentals, Derivatives Market Information and Oil Market Volatility

Michel A. Robe   Jonathan Wallen*

Abstract

We investigate price volatility in the West Texas Intermediate (WTI) and Brent crude oil markets between 2000 and 2014. We provide empirical evidence of a relationship between the term structure of option-implied volatilities and global macroeconomic conditions, physical market fundamentals (OPEC surplus output capacity, oil storage) and economy-wide financial uncertainty (captured by the equity VIX). Based on public data regarding trader positions in U.S. futures markets, the intensity of oil speculation is statistically insignificant. Unexpected disruptions in the crude oil space are associated with large regression residuals. Our findings suggest that derivatives ("paper") market contain information on the magnitude and duration of major oil market disruptions.

Keywords: Crude oil, Implied volatility, VIX, Inventories, Speculation, Disruption

JEL codes: E31, Q4, G140.

* **Robe (corresponding author):** Kogod School of Business at American University, 4400 Massachusetts Avenue NW, Washington, DC 20016 (KSB). Tel: (202) 885-1880. Email: mrobe@american.edu. **Wallen:** KSB. Email: jw6188a@american.edu. We thank without implication Bahattin Büyükşahin, Scott Mixon and Pete Whitman for helpful discussions. We also thank participants to a Department of Energy seminar and to the 2014 annual meeting of the Canadian Economic Association in Vancouver for useful comments. The paper was written while Robe was a consultant to, and Wallen was a research assistant at, the U.S. Department of Energy (DoE). We are grateful to Casey Petroff for help with the public data on futures trader positions. The idea of this paper was first discussed at a time when Michel Robe was a consulting senior economist at the U.S. Commodity Futures Trading Commission (CFTC). No CFTC compensation was received, and no CFTC resources or proprietary information were used, for this project. The paper reflects the opinions of its authors only, and not those of the CFTC, the CFTC Commissioners, or CFTC staff; or the DoE or DoE staff. All errors and omissions, if any, are the authors' sole responsibility.

"Measures of implied and reali(z)ed volatility continue to fall to record lows and, although fundamentals are tightening, geopolitical threats are high and crude oil prices are rising."

Barclays' *Blue Drum*, May 27th, 2014

1. Introduction.

Benchmark crude oil prices have been highly volatile for the past fifteen years. They duodecupled, from $12 in January 1999 to a peak of $145 in July 2008. They then fell by three fourths in the space of just a few months, before almost tripling in 2009. Since 2008, furthermore, Brent crude has – atypically but persistently – traded at a considerable premium over the U.S. West Texas Intermediate (WTI) oil price benchmark. This premium has fluctuated substantially amid structural changes in both physical and derivatives markets.

In this paper, we explore the volatility of oil prices. Specifically, we investigate the term structure of oil option-implied volatilities (IVs). Controlling for fluctuations in global business activity, oil-futures market liquidity and public information on the intensity of oil speculation (none of which is statistically significant), we find empirical evidence of a relationship between oil IV and key physical and derivatives (or "paper") market variables.

Foremost among paper market variables is the contemporaneous level of financial-market stress proxied by the implied volatility of Standard and Poor's S&P500 equity index (the VIX). For both oil price benchmarks, the VIX is statistically significant for the entire WTI and Brent IV term structures; it is most important for explaining short-dated volatility.

Intuitively, shocks to physical market fundamentals should also matter. Indeed, we find links between oil IV and storage market tightness and production capacity constraints. First, the term structure of oil IV shifts upwards during periods of low OPEC effective spare production capacity outside of Saudi Arabia. Furthermore, we show that low OPEC surplus capacity magnifies the impact of oil supply shocks on (Brent) IV. Second, higher levels of oil IV are associated with steeply sloped term structures of oil futures prices. A proxy for the degree of inventory levels and storage capacity utilization at oil-futures delivery points is informative both about near-dated oil IV levels and about the slope of the oil IV term structure. In particular, the fuller the storage tanks in Cushing, OK, the higher the IV levels for WTI; and, the steeper the term structure slope, the steeper the WTI IV term structure.

Between 2000 and 2013, major unexpected oil supply disruptions are associated with large model residuals. In this sense our findings suggest that derivatives ("paper") market contain information on the magnitude and duration of major oil market disruptions.

The large literature on realized volatility including numerous GARCH studies of oil price volatility.[1] A smaller literature deals with implied volatility and, especially, its drivers – which constitute our focus in the present paper. Closest are Mixon (2002) and Guo, Han and Zhao (2014), who document a relationship between fundamental factors and the option-implied volatility surface for the S&P 500 index. Those two articles investigate the predictive power of macroeconomic variables. In contrast, our focus is on crude oil price volatility. Hence, a key contribution of our analysis is to establish the relevance of physical-market fundamentals to oil IV levels as well as the slope of the IV surface. We show, furthermore, that even after controlling for physical market fundamentals the equity-market IV is relevant to studying the term structure of oil IV.[2]

---

[1] See, e.g., Agnolucci (2009), Aloui and Mabrouk (2010), Chang, McAleer and Tansuchat (2011), Arouri, El Hédi, Lahiani, Lévy and Nguyen (2012), Chkili, Hammoudeh and Nguyen (2014), Efimova and Serletis (2014), Gileva (2010), Hou and Suardi (2012)Kang, Kang and Yoon (2009), Koch (2014), Le, (2008), Mohammadi and Su (2010), Narayana and Narayan (2007), Nomikos and Pouliasis (2011), Regnier (2007), Sadorsky (2006), Serra, Zilberman and Gil (2011), Wang and Wu (2012), Wei, Wang and Huang (2010), Yang, Hwang and Huang (2002). For a review, see Gileva (2010).

[2] Silvennoinen and Thorp (2013) document that lagged VIX raises conditional return volatilities for many (though not all) and correlations with equity returns for some (less than half) of 24 commodities between May 1990 and July

Our paper complements a body of work on crude oil price forecasting.[3] That literature has recently shown renewed interest in the importance, for commodity returns, of inventories and of commodity markets' financialization. We do not seek to forecast prices. Rather, our econometric analysis deals with the IV term structure; our analysis of residuals focuses on the magnitude and duration of unexpected oil market disruptions. In this context, we find predictive power for a price-based financial variable (the VIX) but not trading-related variables computed from public data (specifically, the intensity of speculation in U.S. crude oil markets).

Our paper also contributes to a large literature on commodity inventories.[4] Historically, most of that work has focused on shortages or stock-outs. In a recent article on the Brent-WTI (West Texas Intermediate) price differential, however, Büyükşahin, Lee, Moser and Robe (2013) show that storage capacity utilization can also matter. They document that large inventories and a dearth of spare storage space at the WTI futures delivery point in Cushing, OK contributed to large swings in the nearby WTI futures prices in the 2007-2010 period. Building on their approach, we use differentials in Brent and WTI calendar spreads across the futures term structure in order to infer the expected duration of tensions in the oil storage space.

We find that a steeply sloped term structure the oil futures prices is associated with high levels of oil price volatility, even at maturities up to six months. Our result that the shape of the futures term structure helps explain volatility differentials bears similarities to Reeves and Vigfusson's (2011) empirical finding that crude oil futures prices only improve spot price forecasting when spot and futures prices differ substantially. At the same time, it presents an

2009. Their analysis deals with realized conditional moments of near-dated futures returns, whereas we focus on implied volatilities and investigate the entire IV surface for both benchmark crude oil markets.

[3] See, e.g., Reeves and Vigfusson (2011), Kilian and Baumeister (2013) and references cited in those papers.

[4] See, e.g., Alquist and Kilian (2010), Gorton, Hayashi and Rouwenhorst (2013), Kilian and Murphy (2014) and Khan, Khoker and Simin (2011).

interesting counterpoint to Trolle and Schwartz's (2010) finding that it is “difficult to explain the level and variation in energy variance risk premia with (…) inventories.”

On the financial side, it has been argued theoretically – see, e.g., Singleton (2014) – that the sharp growth of commodity index traders (CIT) in the past decade may have contributed to a broad-based increase in commodity prices. The empirical evidence to date, however, shows that CIT positions do not Granger-cause WTI futures prices (Büyükşahin and Harris, 2011).[5] Closer to our query, market observers and policy makers have pondered whether increased hedge fund activity could be responsible for changes in oil price volatility. Using trader-level activity information, Brunetti, Büyükşahin and Harris (2009) show that hedge funds on average have a *moderating* influence on (realized) volatility – see also Büyükşahin (2012) and references therein. In light of this ongoing debate, it is important to investigate whether the intensity of oil speculation has predictive power on oil IV over and above market fundamentals. By assessing the empirical relevance of price- and trading-linked financial variables in an econometric model of (implied) volatility, our analysis sheds light on a dimension of energy markets' financialization.

The remainder of this paper proceeds as follows. Section 2 summarizes the behavior of oil prices since 2000. Section 3 describes the behavior of crude oil option-implied volatilities during the same period. Section 4 discusses the macroeconomic and physical-market variables that we consider in our econometric model of oil IV. Section 5 presents our econometric model and summarizes our empirical results. Section 6 concludes and discusses further research.

---

[5] Although Büyükşahin and Harris' (2011) dataset ends in Spring 2009, we are unaware of more recent empirical papers overturning their main conclusions. Irwin and Sanders (2012) and Irwin (2013), in comprehensive reviews of the literature on CIT activity in agricultural markets, conclude that there is no “compelling evidence that buying pressure from commodity index investment in recent years caused a massive bubble in agricultural futures prices.” For reviews of the literature on the financialization of commodities, see Cheng and Xiong (2013). See Büyükşahin and Robe (2012) and Fattouh, Kilian and Mahadeva (2013) for literature reviews focusing on energy markets.

2. Crude Oil Prices.

Since the late 1980s, "physical benchmarks, such as [West Texas Intermediate or WTI], Dated Brent, and Dubai-Oman [have been] a central feature of the oil pricing system [used to] price cargoes under long-term contracts or in spot market transactions" (Fattouh, 2011 p.7). Insofar as the "link of WTI prices to other international benchmarks [is] partly dictated by infrastructure logistics" (Fattouh, 2007 p.341), the markets for the two main crude benchmarks (WTI and Brent) are not fully integrated. Consequently, we gather data on both benchmarks.

For WTI, we focus on futures prices because the WTI price formation "is originated by the New York Mercantile Exchange (NYMEX). The highly liquid sweet crude futures contract traded on NYMEX provides a visible real-time reference price for the market. In the (Western Hemisphere) spot market, therefore, negotiations for physical oils will typically use NYMEX as a reference point, with bids/offers and deals expressed as a differential to the futures price" (Platts, 2010 p.3). Thus, we use nearby WTI futures settlement prices from the NYMEX. For Dated Brent crude oil, we likewise use futures prices.

We obtain futures and option price data from Bloomberg. The data cover the entire term structures of futures and options on futures prices for WTI and Dated Brent from 1983 through 2013. Figure 1 plots the WTI and Brent nearby futures prices (Panel A) and the WTI-Brent price nearby futures price spread (Panel B) from 2000 through 2013. Panel B plots the spread so that it is positive (*negative*) when Brent trades lower (*higher*) than WTI.[6]

We use two approaches to set roll dates for Dated Brent futures and WTI futures: calendar-based *vs*. open interest-based rolls. Each has its purpose. Much of the prior work on

[6] The nearby-futures price spread in Panel B of Figure 1 is rolled based either on calendar dates (red series) or on open interest (blue series). Büyükşahin, Lee, Moser and Robe (2013) show that the red series is more volatile and tie this behavior to bottlenecks at the WTI futures delivery point in Cushing, OK – especially in 2008 and 2009.

commodity prices focuses on questions best answered by abstracting from volatility around futures expiration dates. To that end, many studies that use futures prices define the "nearby futures" as the "closest-to-delivery contract with the highest open interest."[7] Yet, as pointed out by Büyükşahin *et al* (2013), when investigating price volatility in an environment where a commodity (in this case, WTI) has for several years been characterized by unusual storage conditions, it is also important to consider points in time when such conditions are most likely to matter – namely, around futures expiration dates.

For the purpose of the present study, therefore, we construct for each market (Brent and WTI) two time series of crude oil futures term structures. The first series defines rolls based on expiration (or "calendar") dates – with the "nearby" always defined as the prompt contract, which typically expires 3 business days before the 25th day of the prior month (for example, the May 2014 contract expired on April 22nd, 2014). Our second time series of futures price curves is anchored around a "nearby" contract that we define based on the preponderance of the WTI futures open interest. Figure 1 (Panel C) shows that, in general, the WTI futures "roll" date defined in this manner used to be around the 9th business day of the prior month until December 2004 but, since then, has dropped to around the 7th day of the prior month. One putative explanation for the change, investigated in Petroff, Robe and Wallen (2014), is the sharp growth of commodity index trading after 2003-2004.

[7] "Oil futures trading rarely ends in [delivery]. Two to three weeks before a contract expires, most traders close out their positions altogether or roll over their positions in the expiring contract into the first-deferred contract. This roll can entail price distortions due to liquidity issues in the paper market or storage issues in the physical market – generating a kind of seasonality. To mitigate the resulting measurement issues, [one can] construct a continuous time series of 'nearby-futures' prices by switching from the prompt contract to the first-deferred contract on the first day when the prompt open interest falls below the first-deferred open interest" (Büyükşahin, Haigh, Harris, Overdahl and Robe, 2011 p.6).

3. Oil Option-Implied Volatilities.

The intuition behind the present paper is that financial variables, which reflect traders' information about market conditions, may improve the predictive power of a fundamentals-based model of price volatility. Through this model, we may identify disruptions in oil market conditions at horizons ranging from one to six months.

Prior research on the respective behaviors of oil price levels, spreads and volatility (Büyükşahin, Haigh, Harris, Overdahl and Robe, 2011) and on the extent to which commodity markets move in sync with financial markets (Büyükşahin and Robe, 2011, 2014; Cheng, Kirilenko and Xiong, 2013) suggests two kinds of suitable financial variables for this purpose: price-based and position-based. Trader position information is discussed in Section 4 (4.3.2 and 4.3.3) below. This Section focuses on the information contained in price-based variables.

3.1. Oil price volatility, 2000-2013

Figure 2 plots the price volatilities implied by the nearby, first-deferred and six-month WTI crude oil at-the-money call option prices (with the expiration date of the "nearby" option contract defined to match the "nearby" futures according to an open-interest-based roll). Across the entire term structure of WTI option and futures trading activity, volume and open interest are generally much larger for June and December futures than for all other contract maturity months (except for the prompt and first-deferred contracts). A natural concern is that, five out of every six months, price levels and volatilities may be unreliable for the 6- or 12-month out contracts due to low liquidity. We sidestep this concern by defining the "six-month" prices or implied volatilities as weighted-averages of next-June and next-December figures (with the weights chosen such that the average maturity is a constant six months).

