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Dynamics of Arbitrage

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Abstract

We study the dynamics of cash-and-carry arbitrage using the U.S. crude oil market. Sizable arbitrage-related inventory movements occur at the New York Mercantile Exchange (NYMEX) futures contract delivery point but not at other storage locations, where instead, operational factors explain most inventory changes. We add to the theory-of-storage literature by introducing two new features. First, due to arbitrageurs contracting ahead, inventories respond to not only contemporaneous but also lagged futures spreads. Second, storage-capacity limits can impede cash-and-carry arbitrage, leading to the persistence of unexploited arbitrage opportunities. Our findings suggest that arbitrage-induced inventory movements are, on average, price stabilizing.

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I. Introduction

Cash-and-carry (C&C) arbitrage plays a crucial role in the futures and spot markets for storable commodities. Indeed, as shown by Jarrow and Larsson (2012), an important implication of C&C arbitrage is that the absence of arbitrage implies informational market efficiency. At the same time, there is an intimate link between C&C arbitrage and the theory of storage, as articulated by Kaldor (1939), Working (1949), Brennan (1958), Telser (1958), and many others. The size of the spread between futures and spot prices, accounting for the convenience yield, acts as a trigger for arbitrage trades. Theory tells us that rational arbitrageurs will exploit distortions between spot and futures prices by going short or long in futures contracts while simultaneously buying or selling the product, which translates into the product moving into or out of storage (Pirrong (2012)). Although this hypothesis is well defined in theory, little empirical work exists confirming or disconfirming this prediction. We fill this gap in the literature by examining oil inventory changes in response to situations in which oil futures prices signal the existence of an arbitrage opportunity. Our choice of the crude-oil market is based on two criteria: the availability of inventory information and the availability of futures prices for highly liquid, actively traded contracts.

We present several important and new results contributing to the understanding of the theory of storage as well as the dynamic relation between the futures and spot markets for oil. First, we empirically confirm the theoretically implied C&C arbitrage relation. Specifically, we document that inventory changes are a positive function of changes in futures–spot spreads and that C&C arbitrage occurs in crude-oil markets when arbitrage opportunities arise. Therefore, we show that changes in futures prices (which could be influenced by fundamentals or financial trading that is independent of fundamentals, as in Singleton (2014)), are transmitted to spot prices through C&C arbitrage.

Second, we provide important new empirical evidence that adds to the theory-of-storage literature by showing that inventory adjusts with a lag, consistent with arbitrageurs contracting ahead to exploit distortions between futures prices at different maturities. We further show that such inventory adjustments are concentrated at Cushing, Oklahoma, the delivery point for the NYMEX crude-oil contract. Importantly, changes in crude-oil inventories away from Cushing are mostly explained by operational variables, such as refinery inputs, imports, and production, whereas changes in Cushing inventories are primarily explained by changes in futures spreads. This suggests that the inventory changes we document are, indeed, due to C&C arbitrage.[1] We further find that the execution of arbitrage trades is sometimes constrained as storage levels at Cushing approach capacity limits, implying that in these times, the arbitrage mechanism tying spot to futures prices cannot operate.

Third, we show that arbitrage-induced inventory movements are, on average, price stabilizing; that is, arbitrage resulting from opportunities provided by the futures–spot spread moderates oil price swings. For example, in weeks where the

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[1] The U.S. Energy Information Administration (EIA) reports that as of Sept. 30, 2014, 80% of the storage capacity at Cushing, Oklahoma, was leased to parties other than operating companies. Considerable anecdotal evidence indicates that C&C arbitrage is common; several investment banks and trading companies reportedly rent oil storage space at Cushing, Oklahoma, for trading and arbitrage (Davis (2007)). Various reports suggest that additional storage capacity was added at Cushing to support arbitrage activities.