For all three series (nearby, first-deferred and six-month), Figure 2 identifies three periods with very high volatility: in 2001 (following the 9-11 attack), in 2008-2009 (coinciding with the peak of oil prices in late 2008 and their subsequent collapse in early 2009), and in August 2011 (when oil prices sank amid a U.S. credit-rating downgrade, a sovereign debt crisis in Europe, and renewed uncertainty regarding the state of global demand for crude oil).

Interestingly, we observe historically low implied volatilities in recent years, 2012 and 2013. This could reflect the availability of storage capacity as well as plentiful crude oil supply at the Cushing, Oklahoma delivery point for WTI futures. Or, it could reflect generally low levels of uncertainty in financial markets. Sections 4 and 5 will return to this question.

3.2. High volatility episodes

Figure 1 suggests two structural breaks for oil price volatility in the past fifteen years: the first following the 9-11 attack on the World Trade Center and the second after Lehman Brothers' demise in September 2008. We carry out "structural break" tests by looking for the statistical significance of two time dummies for the periods following 9-11 and the Lehman bankruptcy.

Tables 1 and 2 summarize those tests. Table 1 provides results when the nearby contract is defined using the preponderance of the open-interest. Table 2 uses calendar-based rolls instead. The results are qualitatively similar for both methods.

Volatility levels are statistically significantly higher in the "9-11" and Lehman periods compared to the rest of 2000-2013. In both tables, this result is robust to using implied (Panel A) or realized (Panels B and C) volatilities. For the latter, results are also similar using either simple 20-trading day volatility estimates ("standard deviations", see Panel B in Tables 1-2) or non-parametric realized volatilities (defined as the difference between high and low prices, expressed as a percentage of the relevant futures settlement price and shown; see Panels C in Tables 1-2).

4. Oil Market Fundamentals and Trading Activity.

In this Section, we introduce the macroeconomic fundamentals (4.1), physical-market conditions (4.2) and financial variables (4.3) with which we hypothesize that oil implied volatility (IV) could be related. Table 3 shows summary statistics for the variables we consider.

4.1. Macroeconomic Fundamentals: Demand

Given that the inland U.S. WTI and the seaborne Brent crude oil have been traded in partly segregated markets since 2007 (Borenstein and Kellog, 2012; Büyükşahin *et al*, 2013), changes in the strength of the demand for each crude stream could be relevant to that particular stream's price volatility – with U.S. conditions becoming more relevant to WTI after 2007. Consequently, we consider the strengths of both world and U.S. business cycles when controlling for changes in the overall strength of consumption-linked crude oil demand.

4.1.1. World economy

For global real economic activity, we draw on Kilian (2009) who shows that "increases in freight (shipping) rates may be used as indicators of (demand shifts) in global industrial commodity markets." The Kilian measure is a monthly global index of single-voyage freight rates for bulk dry commodity cargoes. This index accounts for the existence of "different fixed effects for different routes, commodities and ship sizes" (Kilian, 2009 p.1056). It is deflated with the U.S. consumer price index (CPI), and linearly detrended to remove the impact of a "secular decrease in the cost of shipping dry cargo" (*ibidem*).

The Kilian index is available monthly from 1968 to 2013. We construct a weekly series, which we denote *REAL*, applying Kilian's (2009) methodology to Tuesday spot values of the Baltic Dry Index (BDI) for dry-bulk freight rates between 1985 and 2013. The resulting series, while more volatile than the monthly Kilian (2009) series, tracks the latter up to a scale factor and a tilt in the linear trend. Panel A in Table 3 provides summary statistics of our weekly *REAL* variable for our sample period.

Bunker fuel costs are a large component of the BDI, especially between 2004 and 2008 and again after 2010. Due to the risk of endogeneity, using contemporaneous values of the weekly *REAL* index when modeling implied volatilities of crude oil prices would be inappropriate. We therefore use one-week lagged values of the weekly change in *REAL* in the regressions of Section 5.

4.1.2. U.S. economy

We also consider the alternative possibility that U.S., rather than global, macroeconomic conditions could be more relevant to WTI price volatility – especially following the emergence of storage and transportation bottlenecks at Cushing, OK in March 2007. In robustness checks, we replace changes in *REAL* by the Tuesday-to-Tuesday change in the daily index of U.S. business activity developed by Aruoba, Diebold and Scotti (2009). This *ADS* index tracks real business conditions at a high (daily) frequency and is publicly available for our entire sample period. Intuitively, U.S. economic fluctuations should affect the demand for local crude oil, so we expect *ADS* changes to be (if anything) negatively associated with WTI price volatility.

Figure 2 depicts the evolutions of *REAL* and *ADS* between 2000 and 2013. These two indices generally move in tandem. However, the behavior of *ADS* in 2007 suggests that a slowdown in U.S. economic activity started earlier (in the second half of 2007) than the so-called worldwide "Great Recession" did. Still, both the U.S. and the world downturns accelerated sharply after the demise of Lehman Brothers in September 2008.

4.2. Physical-Market Fundamentals: Supply and Storage

Our second set of explanatory variables seeks to capture differential supply-demand balances for WTI and Brent crude oils. Recognizing that the WTI and Brent markets are not fully integrated, we do so by way of several variables. We use the effective "surplus" OPEC production capacity outside of Saudi Arabia to capture general market conditions for seaborne crudes (Section 4.2.1) and supply variables most relevant to Brent (Section 4.2.2) or WTI (Section 4.2.3). Additionally, we include a financial proxy for storage conditions in each oil benchmark's immediate sphere of influence (Section 4.2.4).

4.2.1. OPEC surplus capacity

Büyükşahin and Robe (2011) argue that, as the demand for energy increased amid strong global economic growth in the middle of the past decade, it eventually exhausted the crude oil "surplus" or "spare" production capacity that OPEC has historically tried to maintain – leading to a sharp increase in world oil prices. Conversely, lower energy prices amid greater "surplus" production capacity reflected weak macroeconomic environments early in the past decade as well as in the aftermath of the Lehman collapse. Intuitively, one should *ceteris paribus* expect an inverse relationship between OPEC's spare oil output capacity and oil price volatility.

We use data from the Energy Information Agency (EIA) and the International Energy Agency (IEA) to construct a time series of the total effective spare crude oil production capacity outside of Saudi Arabia (*SPARE*). We focus on non-Saudi figures for three main reasons. First, Büyükşahin and Robe (2011) argue that the clearest evidence of a major change in world energy market fundamentals is reflected in this variable (as opposed to, say, world oil consumption, Saudi surplus production capacity, OECD stocks of crude oil, etc.). Second, Saudi crude is not a direct substitute to other oils. Unlike Brent or WTI, Saudi crude is not light sweet oil – and oil refineries cannot easily switch between vastly different kinds of crude. Third, data on Saudi surplus production capacity is best viewed as theoretical – we are not aware of estimates of *effective* Saudi spare output capacity.

Panel A of Figure 1 plots WTI and Brent crude oil prices (U.S. dollars, left-hand scale) against non-Saudi OPEC effective surplus oil production capacity (as a percentage of world consumption, right-hand scale). Panel A highlights several salient changes in the world crude oil market since 2000.

Between 2000 and Summer 2003, non-Saudi effective spare capacity was relatively plentiful and crude oil prices fluctuated in a relatively narrow dollar range below $30 (with the notable exception of the post-911 period). From 2004 through Summer 2008, crude oil prices all rose massively amid a dearth of spare capacity. Some crude types topped $140 per barrel in July 2008. After the onset of the Great Recession in Fall 2008, however, oil prices collapsed and OPEC spare capacity surged.

From late Fall 2008 to Spring 2009, the WTI-Brent spread widened sharply and became very volatile – especially around WTI futures expiration dates. From mid-2009 through November 2010, the oil market was relatively less volatile, with crude prices fluctuating around $75 amid non-trivial *SPARE*. Strikingly, *SPARE* dropped sharply after February 2011 – a period coinciding with resurgent Brent prices and a large, persistent WTI-Brent differential.

In the econometric analyses of Section 5, we use two spare capacity variables. One, we use a dummy variable that captures supply constraints based on the non-Saudi OPEC effective spare output capacity. The dummy takes the value 0 when spare capacity is low and 1 when it is high, following Brunetti, Büyükşahin, Robe and Soneson (2013). Two, we interact the actual spare capacity (measured as a percentage of world consumption) with WTI and Brent supply changes. Our expectation is that changes in supply are more likely to affect volatility when there is little capacity for OPEC to make up non-OPEC shortfalls.

4.2.2. Government announcements

A number of papers have documented that realized oil return volatility increases ahead of OPEC meetings – see, e.g., Horan, Peterson and Mahar (2004), Schmidbauer and Rösch (2012) and Mensi, Hammoudeh and Yoon (2014). Demirer and Kutan (2010) discuss similar patterns around announcements related to releases of the U.S. strategic petroleum reserve (SPR). In a related vein, Brunetti, Büyükşahin, Robe and Soneson (2013) discuss the possibility of price movements around "fair price" pronouncements by senior officials from OPEC or from OPEC member governments. The current draft of the present paper does not control for those events. Future drafts will.

4.2.3. Brent crude oil production

Amid tight supply-side conditions in the global market, shortages of one or more of the four crude oil streams (BFOE) that make up the Brent crude benchmark have the potential to affect Brent prices more than other major oil benchmarks. North Sea crude oil production has fallen substantially over the course of the past decade. In the case of BFOE, Büyükşahin et al (2013) document that output dropped from over two million barrels per day in 2000 to less than one million in 2012: after stabilizing between mid-2006 and mid-2010, the fall in output accelerated thereafter (see Figure 4). Notably, this recent episode coincides with the beginning of a period of unparalleled, large and volatile WTI-Brent spreads.

4.2.4. North-American crude oil production

Whereas Brent crude oil output has been falling for over a decade, the opposite is true of North-American production – which has been boosted massively since 2007 by the so-called "shale oil revolution." To capture this phenomenon, our main variable is simply U.S. output changes – a weekly time series of which is published by the EIA.

In robustness checks, we proxy for U.S. production using data on production capacity as captured by the number of operating crude oil rigs. This number is sourced by the EIA from Baker Hughes, Inc. and Weatherford International, Ltd. Specifically, the rigs series counts the crude oil rotary rigs (used to drill wells) that are operational onshore and offshore in the fifty United States. The rig count is reported weekly, starting in August 1987.[8]

Figure 5 plots the output and rig series for our sample period (2000-2013). Both variables steadily increase over much of the sample period, accelerating sharply in early 2009. *Ceteris paribus*, one would expect such an increase in local crude oil supply to put downward pressure on the volatility of WTI crude oil – unless the latter faces difficulties in reaching international markets, as discussed in the next sub-section.[9]

4.2.5. Cushing storage capacity and utilization

Several studies (e.g., Fattouh, 2007, 2010; Pirrong, 2010; Borenstein and Kellogg, 2012; Büyükşahin *et al*, 2013) argue that infrastructure constraints in Cushing have historically influenced the differential at which WTI sweet crude trades against other types of crude oil.

[8] We prefer to use a direct measure of U.S. output changes because the rig count does not capture the growing output capacity of rigs due to continuous technological improvements. In further robustness checks, we replace U.S. with North American crude oil output by including Canadian crude flowing into the Petroleum Administration for Defense's Midwestern District ("PADD 2"), where Cushing is located. Our monthly data on crude oil imports from Canada into the PADD 2 region comes from the EIA. In the weekly regression analyses, we use the same value for all weeks of a given month.

[9] In mid-2012, rig count and U.S. output start to diverge due to improved efficiency of unconventional oil extraction methods. The results of Sections 5 and 6 are robust to using the actual U.S. oil output rather than a rig count.

Before 2007, "the main logistical bottleneck was how to get enough oil into Cushing (which) in many instances resulted in serious dislocations and WTI rising to very high levels compared to other benchmarks" (Fattouh, 2007, p.2). After February 2007, amid a greater flow of crude oil into Cushing from Montana, North Dakota and Canada, "the ability to shift this oil out of the region and to provide a relief valve for Cushing has been very limited" (*ibidem*).

Post-2007, Cushing bottlenecks should *ceteris paribus* be accompanied by higher crude storage levels. When oil tanks fill up close to their limit, however, the potential arises for an increase in cross-commodity spread levels (as Cushing oil stocks insulate the WTI market from the price pull stemming from strong world demand) and in price volatility around futures expiration dates (as traders find it expensive to deliver oil and may exit contracts at particularly depressed prices to avoid delivery).

One could apply a Hodrick-Prescott (1980) filter to identify deviations of the amount of crude oil in storage away from its long-term, possibly non-linear trend. One downside of such an approach is that it would require subjective choices to capture the trend and cyclical components.

Alternatively, one could use data on Cushing storage capacity to assess the fraction of the storage used. To our knowledge, the only public source of weekly or monthly data on storage capacity is Genscape, Inc. The Genscape time series, sadly, start in May 2009 – precluding their use to analyze WTI price volatility in earlier years (including from late Fall 2008 to Spring 2009, the period most likely to have been affected by storage capacity exhaustion).

We therefore follow a third approach, suggested by Working (1933, 1948, 1949) and Fama and French (1987, 1988):[10] we proxy the tightness of the oil storage market by way of the

[10] See also Geman & Ohana (2009), Khan, Khoker and Simin (2011), and Gorton, Hayashi & Rouwenhorst (2013) who confirm Fama and French's (1997, 1998) and Ng and Pirrong's (1994) intuitions that the slope of the term structure should be a good proxy for inventories.

slope of the term structure of futures prices. We isolate the impact of interest rate fluctuations by subtracting, from the percentage calendar spread, the appropriately scaled money factor. We use the London Interbank Offered Rate (LIBOR) to compute the money factor under the assumption that it is representative of the funding costs of futures-market participants. Figure 6 plots the nearby WTI futures price and the WTI-Brent nearby spread (left-hand scale, measured in U.S. dollars) *vs*. the net cost of WTI carry (right-hand scale, in annualized percentage terms).

Figure 6 shows a structural break in the stochastic process characterizing the net cost of carry (green curve) after November 2008. Büyükşahin *et al* (2013) show that this *calendar* spread proxy for a high rate of storage utilization in Cushing helps predict the WTI-Brent *commodity* spread. Intuitively, calendar spreads should also be associated with the near-term volatility of near-dated and, possibly, longer-dated oil prices. To test this hypothesis, we use two variables in Section 5: the annualized percentage differences (net of LIBOR) between, respectively, the prices of the first-deferred and nearby futures (denoted *WTI_Slope_1m*) or between the "six-month" and nearby futures (denoted *WTI_Slope_6m*).[11] In regressions that call for the difference between those two slopes, we use the percentage difference between the first-deferred and "six-month" futures.

4.3. Financial Variables

A growing literature, reviewed by Büyükşahin and Robe (2012), Cheng *et al* (2013) and Fattouh *et al* (2013), investigates whether the financialization of commodity markets has impacted some moments of the distribution of commodity prices or returns. To our knowledge,

[11] Similar to our approach for implied volatilities, we define the "six-month" contract price by weight-averaging the prices of the next June and December contracts with weights chosen such that the weighted average of the "blended contract" maturity is 6 months.

the present study is the first to explore the extent to which trading-related variables could help to explain implied volatilities and to identify large disruptions in the crude oil price space. Our econometric analysis includes several explanatory variables to that end.

4.3.1. Stress in financial markets

In light of theoretical work on the limits to arbitrage and contagion – see Gromb and Vayanos (2010) for a thorough review – oil price volatility is intuitively higher during periods of elevated financial-market stress. Hence, the options-implied volatility in equity markets (*VIX*) should *ceteris paribus* be a good predictor of volatility in oil markets.

Figure 7 shows that the VIX indeed rose sharply after 9-11, soared after the Lehman crisis in September 2008, before falling sharply a few months into 2009 in response to central bank interventions to calm financial markets – and rose again in the Summer of 2011 amid a European sovereign debt crisis. These are precisely the periods when Figure 2 shows that oil price volatility surged. This observation suggests a strong connection between macroeconomic and oil-specific market volatilities – providing a visual hint of one of our strongest finding in Section 5.

4.3.2. Paper market liquidity

Intuitively, price volatility and market liquidity should be inversely related. Our regressions rely on time series for prices and volatilities that are rolled based on open-interest. Hence we capture paper-market liquidity effects through lagged weekly changes in the trading volume of oil futures (WTI or Brent, depending on the variable of interest).

Figure 8 plots the futures open interest for both WTI and Brent crude oil markets, focusing on the three nearest-dated contracts (we denote these variables *WTI_OI* and *Brent_OI*, respectively). Figure 8 highlights two key developments. First, oil paper-market positions have grown massively since 2001 (WTI) or 2005 (Brent), with open interest in the three nearest-dated futures tripling in both markets in just a few years. Büyükşahin *et al* (2011) document that much of this increase stems from the financialization of oil markets. Second, after lagging behind WTI for many years, Brent started surging in the second half of 2009 – whereas WTI open interest mostly stagnated during that period. Following a further sharp increase since the end of 2011, the near-dated Brent open interest now exceeds its WTI counterpart.

4.3.3. Financial traders' positions in oil paper markets

Commodity Index Traders' (CITs) arrival in oil markets has garnered a lot of attention from policy makers (see, e.g., ITF 2008) and academic researchers (e.g., Büyükşahin and Harris, 2011; Irwin and Sanders, 2012; Tang and Xiong, 2012; Singleton, 2014)). Within both groups, we see a spirited debate on whether CIT activity impacts commodity price *levels*. CITs, though, are essentially passive, long-only investors. Due to the consistency of CITs, their positions in WTI futures or in Brent futures are unlikely to hold predictive power of oil price volatility.

One possible exception is during the roll period, for which Brunetti and Reiffen (2011) find that CIT activity affects risk premia. Accordingly, we include a dummy variable in the regressions that takes the value 1 for the roll week (i.e., if the preponderance of the futures open interest rolls from the nearby contract to the first-deferred that week) and 0 otherwise.

In contrast to "passive" market participants like CITs, intuition suggests that trading by more active speculators could help predict oil price disruptions. Similar to Brunetti *et al* (2009) and Büyükşahin and Robe (2011, 2014), we focus on hedge fund activity.

We compute an index of speculative intensity for WTI futures using trader-position data published by the U.S. Commodity Futures Trading Commission (CFTC) for the NYMEX's WTI futures markets. Our index choice is motivated by results in Büyükşahin and Robe (2011). Those authors use non-public, trader-level CFTC data to show that fluctuations in Working's (1960) *T* index of speculative intensity in U.S. energy futures markets, which may be computed from public CFTC data, broadly captures changes in the relative importance of specific categories of hedge funds in the last decade (June 2000 to March 2010).

Working's "*T*" compares the activities of all "non-commercial" commodity futures traders ("speculators") to the net demand for hedging originating from all "commercial" traders (called "hedgers"). For every futures market boasting a high enough level of trading activity, including the NYMEX's WTI futures, the CFTC's legacy weekly Commitments of Traders reports (COT) break down the total open interest between these two categories of traders."[12] The "non-commercial" group includes various types of mostly financial traders such as hedge funds, mutual funds, floor brokers, etc.[13]

We use this public information to compute weekly changes in financial speculation for the WTI futures markets. Figure 9 depicts the WTI "*T*" from 2000 to 2013, after netting out 1 from the "*T"* figures to facilitate the interpretation of the graph. Figure 9 illustrates a substantial, long-term increase in the WTI "*T"* index. Notably, the *T* index exhibits substantial volatility: the relevance of its pattern is tested in the analysis below.

[12] COT reports also provide data on the positions of non-reporting (i.e., small) traders. A trading entity generally gets all of its futures and options positions in a given commodity classified as "commercial" by filing a statement with the CFTC that it is commercially "engaged in business activities hedged by the use of the futures or option markets" as defined in CFTC regulations. CFTC staff may exercise judgment in re-classifying a trader if it has additional information about the trader's use of the markets.

[13] Since September 4, 2009, COT reports split non-commercials between "managed money traders" (i.e., hedge funds) and "other non-commercial traders" with reportable positions. As of June 2013, however, the CFTC has not shared any plan to make similarly detailed data available retroactively beyond 2006. We therefore rely on the legacy classification scheme in order to obtain a sufficiently long time series of position data.

5. Econometric Analyses.

We use a regression analysis to predict elements of the term structure of oil price implied volatilities. Using the explanatory variable described above, we explain uncertainty in oil markets with macroeconomic demand and supply effects, storage, and financial variables.

Specifically, the model includes lagged implied volatility, changes in macroeconomic conditions (proxied by lagged changes in the *REAL* index or, in robustness checks, contemporaneous values of the *ADS* index); physical market fundamentals (captured by *SPARE*, the nearby term structure *SLOPE*, North American or North Sea oil production changes, etc.); and the contemporaneous intensities of equity market implied volatility (*VIX*), lagged changes in the intensity of speculation in U.S. oil futures markets (*WTI_T*) and market liquidity measured by lagged changes in trading volume. We then show that large regression residuals correspond to major supply disruptions between 2000 and 2013.

We discuss methodological issues in Section 5.1 and present our results in Section 5.2.

5.1. Methodology

Our focus is on oil option-implied volatilities and market disruptions. Hence, to explain the term structure of IVs, it makes intuitive sense to use the following specification of candidate independent variables: *levels* for key financial indicators (*VIX*, futures term structure *SLOPES*) but *changes* for macroeconomic (business cycle proxies) and trading aggregates (*T*, volume).

Before testing the explanatory power of those variables on the implied volatility of WTI and Brent futures prices, we check the order of integration of all variables using Augmented Dickey Fuller (ADF) tests. The unit root tests, which are summarized in Table 3, show that an autoregressive distributed lag (ARDL) model is not necessary. This is because IVs at all maturities, the VIX, the futures term structure slopes for WTI and Brent, and the effective non-Saudi OPEC spare capacity are stationary in levels while oil prices, both economic activity indices (*REAL*, *ADS*), the U.S. and Brent output levels and the Working's *T* index for WTI futures are all stationary in first differences.

Notwithstanding the stationary behavior of our variables of interest, the implied volatility time series are characterized by autocorrelation. We therefore need to include one or more lagged values of the dependent variable as an independent variable. The Schwarz Bayesian Information Criterion (SIC) suggests using a single lag for the 6-month IV. For uniformity, we use one lag for the nearby and 6-month IV regressions as well as for the regression of the slope of the term structure of IVs.

5.2. Regression Results

Table 4 presents the coefficients in our main regression. Panels A to C are for WTI nearby, 6-month levels of IV and for the IV term structure slope (the difference between the 1- and 6-month IVs). The main regresion, for the full sample, is in the first column; the other columns in each Panel are robustness checks in which we consider two sub-periods separated by February 2007, i.e., before *vs*. after the onset of the partial segmentation between the WTI and Brent crude oil markets. Panel D is similar to Panel A but focuses on Brent.

All contracts are defined using an open interest-based roll to minimize the impact of possible liquidity-based volatility spikes around contract expiration dates. All of our regressions control for oil paper-market liquidity (captured by changes in the total futures trading volume) and use a dummy variable for the roll week.

5.2.1. Global fundamentals

Table 4 shows the importance of controlling for physical constraints on the production of seaborne crudes, proxied by a dummy for high *vs*. low effective spare production capacity outside of Saudi Arabia (*SPARE*). That variable is significant at the 1% level of confidence in all of our models of near-term uncertainty, though it is less significant further out the maturity curve. In all cases, the *SPARE* variable has the expected negative coefficient: more surplus capacity is associated with lower volatility.

5.2.2. Storage

All of our specifications include a proxy for storage-market conditions. Specifically, we use the slope of the part of the term structure that captures storage conditions at the relevant horizon (first-deferred *vs*. nearby for the nearby volatility; 6-month *vs*. nearby for the 6-month volatility; and the difference between the two slopes for the slope of the IV term structure).

The *SLOPE* variable has the expected positive coefficient and is statistically significant at the 10% or better level of confidence regardless of the implied volatility horizon. A variable constructed to capture exceptional storage conditions (the square of the relevant slope) is strongly statistically significant only for the nearby volatility figures and for the IV slope – consistent with the notion that infrastructure bottlenecks in Cushing affect short term price volatility more than long term ones. Overall these findings suggest that only major storage disruptions have long-term effects.

Our proxy for the degree of inventory levels and storage capacity utilization at oil-futures delivery points is informative not only about near-dated oil IV levels but also about the slope of the oil IV term structure. In particular, the steeper the WTI futures term structure slope is, the steeper is the WTI IV term structure.

5.2.3. Financial market stress

Table 4 shows that, over and above global and local physical market fundamentals, financial variables also have explanatory power. In particular, the *VIX* index (our proxy for overall market stress) is strongly positively associated with oil-market volatility. Put differently, generalized uncertainty and oil market uncertainty tend to go together. This finding helps explain the apparent puzzle reported in the quote at the beginning of the paper: the very low level of oil implied volatilities in Spring 2014 is likely the partial reflection of exceptionally low levels of stress in financial markets during the same period.

5.2.4. Speculative activity in oil markets

In the Introduction, we asked whether we can find statistical evidence of a relationship between intensity of oil-market speculation and oil-benchmark price volatility. Table 4 shows that the answer is negative – at least when publicly available information is used to compute the Working *T*. After controlling for macroeconomic and physical-market fundamentals and for price-based financial variables, Table 4 shows that the *T* (computed from public data) contains statistically-insignificant levels of information regarding forward looking volatilities. We obtain consistent results in both the WTI and the Brent markets.

5.3. Identifying unexpected shocks

We assess the empirical model of WTI implied volatilities for periods where it sharply mis-estimates implied volatilities, i.e., when residuals are large. Our model captures physical (supply, demand, storage) and financial variables that should help predict uncertainty in the crude oil space. Hence, we expect that high residuals would reflect unexpected shocks (or shocks to other variables omitted from the model).

Accordingly, we match large residuals and shocks by (i) studying the monthly Short Term Energy Outlook published by the EIA and (ii) identifying declines in world production greater than 1%. Consistent with our prediction, Table 5 shows that episodes characterized by large residuals are associated with substantial unanticipated shocks to oil supply.

5.4. Robustness

We considered a series of alternative explanatory variables, which we discuss in section 4. The results are robust. For example, replacing our proxy for global macroeconomic conditions (*REAL*) by a U.S. business cycle indicator (*ADS*) yields qualitatively similar results: neither variable is ever statistically significant – even when interacted with a dummy variable that captures the landlock issues at the Cushing, OK delivery point for WTI futures after 2007.

6. Conclusions.

We ask whether, after controlling for macroeconomic conditions and physical-market fundamentals, financial variables can help identify major disruptions in the crude oil space. In particular, we investigate the usefulness of three financial variables: the intensity of speculative activity in crude oil futures markets, the term structure of oil futures volatilities, and equity-market option-implied volatilities.

The empirical results support our hypothesis that, even when macroeconomic and physical-market fundamentals are sampled at a high (weekly frequency), financial variables contain information regarding the magnitude and duration of oil price volatility – over and above the information contained in fundamentals. Our analysis shows the importance of accounting for overall uncertainty in financial markets (proxied by the contemporaneous VIX) to explain levels of, and differences between, uncertainty in oil markets measured by implied volatilities at different points along the options maturity curve. In contrast, a measure of speculative intensity in U.S. crude oil futures is statistically insignificantly related to oil price volatility.

The negative results for this trading-based measure may be due to the limitations of public data that are highly aggregated – both across traders and, importantly for the question at hand, across maturities. A natural venue for further research would be to use non-public trader-level data and investigate if the positions of some traders or groups of traders contain information regarding oil volatility – over and above the information content of the aggregate positions of broad trader categories.

Bibliography

Agnolucci, Paolo (2009). "Volatility in crude oil futures: A comparison of the predictive ability of GARCH and implied volatility models." *Energy Economics* 31: 316–321.

Aloui, Chaker and Samir Mabrouk (2010). Value-at-risk estimations of energy commodities via long-memory, asymmetry and fat-tailed GARCH models. Energy Policy 38: 2326–2339

Alquist, Ron and Lutz Kilian (2010). "What Do We Learn from the Price of Crude Oil Futures?" *Journal of Applied Econometrics*, 25 (4): 539–573.

Arouri, Mohamed El Hédi , Amine Lahiani, Aldo Lévy and Duc Khuong Nguyen (2012). "Forecasting the conditional volatility of oil spot and futures prices with structural breaks and long memory models." *Energy Economics* 34: 283–293.

Aruoba, S. Borağan, Francis X. Diebold, Chiara Scotti (2009). "Real-time Measurement of Business Conditions". *Journal of Business and Economic Statistics*. 27 (4): 417–427

Borenstein, Severin and Ryan Kellogg (2012). "The Incidence of an Oil Glut: Who Benefits from Cheap Crude Oil in the Midwest?" NBER Working Paper No. 18127, June.

Brunetti, Celso, Bahattin Büyükşahin, and Jeffrey H. Harris (2009). "Speculators, prices and market volatility." Working Paper, U.S. Commodity Futures Trading Commission (CFTC), June.

Brunetti, Celso, Bahattin Büyükşahin, Michel A. Robe and Kirsten S. Soneson (2013). "OPEC 'Fair Price' Pronouncements and the Market Price of Crude Oil." *Energy Journal*, 34 (4): 79–108.

Büyükşahin, Bahattin (2012). "Speculation Demystified: Virtuous Volatility." *IEA Energy: The Journal of the International Energy Agency*, 3 (Autumn): 33–34. Available at SSRN: http://ssrn.com/abstract=2157832

Büyükşahin, Bahattin, Michael S. Haigh, Jeffrey H. Harris, James A. Overdahl and Michel A. Robe (2011). "Fundamentals, Trading Activity and Derivative Pricing." Paper presented at the *2009 Meeting of the European Finance Association*, August. Revised for the *First CFTC Conference on Commodity Markets*, DC, August 2011. http://ssrn.com/abstract=966692

Büyükşahin, Bahattin and Jeffrey H. Harris (2011). "Do Speculators Drive Crude Oil Futures Prices?" *Energy Journal*, 32 (2): 167–202.