futures–spot spread is likely high enough to trigger arbitrage, the subsequent change in the spot price is significantly more likely to match the sign of the futures–spot spread than to move in the direction opposite to the sign of the spread. We further find evidence that, on average, arbitrage leads to oil moving into inventory when prices are relatively low and being released from inventory when prices are relatively high. These findings add to the literature examining the influence of various traders on commodity market volatility.[2]

Although the extant theory of storage predicts a contemporaneous relationship between inventories and spreads, our results show that a lagged relation is also present that we hypothesize is due to arbitrageurs contracting ahead to exploit distortions across the term structure of futures prices. Specifically, we document that changes in crude-oil inventories are correlated with changes in both current and *past* futures price spreads. Profit-driven arbitrageurs should exploit all available opportunities, including distortions in spreads between proximate- and distant-month futures prices. For example, suppose that in January, the spread between the February (*spot* at that time) and March *futures* contracts exceeds carrying costs.[3] In this situation, arbitrageurs can make a riskless profit by contracting in January to i) buy oil in February, ii) store the oil, and iii) sell in March, causing inventories to rise in February and fall back to nonarbitrage levels in March. Next, suppose that in January, the spread between the April and May *futures* contracts exceeds carrying costs. In this situation, arbitrageurs can make a riskless profit by contracting in January to i) buy oil in April, ii) contract for storage in April, and iii) make delivery in May, causing inventories to increase in April and fall in May. Therefore, because arbitrageurs contract ahead, inventories in any given month could be a function of *past futures–futures* spreads (as in the May–April spread example) as well as of current and recent *futures–spot* spreads (as in the March–February spread example).

We control for various factors that may influence inventory changes in our analysis but acknowledge that there could be reverse causation between inventory levels and oil price spreads. Several points are worth noting in this regard. First, to the extent that inventory levels affect prices, the effect should be greatest on current prices. Current inventories should not affect past prices. Second, reverse causation implies a negative relation between inventories and price spreads, whereas arbitrage predicts a positive relation, which is what we find. According to the theory of storage, when inventories are low, the risk of stock-outs pushes risk-averse investors to demand higher risk premiums. Confirming this, Gorton, Hayashi, and Rouwenhorst (2013) show that current inventories are negatively related to future price spreads. Thus, to the extent that some endogeneity remains after our controls,

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[2] See, for example, Bryant, Bessler, and Haigh (2006), Gilbert (2010), Büyükşahin and Harris (2011), Sanders and Irwin (2011), Irwin and Sanders (2012), Hamilton and Wu (2015), and Brunetti, Büyükşahin, and Harris (2016). Although the majority of this literature uses Granger causality tests to examine the relation between trader positions and prices, we explore whether *arbitrage-induced* inventory movements in response to futures spreads tend to exacerbate or moderate crude-oil price volatility.

[3] Contracts for immediate delivery in the crude-oil market are quite rare. Virtually all contracts are for delivery over a future month(s). What is normally reported as a spot price (on Bloomberg or by the Energy Information Administration (EIA)) is the forward market price for delivery over the next month. For simplicity and because our price data are futures contract prices, we henceforth use the term *futures*, but the model holds for forward contracts as well.

our results likely tend to understate the impact of futures price spreads on inventories.[4]

Finally, we examine physical limits, specifically situations when crude-oil storage tanks in Cushing, Oklahoma, approach their operating capacity. Several recent studies explore possible financial limits to the arbitrage that enforces the law of one price and these limits' implications for asset pricing.[5] Physical limits, specifically limits on the availability of storage capacity, are potentially as important as financial limits in the arbitrage pricing relationship for financial assets whose value is derived from the value of commodities. Although the possibility of stock-outs is considered in the recent theory-of-storage literature, the possibility of storage reaching capacity limits has been largely ignored, to our knowledge.[6] Our data allow us to address this gap in the literature by studying the effects of physical storage limits on commodity market arbitrage. We find evidence that arbitrage is constrained when available storage capacity is limited, implying that the usual mechanism tying spot prices to futures prices cannot operate. These capacity constraints are binding because Cushing storage operators inform us that it takes approximately 18 months to build additional storage in Cushing, Oklahoma. We find mixed evidence that crude-oil arbitrage activity is inhibited by financial constraints.