Büyükşahin, Bahattin, Thomas K. Lee, James T. Moser and Michel A. Robe (2013). "Physical Markets, Paper Markets and the WTI-Brent Spread." *Energy Journal*, 34 (3): 129–51.

Büyükşahin, Bahattin and Michel A. Robe (2011). "Does Paper Oil Matter?" Working Paper, CFTC and American University, July. http://ssrn.com/abstract=1855264

—— (2012). "Does It Matter Who Trades Energy Derivatives?" *Review of Environment Energy and Economics (RE3).* Available online at: http://www.feem.it/getpage.aspx?id=4638

—— (2014). "Speculators, Commodities, and Cross-Market Linkages." *Journal of International Money and Finance* 42: 38–70.

Chang, Chia-Lin, Michael McAleer and Roengchai Tansuchat (2011). "Crude oil hedging strategies using dynamic multivariate GARCH." *Energy Economics* 33: 912–923.

Chkili, Walid , Shawkat Hammoudeh and Duc Khuong Nguyen (2014). "Volatility forecasting and risk management for commodity markets in the presence of asymmetry and long memory." *Energy Economics* 41: 1–18.

Efimova, Olga and Apostolos Serletis (2014). "Energy markets volatility modelling using GARCH." *Energy Economics* 43: 264–273.

Fama, Eugene F. and Kenneth R. French (1987). "Commodity Futures Prices: Some Evidence on Forecast Power, Premiums, and the Theory of Storage." *Journal of Business* 60 (1): 55–73.

—— (1988). "Business Cycles and the Behavior of Metals Prices." *Journal of Finance* 43 (5): 1075–1093.

Fattouh, Bassam (2007). "WTI Benchmark Temporarily Breaks Down: Is It Really a Big

Deal? Oxford Energy Comment, Oxford Institute for Energy Studies, April.

—— (2010). “The Dynamics of Crude Oil Price Differentials.” *Energy Economics* 32 (2): 334–342.

——. (2011). “An Anatomy of the Crude Oil Pricing System.” Working Paper WPM40, Oxford Institute for Energy Studies, January.

Fattouh, Bassam, Lutz Kilian and Lavan Mahadeva (2013). “The Role of Speculation in Oil Markets: What Have We Learned So Far?” *The Energy Journal*, 34(3), pp. 7–.

Geman, Hélyette, and Steve Ohana (2009). “Forward Curves, Scarcity, and Price Volatility in Oil and Natural Gas Markets.” *Energy Economics* 31 (4): 576–585.

Gileva, Tatyana (2010). *Econometrics of Crude Oil Markets*. Graduate Thesis, Université Paris 1 (Panthéon-Sorbonne), June.

Gorton, Gary B., Fumio Hayashi and K G. Rouwenhorst (2013). “The fundamentals of Commodity Futures Returns.” *Review of Finance,* 17 (1): 35v105.

Gromb, Denis and Dimitri Vayanos (2010). “Limits of Arbitrage: The State of the Theory”. NBER Working Paper No. 15821, March.

Hodrick, Robert J. and Edward C. Prescott (1980). “Postwar U.S. Business Cycles: An Empirical Investigation,” Carnegie Mellon University discussion paper no. 451 (1980).

Horan, Stephen M., Jeffrey H. Peterson and James Mahar (2004). “The Behavior of Implied Volatility of Oil Futures Options Surrounding OPEC Meetings.” *Energy Journal* 25 (3), 103–125.

Hou, Aijun and Sandy Suardi (2012). “A nonparametric GARCH model of crude oil price return volatility.” *Energy Economics* 34: 618–626.

Irwin, Scott H. (2013). “Commodity Index Investment and Food Prices: Does the “Masters Hypothesis” Explain Recent Price Spikes? *Agricultural Economics,* 44 (s1): 29–41

Irwin, Scott H. and Dwight R. Sanders (2012). “Testing the ‘Masters Hypothesis’ in Commodity Futures Markets.” *Energy Economics* 34 (1): 256–69.

ITF (2008). “Interim Report on Crude Oil”. Interagency Task Force on Commodity Markets of the U.S. Government, Washington D.C.

Kang, Sang Hoon, Sang-Mok Kang and Seong-Min Yoon (2009). “Forecasting volatility of crude oil markets.” *Energy Economics* 31: 119–125.

Khan, Saqib A., Zeigham I. Khoker, and Timothy T. Simin (2011). “Expected Commodity Futures Returns.” Working paper, Penn State University, March 2008; updated 2011.

Kilian, Lutz (2009). “Not All Oil Price Shocks Are Alike: Disentangling Demand and Supply Shocks in the Crude Oil Market.” *American Economic Review*, 99 (3): 1053–1069

Kilian, Lutz and Dan Murphy (2014). “The Role of Inventories and Speculative Trading in the Global Market for Crude Oil.” *Journal of Applied Econometrics*, 29 (3): 454–478.

Koch, Nicolas (2014). “Tail events: A new approach to understanding extreme energy commodity prices.” *Energy Economics* 43: 195–20.

Lanza, A., Matteo Manera and M. Giovannini (2005). “Modelling and Forecasting Co-integrated Relationships Among Heavy Oils and Product Prices.” *Energy Economics* 27: 831–48.

Mensi, Walid, Shawkat Hammoudeh and Seong-Min Yoon (2014). “How Do OPEC News and Structural Breaks Impact Returns and Volatility in Crude Oil Markets? Further Evidence from a Long Memory Process.” *Energy Economics*, 42 (March): 343-354.

Le, Duong T. (2008). “Volatility in the Crude Oil and Natural Gas Markets: GARCH, Asymmetry, Seasonality and Announcement Effects.” Division of Finance Working Paper, Michael F. Price College of Business, University of Oklahoma, May.

Mohammadi, Hassan and Lixian Su (2010). “International evidence on crude oil price dynamics: Applications of ARIMA-GARCH models.” *Energy Economics* 32: 1001–1008.

Narayana, Paresh Kumar and Seema Narayan (2007). "Modelling oil price volatility." *Energy Policy* 35: 6549–6553

Ng, Victor K. and Stephen C. Pirrong (1994). "Fundamentals and Volatility: Storage, Spreads, and the Dynamics of Metals Prices." *Journal of Business* 67 (2): 203–30.

Nomikos, Nikos K. and Panos K. Pouliasis (2011). "Forecasting petroleum futures markets volatility: The role of regimes and market conditions." *Energy Economics* 33: 321–337.

Pesaran, M. Hashem and Yongcheol Shin, 1999. "An Autoregressive Distributed Lag Modelling Approach to Cointegration Analysis." In S. Strom, ed., *Econometrics and Economic Theory in the Twentieth Century*. New York, NY: Cambridge University Press.

Pirrong, Craig (2010). "An Evaluation of the Performance of Oil Price Benchmarks during the Financial Crisis." Bauer College of Business Working Paper, University of Houston, January. Available online: http://www.bauer.uh.edu/downloads/Pirrong_WTI_Report_091116_Final.pdf

Platts (2010). "Platts Oil Pricing and MOC Methodology Explained." Backgrounder, June: http://www.platts.com/IM.Platts.Content/InsightAnalysis/IndustrySolutionPapers/moc.pdf

Reeve, Trevor A. and Robert J. Vigfusson (2011). "Evaluating the Forecasting Performance of Commodity Futures Prices." International Finance Discussion Paper No. 2011-1025, Board of Governors of the Federal Reserve System, August.

Regnier, Eva (2007). "Oil and energy price volatility." *Energy Economics* 29: 405–427.

Sadorsky, Perry (2006). "Modeling and forecasting petroleum futures volatility." *Energy Economics* 28: 467–488.

Schmidbauer, Harald and Angi Rösch (2012). "OPEC News Announcements: Effects on Oil Price Expectation and Volatility." 35 (5): 1656–1663.

Serra, Teresa, David Zilberman and José Gil (2011). "Price volatility in ethanol markets." *European Review of Agricultural Economics* 38 (2): 259–280.

Silvennoinen, Annastiina and Susan Thorp (2013). "Financialization, Crisis and Commodity Correlation Dynamics." *Journal of International Financial Markets, Institutions and Money*, 24 (1): 42–65.

Singleton, Kenneth J. (2014). "Investor Flows and the 2008 Boom/Bust in Oil Prices". *Management Science*, 60 (2): 300–318.

Trolle, Anders B. and Eduardo S. Schwartz (2010). "Variance Risk Premia in Energy Commodities." *Journal of Derivatives*, Spring: 15–32.

Wang, Yudong and Chongfeng Wu (2012). "Forecasting energy market volatility using GARCH models: Can multivariate models beat univariate models?" *Energy Economics* 34 (6): 2167–2181.

Wei, Yu, Yudong Wang and Dengshi Huang (2010). "Forecasting crude oil market volatility: Further evidence using GARCH-class models." *Energy Economics* 32 (6): 1477–1484.

Working, Holbrook (1933). "Price Relations between July and September Wheat Futures at Chicago since 1885." *Wheat Studies of the Food Research Institute* 9 (6): 187–238.

——. 1948. "Theory of the Inverse Carrying Charge in Futures Markets." *Journal of Farm Economics* 30 (1): 1–28.

——. 1949. "The Theory of Price of Storage." *American Economic Review* 39(6): 1254–1262.

——. 1960. "Speculation on Hedging Markets." Stanford University Food Research Institute Studies 1: 185–220.

Yang, C.W., M.J. Hwang and B.N. Huang (2002). "An analysis of factors affecting price volatility of the US oil market." *Energy Economics* 24 (2): 107-119.

Table 1: Volatility – Structural Breaks Tests (*Open Interest-Based Rolls*)

	9/11		Great Recession	
	Begin	End	Begin	End
Dates	9/11/2001	12/31/2001	9/15/2008	6/30/2009
Panel A: Implied Volatility				
Nearby	**25.375*** **		**38.530*** **	
	(2.180)		(3.085)	
Deferred	**22.832*** **		**32.234*** **	
	(1.580)		(2.458)	
6-Month	**13.328*** **		**22.148*** **	
	(1.265)		(1.487)	
Panel B: Realized Volatility *(Standard Deviation)*				
Nearby	**2.622*** **		**5.100*** **	
	(0.580)		(0.532)	
Deferred	**2.657*** **		**4.713*** **	
	(0.548)		(0.502)	
6-Month	**1.832*** **		**4.300*** **	
	(0.394)		(0.452)	
Panel C: Realized Volatility *(High* minus *Low)*				
Nearby	**1.272** **		**3.643*** **	
	(0.500)		(0.454)	
Deferred	**1.146** **		**3.250*** **	
	(0.454)		(0.421)	
6-Month	0.139		**2.047*** **	
	(0.321)		(0.273)	

Notes: Table 1 summarizes simple structural break tests in the volatility (Implied volatility, Panel A; Realized volatility, Panels B and C) of the nearby, first-deferred and 6-month-out WTI sweet crude oil futures prices. The "nearby" contract anchors the term structure of futures prices. In Table 1, it is defined as the nearest maturity contract with the highest open interest. Until December 2004, the roll from the prompt to the first-deferred typically takes place around the 9th business day of the spot month; from 2005 onwards, the roll day is usually the 7th business day of the month – see Figure 1, Panel C. Tests are performed on the statistical significance of two time dummies – one for the post-9/11 period (September 11th through December 31st, 2001; left-hand side) and the other for the post-Lehman period (September 16, 2008 through June 30, 2009; right-hand side). **Implied volatilities** in **Panel A** are backed out using the Black and Scholes option pricing formula (Source: Bloomberg). **Realized volatilities** in Panels B and C are based on the authors' computations – 20-trading day standard deviations in **Panel B** and the difference between the daily high and low prices expressed as percentage of the relevant settlement price in **Panel C**. The 6-month out figures are constant-maturity, weighted averages of the figures for the next June and December contracts. Sample: Tuesdays from June 6th, 2000 to December 31st, 2013.

Table 2: Structural Breaks Tests (*Calendar-Based Rolls*)

	9/11		**Great Recession**	
	Begin	End	Begin	End
Dates	9/11/2001	12/31/2001	9/15/2008	6/30/2009
	Panel A: Implied Volatility			
Nearby	**20.654*** **		**37.342*** **	
	(1.037)		(1.400)	
Deferred	**21.387*** **		**32.316*** **	
	(0.883)		(1.070)	
6 Month	**16.209*** **		**22.191*** **	
	(1.021)		(0.643)	
	Panel B: Realized Volatility *(Standard Deviation)*			
Nearby	**2.484*** **		**5.912*** **	
	(0.283)		(0.237)	
Deferred	**2.501*** **		**4.969*** **	
	(0.261)		(0.222)	
6 Month	**1.778*** **		**4.383*** **	
	(0.189)		(0.206)	
	Panel C: Realized Volatility *(High* minus *Low)*			
Nearby	**2.125*** **		**4.062*** **	
	(0.338)		(0.238)	
Deferred	**1.995*** **		**3.420*** **	
	(0.313)		(0.189)	
6 Month	**0.315***		**2.514*** **	
	(0.187)		(0.158)	

Notes: Table 2 summarizes simple structural break tests in the volatility (Implied volatility, Panel A; Realized volatility, Panels B and C) of the nearby, first-deferred and 6-month-out WTI sweet crude oil futures prices. The "nearby" contract anchors the term structure of futures prices; in Table 2, it is defined as the prompt contract (which usually expires on the third business day before the 25th calendar day of the spot month). Tests are performed on the statistical significance of two time dummies – one for the post-9/11 period (September 11th through December 31st, 2001; left-hand side) and the other for the post-Lehman period (September 16, 2008 through June 30, 2009; right-hand side). Implied volatilities in Panel A are backed out using the Black and Scholes option pricing formula (Source: Bloomberg). Realized volatilities in Panels B and C are based on the authors' computations – 20-trading day standard deviations in Panel B and the difference between the daily high and low prices expressed as percentage of the relevant settlement price in Panel C. The 6-month out figures are constant-maturity, weighted averages of the figures for the next June and December contracts. Sample: Tuesdays from June 6th, 2000 to December 31st, 2013June 6th, 2000 to December 31st, 2013.