To summarize, we find that via C&C arbitrage, crude-oil inventories, and therefore physical supply and demand, vary substantially in response to changes in contemporaneous and *past* futures price spreads.[7] These arbitrage-related movements in crude-oil inventory occur primarily at Cushing, Oklahoma, the NYMEX futures delivery point, whereas inventories at other U.S. storage locations are explained principally by operational factors. We further find that this arbitrage mechanism is sometimes constrained by storage limitations. Our study is relevant to the vast literature on the theory of storage, the literature on limits to arbitrage, and the public policy debate regarding the financialization of commodity markets as it pertains to the mechanism through which temporary distortions in futures prices can affect spot prices. Although speculative trading can normally increase oil prices above levels consistent with market fundamentals only if accompanied by significant inventory changes (Smith (2009)) or in the presence of informational frictions

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[4] The financial reports of firms that own or rent oil storage, including SemGroup, Plains All American, BP, and NGL Energy Partners, state that these firms build up storage in response to favorable spread conditions. For example, in its 2015 second-quarter 10Q filing, Plains All American Pipeline mentions that during the 6 months ended June 30, 2015, it increased the volume of crude-oil inventory, "primarily as a result of storing such inventory due to contango market conditions."

[5] See, for example, Shleifer and Vishny (1997), Gromb and Vayanos (2002), Mitchell, Pulvino, and Stafford (2002), Gabaix, Krishnamurthy, and Vigneron (2007), Etula (2013), Acharya, Lochstoer, and Ramadorai (2013), and Cheng, Kirilenko, and Xiong (2015).

[6] Exceptions include Kogan, Livdan, and Yaron (2009), Reeve and Vigfusson (2011), and Knittel and Pindyck (2016). Additionally, the failure of maturing grain futures prices to converge to spot prices has been attributed to artificially low storage rates set by the futures exchange during periods of high storage demand (Irwin (2020)).

[7] Although we do not examine long-run effects, they have been examined by Chen and Linn (2017) and Goldstein and Yang (2016). Chen and Linn show drilling activity to be more affected by futures price changes than cash price changes. Goldstein and Yang find that in the long run, wheat producers grow, and therefore supply, more wheat in response to higher futures prices.

and heterogeneous expectations (Singleton (2014)), our finding of inventory changes due to past spreads provides an alternative explanation for the evidence provided by Singleton of oil price changes occurring without significant inventory changes.

II. Background and Literature

The literature on the financialization of commodity markets suggests that changes in futures prices can be driven by noise traders whose activities are divorced from fundamentals[8] or by changes in trader beliefs about fundamental supply-and-demand conditions.[9] Distortions of the C&C relation caused by futures price changes, irrespective of the cause, can potentially influence spot prices. We do not examine whether and why the futures spread becomes distorted, a debate that has been dealt with extensively in the financialization literature. Rather, our primary focus is on the implications of such spread distortions for inventories. As such, we address an unresolved issue lying at the heart of the debate over whether financialization affects spot prices, by focusing on the channel through which futures trading affects spot prices. Specifically, we test whether the influence of the financial futures market on physical spot prices can be traced through inventories via C&C arbitrage. Smith ((2009), p.159) argues, "The only avenue by which speculative trading might raise spot prices is if it incites participants in the physical market to hold oil off the market—either by amassing large inventories or by shutting in production." But Singleton (2014) and Sockin and Xiong (2015) suggest that it is possible for financial speculators and index fund investors to move prices without influencing inventories if informational frictions and heterogeneous expectations are present.