Table 3: Summary Statistics

Panel A: WTI and Brent Oil Prices, Spreads and Volatilities

Variable	mean	median	max	min	stdev	skewness	kurtosis	sum	obs	adf_level		adf_diff	
WTI_Price_1m	63.93	64.16	140.97	18.08	28.81	0.16	1.94	45325	709	0.551		**0.000**	***
WTI_Ivol_1m	37.63	34.94	114.41	13.18	13.39	2.24	10.41	26677	709	**0.043**	**	**0.000**	***
WTI_Slope_1m	1.63	3.97	114.23	-66.09	21.21	0.79	7.97	1156	709	**0.000**	***	**0.000**	***
WTI_Slope_1m_sq	4.52	0.97	130.49	0.00	12.09	6.29	51.37	3203	709	**0.000**	***	**0.000**	***
WTI_Price_6m	64.38	67.03	141.39	19.37	29.48	0.05	1.88	45647	709	0.567		**0.000**	***
WTI_Ivol_6m	33.44	32.09	72.15	17.11	8.35	1.41	6.26	23711	709	**0.042**	**	**0.000**	***
WTI_Slope_6m	-1.86	0.55	61.02	-46.22	14.68	0.43	5.53	-1317	709	**0.010**	**	**0.000**	***
WTI_Slope_6m_sq	218.61	64.35	3722.91	0.00	450.41	4.42	27.05	154992	709	**0.000**	***	**0.000**	***
Brent_Price_1m	66.33	64.29	141.46	18.12	33.24	0.23	1.74	47025	709	0.690		**0.000**	***
Brent_Ivol_1m	36.64	34.29	103.05	13.33	12.45	1.85	8.22	25977	709	**0.037**	**	**0.000**	***
Brent_Slope_1m	-1.02	-2.63	83.44	-62.04	15.50	0.77	7.74	-725	709	**0.000**	***	**0.000**	***
Brent_Slope_1m_sq	2.41	0.77	69.62	0.00	6.15	6.22	53.23	1708	709	**0.000**	***	**0.000**	***
WTI_Volume_1m	196043	185334	638193	3592	114759	0.58	2.56	138994656	709	0.097		**0.000**	***
Brent_Volume_1m	107884	91502	328741	347	69535	0.71	2.43	76489448	709	0.129		**0.000**	***

Notes: The ***Price*** and ***IVol*** variables are self-explanatory**.** The three ***SLOPE*** variables measure percentage differences between the nearby and first-deferred contracts (WTI_Slope_1m, Brent_Slope_1m) or the first- and sixth-deferred WTI sweet crude oil futures contracts (WTI_Slope_6m), where the nearby futures that anchors the term structure is defined as the nearest-maturity contract with the highest open interest and the six-month-out contract is defined by weight-averaging figures for the next June and December contracts to keep a constant 6-month contract maturity. For the augmented Dickey-Fuller (ADF) tests, we provide p-values. Stars (*, **, ***) indicate the rejection of non-stationarity at standard levels of statistical significance (10%, 5% and 1%, respectively). The lag length is set equal to 4 for all series. Sample period for all statistics: Tuesdays from June 6th, 2000 to December 31st, 2013.

Table 3: Summary Statistics

Panel B: Macroeconomic, Physical and Financial Market Conditions

REAL	0.0513	0.0304	0.8154	-0.5837	0.3564	0.1846	2.032	36	709	**0.095**	*	**0.000**	***
ADS	-0.3984	-0.2076	0.9107	-3.9225	0.7763	-2.2100	8.951	-282	709	0.114		**0.000**	***
Crude_Rigs	480	278	1432	115	430	1.27	3.006	340063	709	0.998		**0.000**	***
US_Supply	5648.7	5575.0	8121.0	3813.0	668.1	1.34	6.052	4004916	709	0.968		**0.000**	***
Canada_PADD2	36546.0	33968.0	59119.0	20241.0	8320.2	1.00	3.192	25911108	709	0.584		**0.000**	***
SPARE_Dummy	0.43	0.00	1.00	0.00	0.50	0.28	1.080	305	709	0.195		**0.000**	***
VIX	21.32	19.47	69.65	9.90	8.98	1.84	8.057	15118	709	**0.004**	***	**0.000**	***
Working_T	0.27	0.28	0.57	0.06	0.12	-0.02	1.818	194	709	0.472		**0.000**	***

Notes: ***REAL*** is a measure of world business activity based on an index of shipping rates for dry bulk cargoes on oceanic routes (Kilian, 2009). Weekly values are calculated using the Baltic Dry index, deflated and detrended following Kilian (2009). ***ADS*** is the Aruoba-Diebold-Scotti (2009) U.S. Business Conditions Index (Source: Federal Reserve Bank of Philadelphia). ***Crude_Rigs*** is the number of active oil rigs located in the USA (Source: Baker Hughes, Inc.). ***US_Supply*** is the weekly US crude oil output (thousands of barrels; source: EIA, U.S. Energy Information Administration). ***Canada_PADD2*** is the weekly crude oil imports from Canada into PADD 2 (thousands of barrels; source: EIA). ***Spare*** is a dummy that measures supply constraints based on the non-Saudi OPEC effective spare output capacity (Source: IEA, International Energy Agency); the **dummy** takes the value 0 when spare capacity is low and 1 when it is high, following Brunetti, Büyükşahin, Robe and Soneson (2013). ***VIX*** is the return volatility (in percent) implied by Standard and Poor's S&P500 equity index options (Source: Chicago Board Options Exchange). ***Working's T*** (1960) is an index (Working, 1960) of speculative intensity in the WTI swewet crude oil futures market (Source: Commodity Futures Trading Commission public Commitment of Traders Reports). For the augmented Dickey-Fuller (ADF) tests, we provide p-values. Stars (*, **, ***) indicate the rejection of non-stationarity at standard levels of statistical significance (10%, 5% and 1%, respectively). The lag length is set equal to 4 for all series. Sample period for all statistics: Tuesdays from June 6th, 2000 to December 31st, 2013.

Table 4: Macroeconomic, Physical and Financial Predictors of Oil Price Volatilities

Panel A: WTI – Nearby IV

	Full Sample	**Pre-Feb_2007**	**Post-Feb_2007**
VARIABLES	WTI_ivol_1m_oi	WTI_ivol_1m_oi	WTI_ivol_1m_oi
Lagged IV	**0.7753*** **	**0.7697*** **	**0.6330*** **
	(0.0410)	*(0.0401)*	*(0.0888)*
Lagged REAL (Change)	-3.0522	7.5228	-5.2669
	(5.1098)	*(9.0802)*	*(5.4406)*
US Supply (Change)	-0.6267	-2.2275	-10.1100
	(5.1074)	*(4.6372)*	*(13.9308)*
Dummy Spare	**-1.3197*** **	0.2351	**-0.8541***
	(0.3991)	*(0.7750)*	*(0.4889)*
Effective Spare x US Supply Change	-7.5860	-33.0457	25.6226
	(17.8369)	*(25.5550)*	*(18.1937)*
WTI Slope	**0.0252** **	0.0408	**0.0530** **
	(0.0104)	*(0.0261)*	*(0.0248)*
WTI Slope Squared	**0.0487***	**0.1290** **	0.0585
	(0.0276)	*(0.0574)*	*(0.0359)*
Lagged WTI Working T (Change)	14.4140	18.7458	14.8490
	(10.6666)	*(20.5279)*	*(13.2341)*
VIX	**0.2609*** **	0.1394*	**0.4828*** **
	(0.0489)	*(0.0799)*	*(0.1035)*
Roll dummy	**-1.5336*** **	**-2.2211*** **	-0.5616
	(0.4843)	*(0.6646)*	*(0.6464)*
Lagged Volume (Change)	0.0366	0.8768	-1.4847
	(0.6573)	*(0.7979)*	*(1.0114)*
Constant	3.5106***	6.2213***	2.1358*
	(0.9286)	*(1.7103)*	*(1.1099)*
Observations	707	349	358

Notes: Table 4 shows the estimated coefficients from the weekly model described in Section 5. The dependent variable is the implied oil price volatility; the roll day is determined based on the preponderance of the open interest. The variables are described in Table 3 with the exceptions of Roll. This variable is a time dummy that takes the value 1 for weeks when the GSCI roll takes place. Sample period: June 2000 to December 2013. Stars (*, **, ***) indicate different levels of statistical significance (10%, 5% and 1%, respectively). Sample period: June 2000 to December 2013.

Table 4: Macroeconomic, Physical and Financial Predictors of Oil Price Volatilities

Panel B: WTI – 6-Month IV

VARIABLES	**Full Sample** WTI_ivol_6m_oi	**Pre-Feb_2007** WTI_ivol_6m_oi	**Post-Feb_2007** WTI_ivol_6m_oi
Lagged IV	**0.8960*** **	**0.8764*** **	**0.8385*** **
	(0.0178)	*(0.0352)*	*(0.0327)*
Lagged REAL (Change)	-2.9590	3.8111	-4.7064
	(2.5629)	*(4.0957)*	*(2.9122)*
US Supply (Change)	0.4447	-2.2640	1.2833
	(2.8495)	*(2.8306)*	*(5.2473)*
Dummy Spare	**-0.3971** **	0.5700	**-0.4255***
	(0.1984)	*(0.7042)*	*(0.2240)*
Effective Spare x US Supply Change	-0.3129	0.4021	1.2782
	(7.7320)	*(15.4526)*	*(7.7729)*
WTI Slope	**0.0148***	0.0229	**0.0447*** **
	(0.0080)	*(0.0232)*	*(0.0160)*
WTI Slope Squared	0.0000	0.0006	-0.0003
	(0.0003)	*(0.0007)*	*(0.0004)*
Lagged WTI Working T (Change)	3.3467	5.2083	1.4240
	(4.8840)	*(8.6984)*	*(5.7795)*
VIX	**0.0897*** **	0.0329	**0.1431*** **
	(0.0177)	*(0.0374)*	*(0.0291)*
Roll dummy	**-0.4999*** **	**-0.5872** **	-0.3830
	(0.1829)	*(0.2392)*	*(0.2550)*
Lagged Volume (Change)	-0.0947	-0.1799	0.0797
	(0.1756)	*(0.2070)*	*(0.3044)*
Constant	1.8580***	3.5011**	2.2581***
	(0.4532)	*(1.3671)*	*(0.7662)*
Observations	707	349	358

Notes: Table 4 shows the estimated coefficients from the weekly model described in Section 5. The dependent variable is the implied oil price volatility; the roll day is determined based on the preponderance of the open interest. The variables are described in Table 3 with the exceptions of Roll. This variable is a time dummy that takes the value 1 for weeks when the GSCI roll takes place. Sample period: June 2000 to December 2013. Stars (*, **, ***) indicate different levels of statistical significance (10%, 5% and 1%, respectively). Sample period: June 2000 to December 2013.

Table 4: Macroeconomic, Physical and Financial Predictors of Oil Price Volatilities

Panel C: WTI – IV Slope (6-month *vs.* 1-month)

VARIABLES	Full Sample WTI_ivol_1m_6m_oi	Pre-Feb_2007 WTI_ivol_1m_6m_oi	Post-Feb_2007 WTI_ivol_1m_6m_oi
Lagged IV	**0.6959*** **	**0.7174*** **	**0.5273*** **
	(0.0484)	*(0.0518)*	*(0.1160)*
Lagged REAL (Change)	1.0439	6.0300	-2.7580
	(3.4537)	*(5.9735)*	*(3.7999)*
US Supply (Change)	-0.1364	-0.1025	-5.0910
	(4.0277)	*(3.5229)*	*(9.9189)*
Dummy Spare	**-1.1258*** **	-1.1135	-0.5703
	(0.3452)	*(0.9118)*	*(0.4017)*
Effective Spare x US Supply Change	-7.1299	**-34.2356** **	16.2261
	(12.4349)	*(13.3526)*	*(12.6101)*
WTI Slope	**0.0368** **	0.0374	-0.0222
	(0.0162)	*(0.0348)*	*(0.0209)*
WTI Slope Squared	**0.3024*** **	0.1640	**0.7721*** **
	(0.0903)	*(0.1152)*	*(0.2926)*
Lagged WTI Working T (Change)	12.0075	15.6898	13.9591
	(7.8818)	*(15.6493)*	*(10.2825)*
VIX	**0.1191*** **	0.1091	**0.2192*** **
	(0.0276)	*(0.0694)*	*(0.0543)*
Roll dummy	**-0.9889*** **	**-1.6215*** **	-0.4066
	(0.3779)	*(0.5712)*	*(0.4672)*
Lagged Volume (Change)	0.1603	0.2646	0.0590
	(0.3207)	*(0.4421)*	*(0.4041)*
Constant	-0.9700**	-0.0221	-3.9070***
	(0.4148)	*(1.0031)*	*(0.9578)*
Observations	707	349	358

Notes: Table 4 shows the estimated coefficients from the weekly model described in Section 5. The dependent variable is the implied oil price volatility; the roll day is determined based on the preponderance of the open interest. The variables are described in Table 3 with the exceptions of Roll. This variable is a time dummy that takes the value 1 for weeks when the GSCI roll takes place. Sample period: June 2000 to December 2013. Stars (*, **, ***) indicate different levels of statistical significance (10%, 5% and 1%, respectively). Sample period: June 2000 to December 2013.

Table 4: Macroeconomic, Physical and Financial Predictors of Oil Price Volatilities

Panel D: Brent – Nearby IV Slope

	Full Sample	Pre-Feb_2007	Post-Feb_2007
VARIABLES	Brent_ivol_1m_oi	Brent_ivol_1m_oi	Brent_ivol_1m_oi
Lagged IV	**0.6847*** **	**0.5599*** **	**0.6401*** **
	(0.0606)	*(0.1161)*	*(0.0463)*
Lagged REAL (Change)	-0.2575	-0.1938	2.7833
	(5.1661)	*(8.1211)*	*(4.6783)*
US Supply (Change)	4.5326	5.8475	2.0164
	(5.1857)	*(11.8696)*	*(4.7449)*
Dummy Spare	**-5.6726*** **	**-56.7795*** **	0.3132
	(1.4372)	*(20.9153)*	*(2.2008)*
Effective Spare x US Supply Change	**0.0010*** **	**0.0092*** **	-0.0005
	(0.0003)	*(0.0034)*	*(0.0006)*
WTI Slope	**0.0627*** **	-0.0212	**0.1777*** **
	(0.0212)	*(0.0414)*	*(0.0374)*
WTI Slope Squared	**0.2833*** **	0.1389	0.0909
	(0.0684)	*(0.1413)*	*(0.0656)*
Lagged WTI Working T (Change)	1.9715	9.8918	-5.6067
	(8.9446)	*(23.6711)*	*(7.9607)*
VIX	**0.2227*** **	**0.1740** **	**0.3249*** **
	(0.0480)	*(0.0822)*	*(0.0452)*
Roll dummy	-0.2385	0.0613	-0.5599
	(0.4113)	*(0.6737)*	*(0.4405)*
Lagged Volume (Change)	0.7544*	0.8478	0.3337
	(0.4370)	*(0.5886)*	*(0.6162)*
Constant	6.9291***	12.8003***	5.5487***
	(1.6110)	*(4.0020)*	*(1.1334)*
Observations	707	349	358

Notes: Table 4 shows the estimated coefficients from the weekly model described in Section 5. The dependent variable is the implied oil price volatility; the roll day is determined based on the preponderance of the open interest. The variables are described in Table 3 with the exceptions of Roll. This variable is a time dummy that takes the value 1 for weeks when the GSCI roll takes place. Sample period: June 2000 to December 2013. Stars (*, **, ***) indicate different levels of statistical significance (10%, 5% and 1%, respectively). Sample period: June 2000 to December 2013.

Table 5: Large Residual Analysis and Crude Oil Market Disruptions

Notes: We assess our model of nearby WTI option-implied IV for periods where it sharply mis-estimates implied volatilities, i.e., when there are large residuals. Our regression model captures U.S. domestic supply, demand, storage and financial variables that may help predict uncertainty in the crude oil space. Hence, we expect that high residuals would reflect shocks to other variables not included in the model. Consistent with this prediction, we find that large residual periods correspond to notable unanticipated shocks to energy markets. We match large residuals and shocks by (i) studying the monthly Short Term Energy Outlook published by the EIA and (ii) identifying declines in world production greater than 1%. Sample period: June 2000 to December 2013.

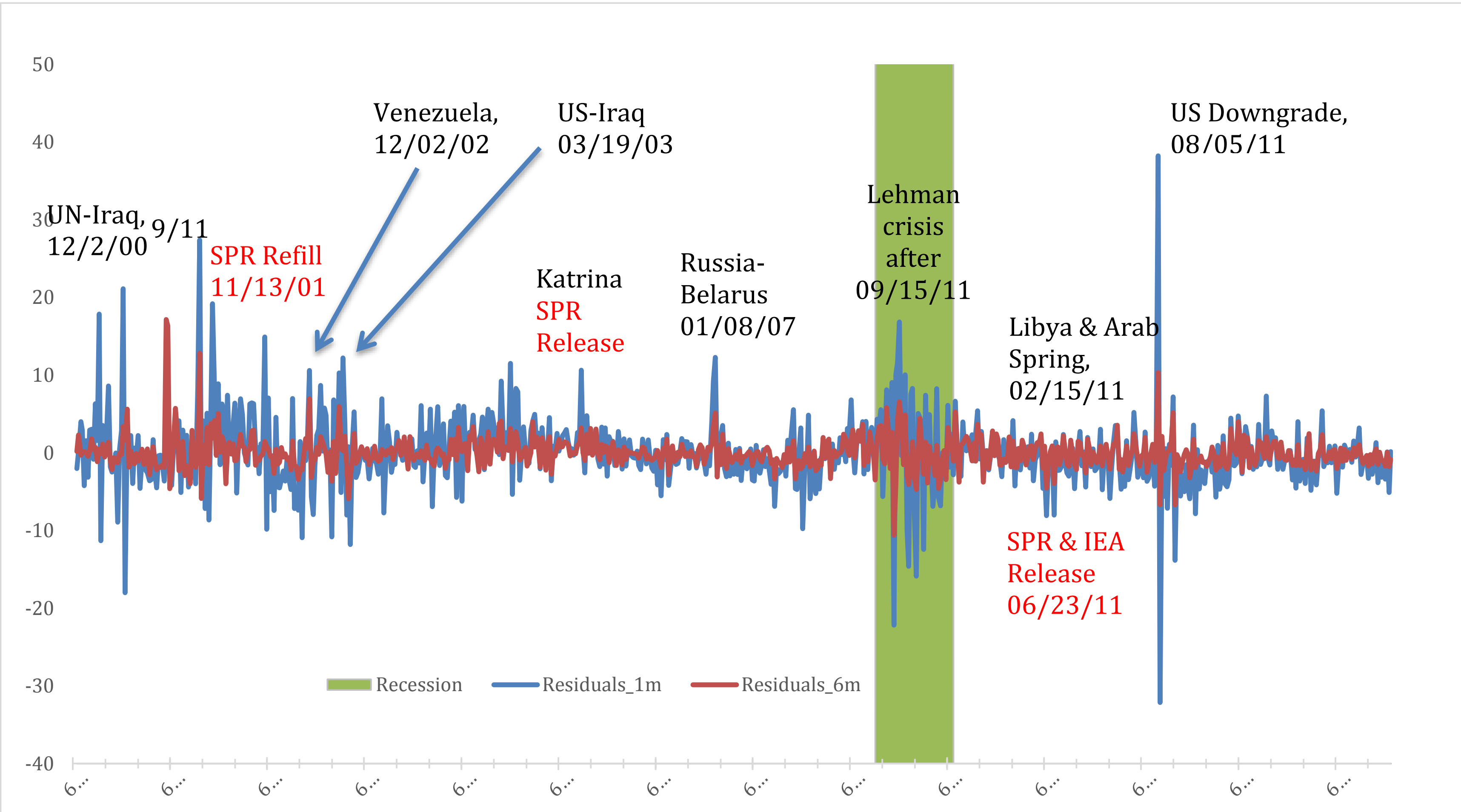
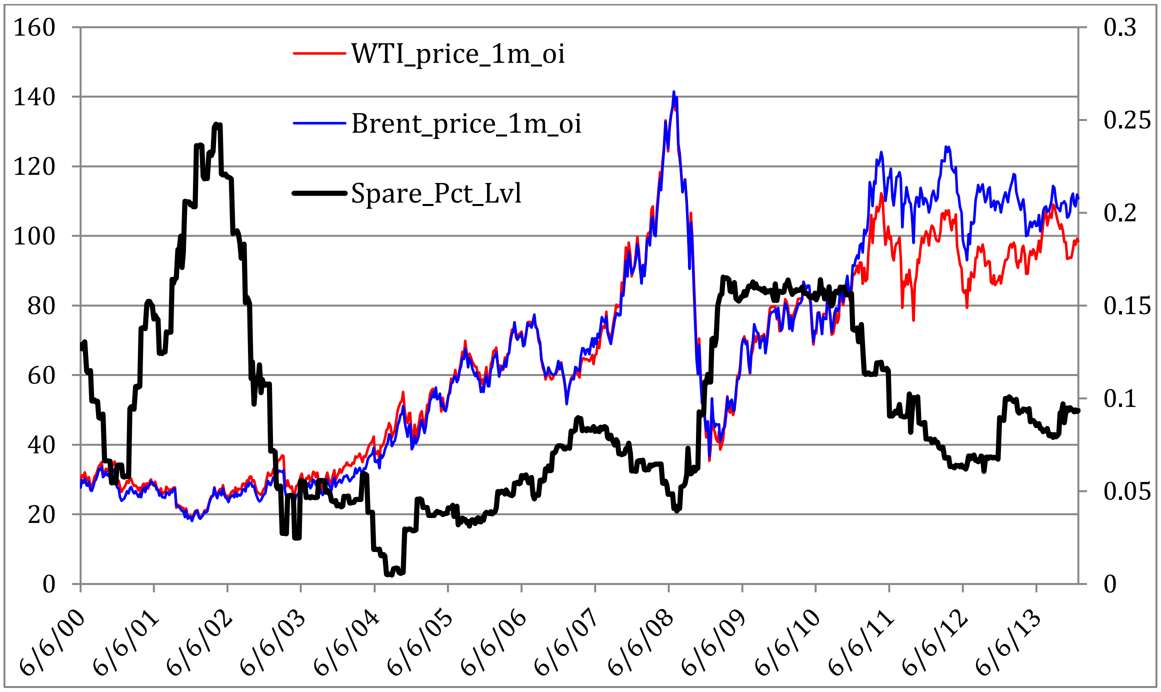


Table 5 (continued)

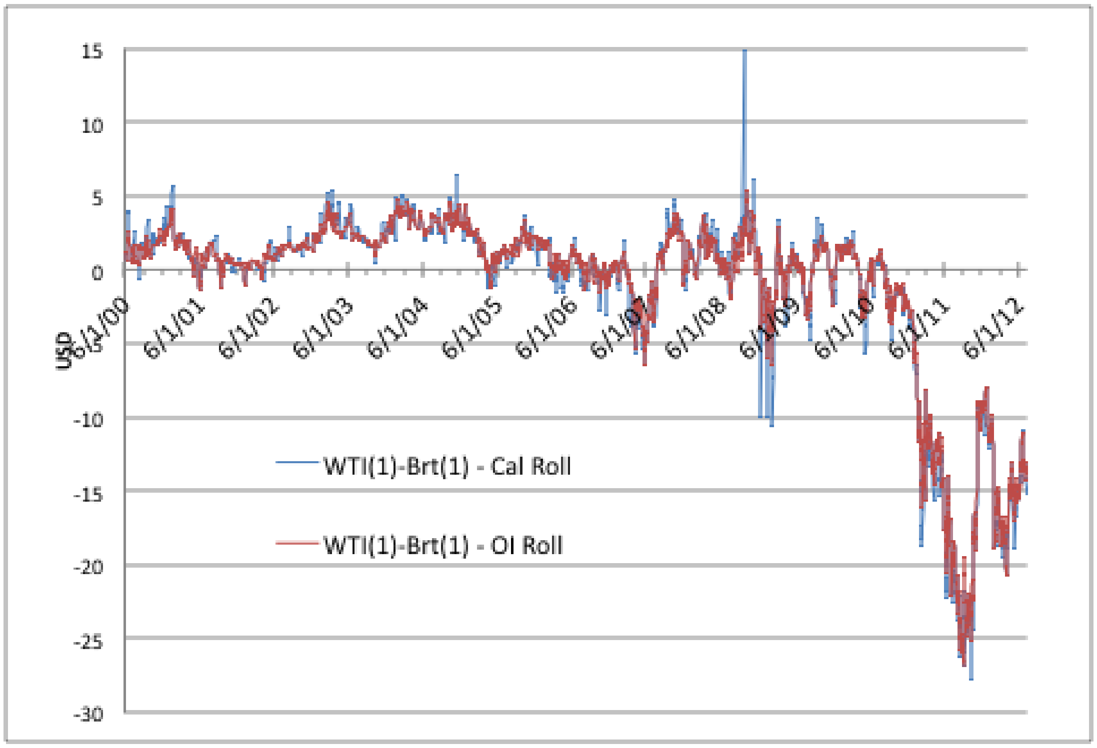
Event	Date	Description	Source
UN – Iraq	12/1/2000-12/12/2000	From the 1st to 12th of December 2000, Iraq suspends oil exports under the United Nations oil-for-food program due to oil pricing disagreement with the United Nations.	http://www.un.org/Depts/oip/background/chron.html
9/11	9/11/2000	Terrorists attack the United States destroying the World Trade Center in New York and damaging the Pentagon, U.S. Department of Defense.	http://govinfo.library.unt.edu/911/report/911Report.pdf
SPR Refill	11/13/2001	On November 13th, 2001, President George W. Bush ordered the Strategic Petroleum Reserve to be filled up to its capacity: 700 million barrels.	http://www.gpo.gov/fdsys/pkg/WCPD-2001-11-19/pdf/WCPD-2001-11-19-Pg1664-2.pdf
Venezuela	12/2/2002	Strikes in Venezuela decreased crude oil production by 3 million barrels per day of which the U.S. imported approximately half.	http://www.eia.gov/pub/oil_gas/petroleum/feature_articles/2003/venezuelan/vzimpacts.htm
US – Iraq	03/19/2003	On March 19th 2003, the United States declares war on Iraq.	http://www.cfr.org/iraq/timeline-iraq-war/p18876
Katrina SPR Release	08/23/2005 09/02/2005	In response to hurricane Katrina's destruction of U.S. oil production infrastructure, the SPR released 30 million barrels of oil.	http://energy.gov/fe/services/petroleum-reserves/strategic-petroleum-reserve
Russia-Belarus	01/08/2007	Russia halted oil supplies to Germany, Poland and Ukraine due to a disagreement with Belarus over energy prices.	http://news.bbc.co.uk/2/hi/business/6240473.stm
Lehman-Great Recession	09/15/2008-06/30/2009s	WTI prices sharply increased from about $60 per barrel in early 2007 to over $140 per barrel in mid-2008. The Great Recession, a global recession due to financial crises, pushed prices down and due to decreased demand and OPEC responded by cutting production by 4.2 millions of barrels of oil per day.	http://www.eia.gov/finance/markets/reports_presentations/eia_what_drives_crude_oil_prices.pdf http://www.opec.org/opec_web/en/945.htm
Libya Civil War and Arab Spring	02/15/2011	Libya's civil unrest decreased its oil and gas production by 60-90%. This coincided with the Arab Spring revolutions of 2011	http://www.eia.gov/todayinenergy/detail.cfm?id=390 http://in.reuters.com/article/2012/01/13/tunisia-revolution-anniversary-idINDEE80C0IT20120113
SPR & IEA Release	06/23/2011	On June 23, 2011, the SPR and EIA coordinated an international release of 60 million barrels of oil. The release responded in part to supply disruptions in Libya.	http://energy.gov/fe/services/petroleum-reserves/strategic-petroleum-reserve
US credit-rating Downgrade	08/05/2011	Due to budget concerns and concerns about political gridlock, Standard & Poor's downgraded the long term sovereign credit rating of the U.S. from AAA to AA+.	http://www.standardandpoors.com/ratings/articles/en/us/?assetID=1245316529563

Figure 1A: Crude Oil Prices and OPEC Effective Surplus Output Capacity



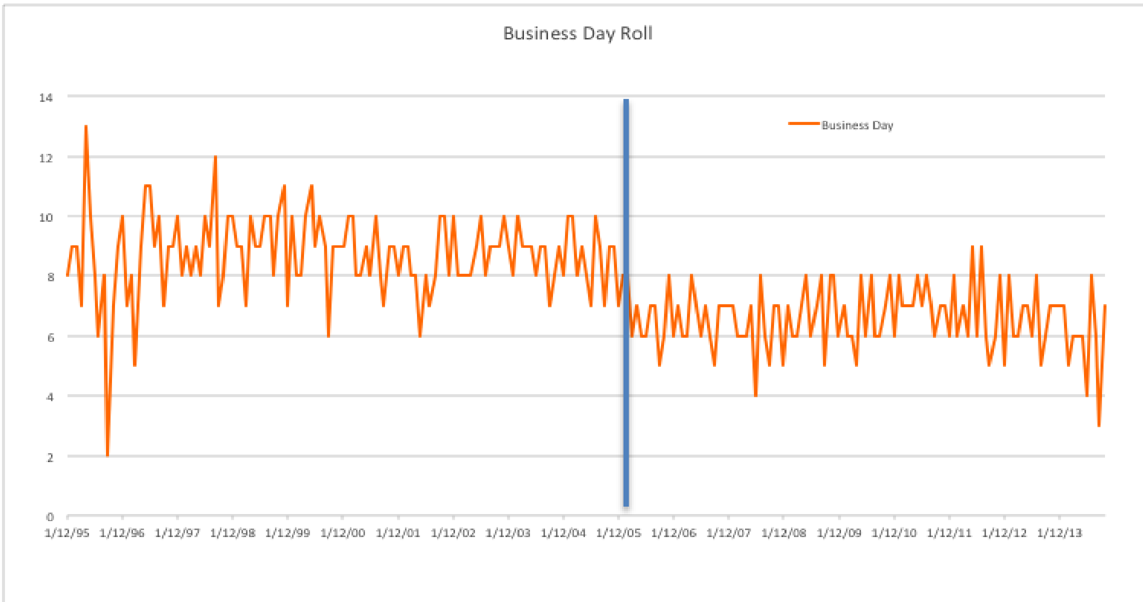
Notes**: Panel A of Figure 1** plots the nearby-futures prices (U.S. dollars per barrel, roll based on the preponderance of the WTI open interest) of West Texas Intermediate (WTI, in **red**) and Brent crude oils (in **blue**). It also plots OPEC's effective crude oil surplus production capacity outside of Saudi Arabia (*SPARE*, expressed as a percentage of total consumption; in **black**, right hand scale). Oil prices are in USD. Monthly *SPARE* figures from June 2000 through December 2013 are computed using the procedure of Büyükşahin and Robe (2011) and raw data from the Energy Information Administration (U.S. Department of Energy) and the International Energy Agency (IEA). Figure 1A illustrates the sharp rise of both crude oil benchmarks from 2003 till July 2008 amid a dearth of surplus capacity. A second episode of production capacity exhaustion after February 2011 affected Brent prices more than WTI prices amid a partial decoupling of the two oil benchmarks due to transportation and storage infrastructure bottlenecks at the WTI hub of Cushing, OK.