Some studies show that the positions of various traders (speculators, index funds, hedge funds, etc.) are correlated with spot crude-oil prices, whereas in others, no such correlation exists (Sanders and Irwin (2010), (2011), Irwin and Sanders (2012), Tang and Xiong (2012), Singleton (2014), Hamilton and Wu (2015), and Brunetti et al. (2016)). However, the finding that the positions of various traders do not lead prices establishes that particular trading groups are not able to anticipate future price changes and trade ahead of them. Their trading could still affect prices because the impact of trades on prices should occur at the time of the trade and not later. Indeed, although they find no evidence that hedge fund positions lead prices,

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[8] For example, Masters (2008), Einloth (2009), Kaufmann and Ullman (2009), Sornette, Woodard, and Zhou (2009), Parsons (2010), Tang and Xiong (2012), Büyükşahin and Robe (2014), Singleton (2014), Henderson, Pearson, and Wang (2015), Baker (2020), Basak and Pavlova (2016), and Sockin and Xiong (2015). Yet, Manera, Nicolini, and Vignati (2016) test whether speculation affects energy futures price volatility in generalized autoregressive conditional heteroscedasticity (GARCH)-type models and shows that higher speculation is, in fact, associated with lower volatility.

[9] For example, Interagency Task Force on Commodity Markets (2008), Gilbert (2010), International Energy Agency (2008), Büyükşahin and Harris (2011), Hamilton (2009), Kilian (2009), Stoll and Whaley (2010), Sanders and Irwin (2010), (2011), Irwin and Sanders (2012), Kilian and Hicks (2013), Fattouh, Kilian, and Mahadeva (2013), Kilian and Murphy (2014), and Hamilton and Wu (2014), (2015).

Büyükşahin and Harris (2011) and Brunetti et al. (2016) report significant positive correlations between changes in hedge fund positions and same-day changes in futures prices, which would be consistent with hedge fund and swap dealer trading affecting futures prices. However, it could also be the case that these traders are reacting to changes in futures prices. The studies examining the connection between trader positions and prices, although providing important insights, do not directly explore the mechanism through which activity in the futures market is transmitted to spot prices. This unresolved question is the primary focus of our study.

Related to our study, Singleton (2014) calculates simple correlations between the futures–spot spread and inventories. Kilian and Murphy (2014) and Kilian and Lee (2014) develop and estimate structural vector autoregressive models that include measures of crude-oil prices and production, economic activity, and inventories. The authors examine monthly data and conclude that at long horizons, global spot prices, futures prices, and inventories are jointly determined. Our emphasis is on the short horizon and the mechanism through which changes in futures prices (likely due to anticipated future events) affect current supply and demand and hence spot prices. Kogan et al. (2009) highlight the difference between long- and short-run effects of inventory and price dynamics. Overall, no study, to our knowledge, uses a setting similar to ours and controls for factors that affect inventories in the short term, especially supply-and-demand shocks (specifically production, exports, and refinery demand), examines Cushing separately, and tests for the impact of past futures–futures spreads.

III. Cash-and-Carry Arbitrage

A. The Basic Theory of Storage

In the classical theory of storage (Kaldor (1939), Working (1949), Brennan (1958), and Telser (1958)), oil inventories are connected to the futures–spot spreads through C&C arbitrage. In equilibrium,

$$F_{t,t+s} = S_t\, e^{(r+\mathrm{sc}-c)s}, \tag{1}$$

where $F_{t,t+s}$ is the time $t+s$ futures price at time t, S_t is the time t spot price, r is the continuous interest rate per unit time, c is the continuous convenience yield per unit time, and sc is the continuous storage cost rate per unit time. The cost of carry of the oil inventory, $e^{(r+sc-c)}$, increases with r and sc but is reduced by the convenience of holding physical stocks, measured by c.