Figure 1 – *Panel B*: WTI-Brent Nearby Price Spread, 2000-2012



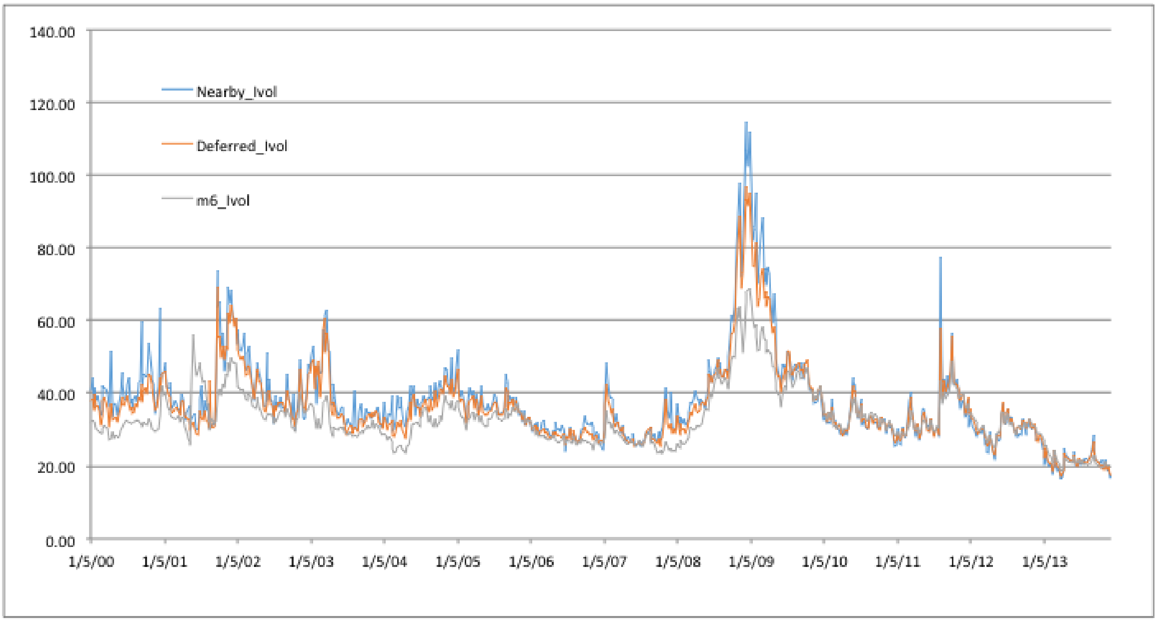
***Notes*: Panel B** of **Figure 1** depicts the increase in the volatility of the nearby WTI-Brent futures price spread after Fall 2008, and the large and persistent increase in the magnitude of this spread in 2011-2012. The spread is defined as the difference between the "nearby" prices of the West Texas Intermediate (WTI) and Brent crude oil futures contracts. The red series defines the nearby contracts as rolling over based on their calendar date of expiration (for WTI, this is the third business day before the 25^{th} of the month preceding the contract month if the 25^{th} is a business day and, if it is not, the fourth business day; for Brent, this is the 15^{th} day before the first day of the contract month if the 15^{th} is a business day, or the next preceding business day if it is not). The blue series defines the nearby contracts as rolling over based on the day when the WTI open interest tends to switch into the next-deferred contract; before 2006, the median day is the ninth business day of the month; after 2005 the seventh business day of the month (see Appendix 1). Sample period: June 2000-July 2012.

Figure 1 – *Panel C:* WTI roll date, 2000-2013



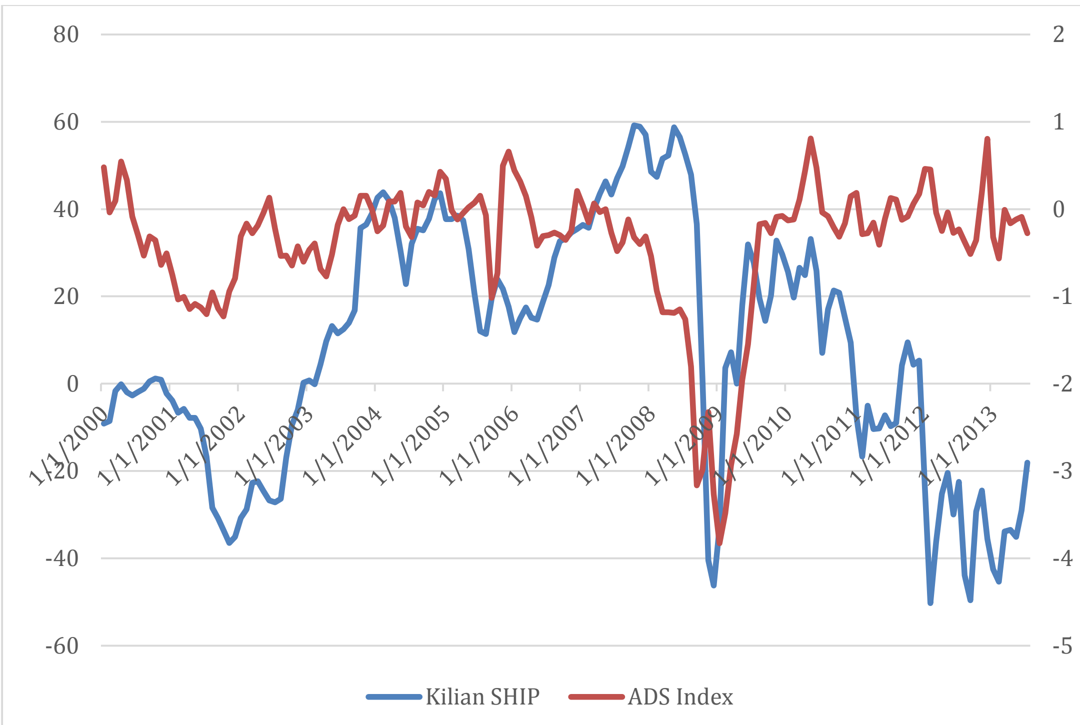
Note: Per the rules of the New York Mercantile Exchange (NYMEX, part of the CME Group), the WTI prompt futures for a given month typically expires 3 business days before the 25th calendar day of the previous month. The preponderance of the WTI futures open interest, however, rolls into the first-deferred contract approximately 5 to 10 days prior to the prompt contract's expiration date. Using the preponderance of the open interest to define the roll date, **Panel C of Figure 1** shows that the mode of the "roll" date used to be the 9th business day of the previous month (through December 2004) but, amid that onset of commodity index trading, has moved to the 7th business day thereafter.

Figure 2: Option-Implied Price Volatility, 2000-2013



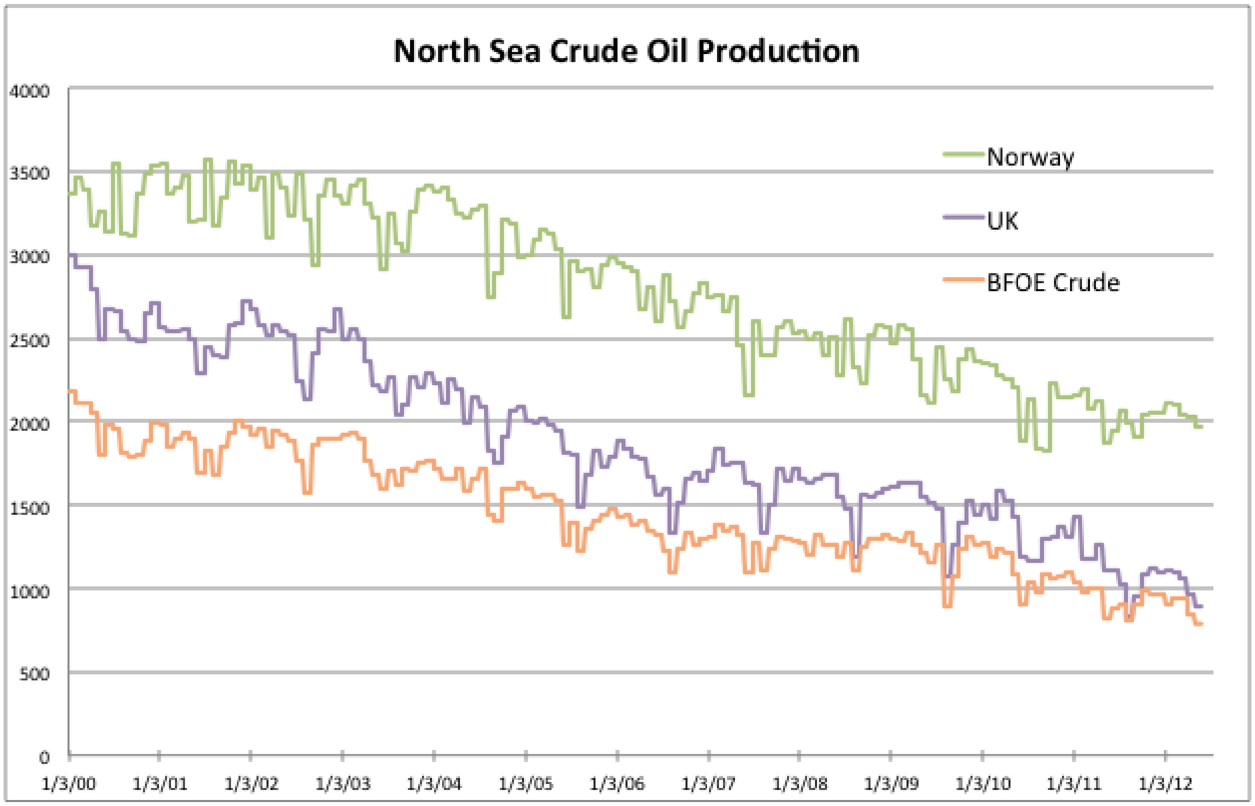
Notes: **Figure 2** plots the option-implied volatility of the nearby, first-deferred and 6-month out WTI futures contracts. The three highest volatility levels are in 2001 (following the 9-11 attack), 2008-2009 (coinciding with the peak of oil prices in late 2008 and their subsequent collapse in early 2009) and August 2011 (short-lived). Furthermore, we observe historically low implied volatilities within the past two years (2012 and 2013), reflecting the plentiful supply of West Texas Intermediate in Cushing, Oklahoma.

Figure 3: World and U.S. Macroeconomic Fundamentals, 2000-2013



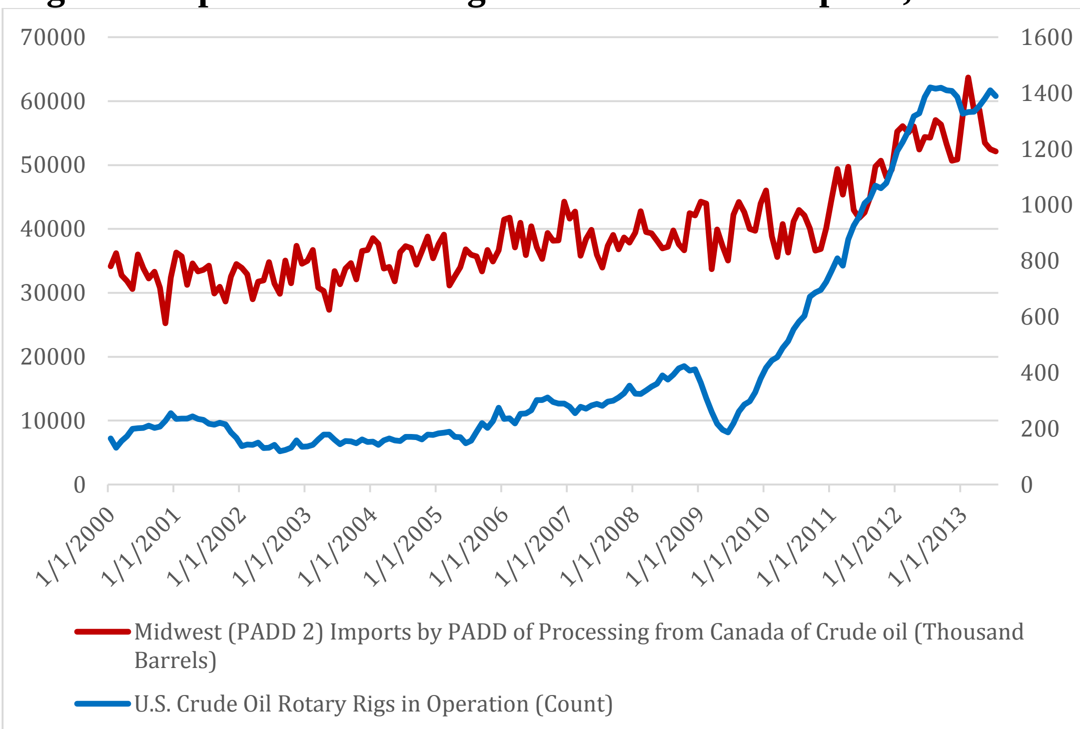
Notes**: Figure 2** plots two indicators of macroeconomic activity. The **blue** series is the monthly Kilian (2009) Dry Bulk Shipping Cost Index, a proxy for worldwide economic demand. The **red** series is the Federal Reserve Bank of Philadelphia ADS business conditions index (Aruoba, Diebold and Scotti, 2009). This daily indicator tracks U.S. "weekly initial jobless claims; monthly payroll employment, industrial production, personal income less transfer payments, manufacturing and trade sales; and quarterly real GDP."