If

$$F_{t,t+s} > S_t\, e^{(r+\mathrm{sc}-c)s}, \tag{2}$$

arbitrageurs can earn a riskless profit by engaging in C&C arbitrage, that is, buying oil in the spot market for S_t, simultaneously shorting the futures contract at price $F_{t,t+s}$, and storing the oil at a unit-carrying cost of $\mathrm{SC}_{t,t+s} = (e^{(r+sc-c)s} - 1)$. At time $t+s$, they will deliver on the futures contract, collecting $F_{t,t+s}$ and realizing a profit of $F_{t,t+s} - S_t\, e^{(r+sc-c)s}$.

Hence, if the futures price is bid up by speculators and flows into commodity index funds or similar price pressure to a level above $S_t\, e^{(r+sc-c)s}$, arbitrage will be set off in which oil is pulled off the market and placed in inventory at time t, thus tending to increase S_t, and oil comes back on the market at time $t+s$, tending to reduce S_{t+s}. Consistent with this logic, if spot prices rise in the future, as the future–spot spread predicted, oil is reallocated from a time of relative plenty to a time of relative scarcity, and the arbitrage tends to moderate price volatility. However, if the expected future shortage does not materialize, the C&C arbitrage-induced inventory changes may exacerbate price volatility.

Opportunities for profitable arbitrage can also arise through reverse C&C arbitrage if

$$F_{t,t+s} < S_t\, e^{(r+\mathrm{sc}-c)s}. \tag{3}$$

Arbitrageurs who currently have oil in storage can earn a riskless profit by selling oil in the spot market for S_t, simultaneously going long in the futures contract at price $F_{t,t+s}$ and investing the proceeds from selling the oil at the interest rate of r. In doing so, the arbitrageur would avoid the cost of storage but forego the convenience yield of holding physical inventory. Consequently, the arbitrageur would realize a unit net return of $\mathrm{SSC}_{t,t+s} = (e^{(r+sc-c)s} - 1)$ from short-selling the oil. At time $t+s$, the arbitrageur will replenish the inventory by receiving delivery on the forward contract and paying $F_{t,t+s}$, realizing a profit of $S_t\, e^{(r+sc-c)s} - F_{t,t+s}$. Again, these arbitrage-induced inventory movements may stabilize oil prices because oil would be moved from inventory to the market at time t, thus lowering S_t, and returned to storage at time $t+s$, thus increasing S_{t+s}.

B. The Forward Curve

From the theory of storage, in equilibrium:

$$F_{t,t+s} = S_t\, e^{(r+\mathrm{sc}-c)s} \tag{4}$$

and

$$F_{t,t+v} = S_t\, e^{(r+\mathrm{sc}-c)v}, \tag{5}$$

where $F_{t,t+s}$ is the time t futures price for delivery at time $t+s$, and $F_{t,t+v}$ is the time t futures price for delivery at time $t+v$, where $s > v$. Equations (4) and (5) yield the relationship between futures prices of different maturities:

$$F_{t,t+s} = F_{t,t+v}\, e^{(r+\mathrm{sc}-c)(s-v)}. \tag{6}$$

The violation of the relationship in equation (6) will also give rise to arbitrage opportunities. For example, if $F_{t,t+s} > F_{t,t+v}\, e^{(r+sc-c)(s-v)}$, arbitrage will take place in which arbitrageurs will sell the time $t+s$ futures contract at time t, go long in the time $t+v$ futures contract, take physical delivery at time $t+v$, and store the oil until time $t+s$. Likewise, if $F_{t,t+s} < F_{t,t+v}\, e^{(r+sc-c)(s-v)}$, arbitrage will take place in which arbitrageurs will sell the time $t+v$ futures contract, go long the time $t+s$ futures contract, sell oil from inventory at time $t+v$ to fulfill the short position in the time

$t+v$ futures contract, and replenish their inventory by taking physical delivery at time $t+s$ when the time $t+s$ futures contract matures.