Figure 4: Brent Output



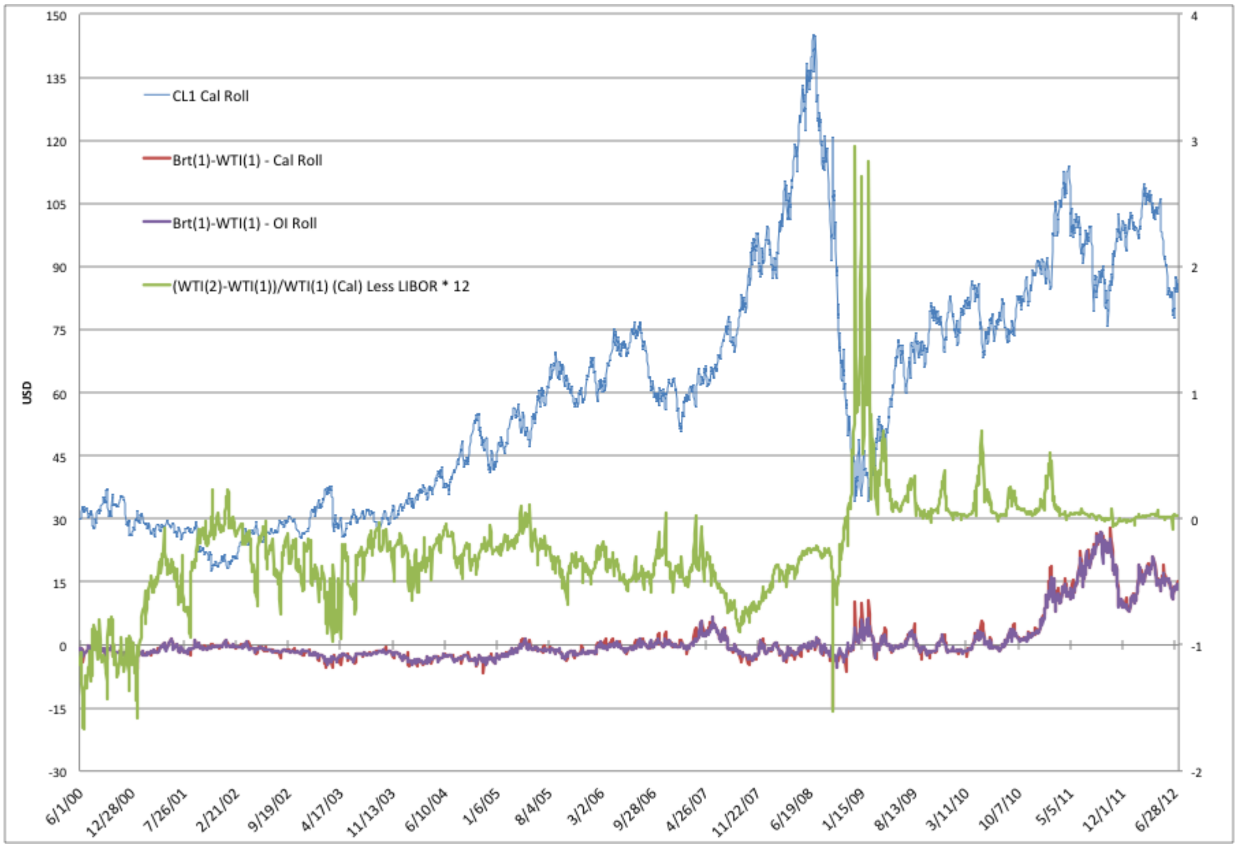
Notes**: Figure 4** is reproduced from Büyükşahin *et al* (2013). It plots the production of crude oil in the North Sea (thousands of barrels per day). Monthly data from January 2000 to May 2012 are from the International Energy Agency (IEA). The output of the four crude oil streams that make up the Brent crude benchmark (Brent Blend, Forties Blend, Oseberg and Ekofisk or "BFOE" is plotted in orange.

Figure 5: Operational Oil Rigs & Canadian Oil Imports, 2000-2013



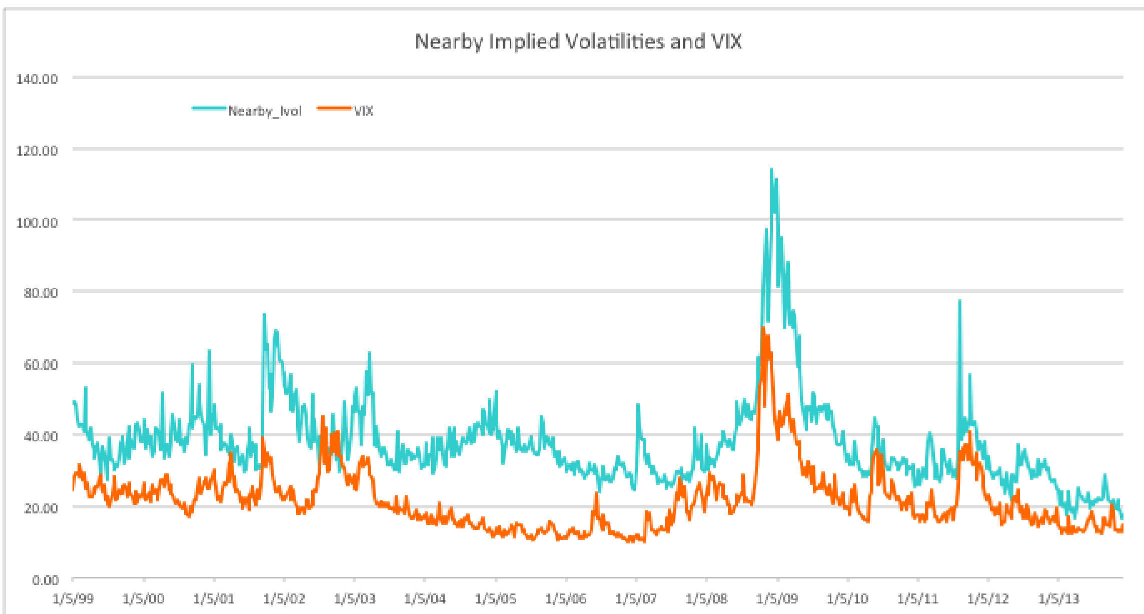
Notes: **Figure 5** plots (in **red** on the left-hand axis) imports into PADD 2 of Canadian crude oil (in thousands of barrels) and (in **blue** on the right-hand axis) the number of operational crude oil rotary rigs in the 50 United States and the District of Columbia. Data on operating crude oil rigs come from the U.S. Energy Information Administration (EIA), which sources it from Baker Hughes, Inc. and Weatherford International, Ltd. Specifically, the series provides a number of operational crude oil rotary rigs, which are used to drill wells, both onshore and offshore throughout the fifty states of the U.S. The data are reported monthly as the average of values from a four- or five-week reporting period. Data on crude oil imports (in thousands of barrels) into the Midwestern PADD 2 also come from the EIA.

Figure 6: WTI Price, Inverted WTI-Brent Spread and Calendar Spread Yield



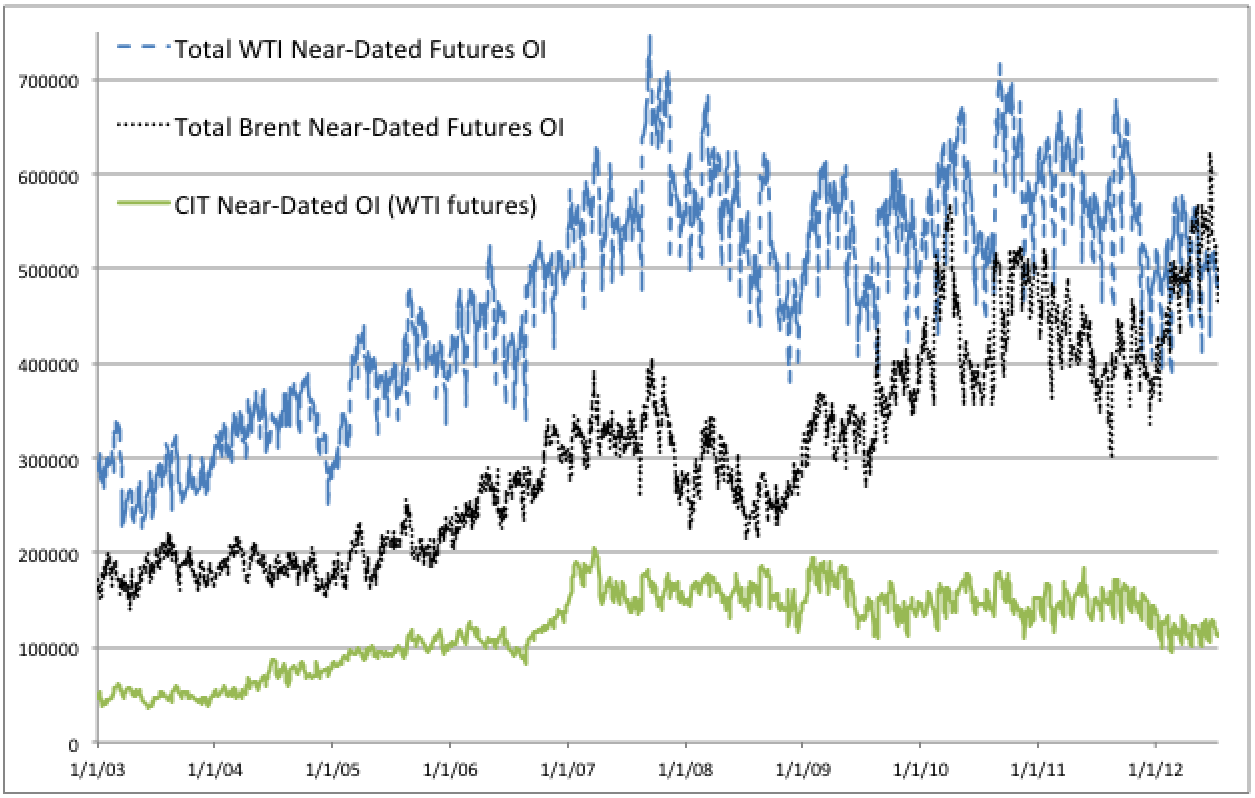
Notes: Figure 6 plots the West Texas Intermediate nearby contract price, using a calendar roll date based on the prompt contract expiration day (in blue). Figure 6 also plots the difference between Brent and WTI using two different methods to roll: the calendar roll in red highlights the increase in volatility at expiration of the prompt contract; the open-interest based roll (in purple) show a similar trend but less daily volatility. Finally, Figure 6 plots the calendar spread yield (in green) calculated as the annualized percentage difference between the prompt and first-deferred WTI contract net of LIBOR. The green curve shows a structural break in levels and volatility after November 2008. All prices are in USD.

Figure 7: Equity-Market *vs*. Oil-Market Volatilities, 2000-2013



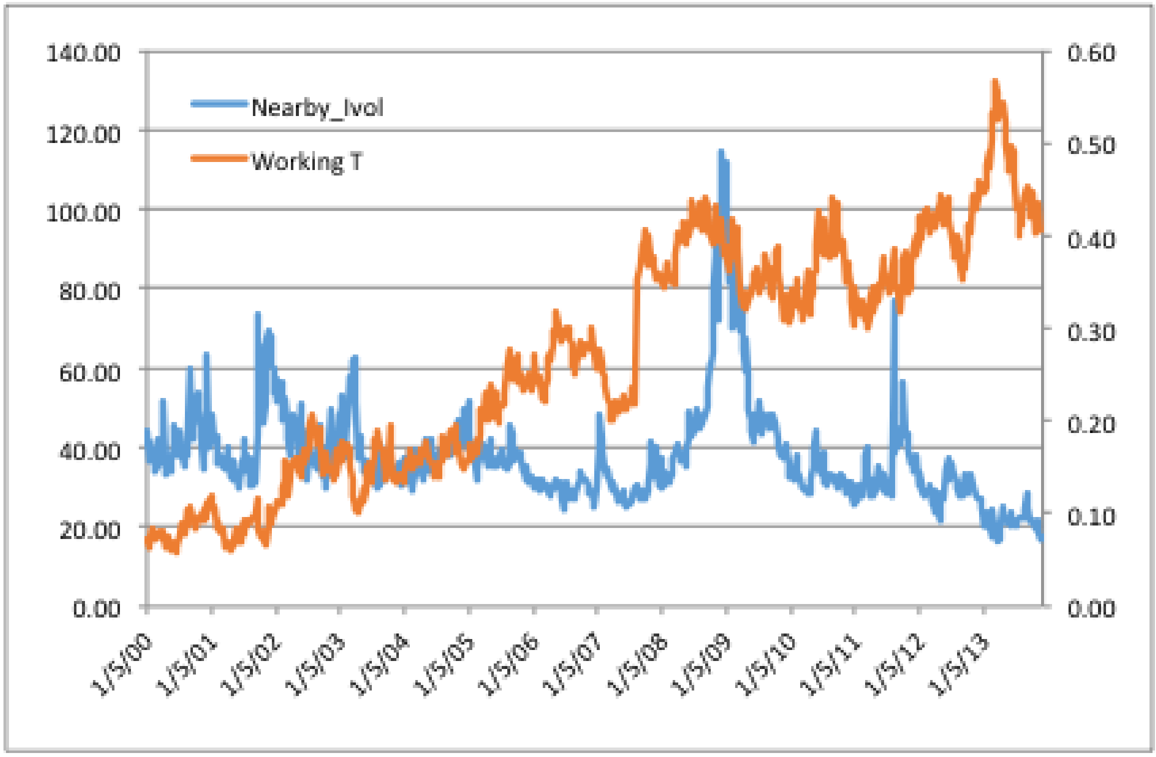
Notes: Figure 7 plots the percentage price volatilities implied by nearby equity (VIX) and crude oil at-the-money call option prices between 1999 and 2013 (Source: Bloomberg). Both time series show concomitant large increases in 2001 (after the 9-11 attacks on New York City's World Trade Center), in the second half of 2008 and the first quarter of 2009 and again in late Summer 2011 (following a credit-rating downgrade of the U.S. sovereign debt).

Figure 8: WTI and Brent Near-Dated Open Interest
(First three Calendar Months)



Notes: **Figure 8** is reproduced from Büyükşahin *et al* (2013). It plots the overall futures open interests for the NYMEX WTI (top curve, in **blue**) and ICE Brent (dotted middle **black curve**) crude oil markets for the three nearest-dated futures. The bottom curve plots the *aggregate* "open interest" (in **green**), across the same three contracts, of all large futures traders classified by the U.S. CFTC as Commodity Index Traders (CITs). Precisely, WTI futures-only positions are aggregated across those traders and across the three nearest-dated WTI futures contract maturities. The "open interest" is the average of the absolute values of those traders' long and short positions. Source: Bloomberg (Brent) and CFTC (WTI, CIT), January 2003 to July 2012.

Figure 9: Speculative Intensity and Implied Volatility – WTI Futures, 2000-2013



***Notes*: Figure 9** plots, from January 2000 through May 2013, indices of speculative intensity (Working's "*T*" *minus* 1) in WTI futures markets (orange line) against the implied volatility of WTI nearby crude oil prices (blue line). We use data on trader positions published by the U.S. Commodity Futures Trading Commission (CFTC Commitments of Traders Reports) to compute weekly index values of "*T*".