Therefore, inventory levels could be related to past spreads between longer-term and shorter-term futures if arbitrage opportunities presented themselves in the past. For instance, suppose that in January, the price of the April futures contract exceeds the price of the March futures contract by more than the net cost of storage between March and April. In this case, arbitrageurs could lock in a riskless profit in January by buying the March contract, shorting the April contact, and arranging future storage from March to April. In March, they could take delivery on the March contract, store the oil, and make delivery on the April contract. In this case, we would observe an increase in oil inventories in March and a fall in April in response to the April–March futures–futures spread observed back in January.[10]

Note that the ability to arbitrage price differences between futures contracts of different maturities implies that the inventory level at any given point in time t can potentially be a function of numerous past spreads between longer- and shorter-dated futures prices, where the longer-dated futures contract maturities are after time t, and the shorter-dated futures contracts matured prior to time t. Specifically, inventories at time t could be a positive function of all $F_{t-s,t+u} - F_{t-s,t-w}$ for $s \geq 0$, $u \geq 1$, $w \geq 0$, and $s \geq w$.

C. Optionality Associated with Arbitrage Trades

The discussion in the prior two subsections assumes that arbitrageurs will hold their arbitrage trades to maturity. However, if prices move in their favor, arbitrageurs may choose to close out their trades prior to maturity (Brennan and Schwartz (1990)). For example, consider a trader who places a C&C arbitrage trade at time t by purchasing oil at the current spot price S_t, storing the oil at a unit cost of $\mathrm{SC}_{t,t+s} = (e^{(r+sc-c)s} - 1)$, and selling the time $t+s$ futures contract at price $F_{t,t+s}$ to lock in a riskless profit of $F_{t,t+s} - S_t e^{(r+sc-c)s} > 0$. If the spread narrows prior to time $t+s$ due to a drop in the futures price, an increase in the spot price, or both, the trader might choose to exercise the option to close out the trade early.

Kondor (2009) shows that arbitrageurs who experience capital constraints may also be forced to close out trades early even if spreads widen because wider spreads cause mark-to-market losses and could create the need to liquidate positions. Additionally, as Kondor (2009) also notes, capital-constrained arbitrageurs may not enter a trade when the opportunity first presents itself if there is a possibility that the opportunity might become more attractive later. A similar argument would apply if storage capacity is limited: Using up the capacity now forecloses the possibility of using it later. In both cases, entering the trade now creates a potential opportunity cost of foregoing a more profitable trade in the future.

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[10] In practice, the arbitrageur will first need to ensure that the infrastructure necessary to complete the trade is available before the trade is executed, especially if the arbitrageur does not already own storage capacity. Generally, storage leases are bilaterally negotiated between storage owners or market participants with contracted storage leases and physical traders. Storage can be leased for periods extending from 1 month to several years. As such, storage leases can start at future dates.

D. Convenience Yields and Storage Costs

As noted in Section III.A, the cost of carry of C&C arbitrage trades is partially offset by any convenience yield of having oil in storage, which Brennan and Schwartz (1985) define as the value of the flow of services that accrues to an owner of the physical commodity but not to an owner of a contract for future delivery of the commodity. Traditionally, the convenience yield in the oil market has been viewed as the benefit derived by the owner of physical oil inventory from avoiding the risk of a stock-out. For example, if a refiner reduces its inventory and actual future crude oil deliveries are less than expected, then the refinery may have to reduce production or shut down. Likewise, by carrying insufficient inventory, the refinery loses the opportunity to respond to unexpected increases in demand. For a crude-oil arbitrageur, holding spot oil allows the arbitrageur to potentially take advantage of profitable future C&C arbitrage opportunities in the future if the futures–spot spreads widen.

C&C arbitrage opportunities typically arise when oil is plentiful and spot prices are depressed, that is, when the risk of a stock-out is very low, and consequently, the convenience yield from holding physical oil inventories is small (Routledge, Seppi, and Spatt (2000)). Conversely, reverse C&C opportunities tend to arise when spot prices are elevated relative to forward prices, that is, when the market is in backwardation. Such situations often occur when physical oil inventories are depleted and the convenience yield is high.

Storage costs also likely vary by trader. For example, consider two traders: one who leases temporary storage today as needed to execute a specific C&C trade and another who has leased storage capacity for a year at $0.40 a barrel/month. Whereas the full storage costs should be considered by the first trader in the profitability analysis of a trade, what matters for the second trader is the marginal opportunity cost because the $0.40 is a sunk cost. Depending on whether it is possible to sublease the storage capacity, this marginal opportunity cost may vary from 0 to the sublease rate or even higher if the excess storage capacity provides the trader the option to undertake future trades during the term of the lease.

Storage costs also depend on capacity utilization. If there is plentiful unused storage capacity, storage costs will likely be low, and the opportunity cost of using up existing capacity will be negligible. Conversely, if there is little or no unused storage, the storage costs and opportunity costs of using up existing capacity will be high. Because storage levels are high when forward–spot spreads are high, this implies a positive relation between spreads and storage costs.

E. Effect of Storage-Capacity Limits

The availability of inventory (for purposes of a reverse C&C arbitrage transaction) is the usual friction considered in models of commodity spot and futures price determination (Deaton and Laroque (1992) and Routledge et al. (2000)). In particular, reverse C&C arbitrage cannot occur in a stock-out condition where there is no inventory that is available to sell (or short-sell) for arbitrage purposes. However, a friction that is seldom considered is that of storage-capacity limitations, which can also inhibit attainment of the no-arbitrage futures–spot and futures–

futures relations (Pirrong (2012)).[11] Specifically, if storage capacity is unavailable or cannot be contracted for, an arbitrage transaction in which oil is purchased on the spot market and stored cannot be accomplished, and any spread that would otherwise reflect an arbitrage opportunity will not be immediately corrected.

IV. Data and Methodology

A. Crude-Oil Storage

Oil inventory data are collected from the U.S. EIA website. Each Wednesday, the EIA releases figures on crude storage in the United States as of the previous Friday. The inventory data released by the EIA are further broken down by region or Petroleum Administration for Defense District (PADD). We examine inventories at i) Cushing, Oklahoma; ii) U.S. crude-oil inventories excluding the Strategic Petroleum Reserve (SPR) and excluding Cushing; iii) PADD2 (the Midwest district that includes Cushing), and iv) the other four PADDs (East Coast, Gulf Coast, Rocky Mountain, and West Coast).[12] Our main sample is from Apr. 9, 2004 (when the EIA began separately reporting storage levels at Cushing, Oklahoma, the delivery point for the NYMEX West Texas Intermediate (WTI) crude-oil futures contract), to Dec. 29, 2017. Because inventory data are reported weekly, we conduct our analysis using a weekly frequency.

Although it is possible to conduct C&C arbitrage based on forward and spot contracts calling for delivery at a location other than Cushing or for delivery of an oil grade other than WTI, arbitrage based on the WTI futures contract for delivery at Cushing offers lower cost and/or risk. If an arbitrageur is conducting arbitrage based on the WTI futures contract, storage away from Cushing either entails transportation cost to get the oil to or from Cushing or the arbitrageur has to bear the basis risk that the price at which the arbitrageur sells or buys oil at the conclusion of the arbitrage may not equal the Cushing price. Likewise, if the arbitrageur is trading and storing non-WTI-grade oil, the arbitrageur must either bear the risk that the differential between the WTI and non-WTI grades may vary or substitute a less liquid non-WTI forward contract for the futures contract.

B. The WTI Futures Contract and Futures–Spot and Futures–Futures Spreads

We collect futures prices from the EIA website. To be consistent with weekly inventory numbers that disclose Friday oil storage, we use weekly prices, specifically Friday's settlement price for the NYMEX WTI contract, from Apr. 9, 2004 to Dec. 29, 2017. Prices are quoted in U.S. dollars per barrel, and each contract is for

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[11] Kogan et al. (2009) present an equilibrium model of oil production and add finite storage capacity. They suggest that adding capacity constraints would likely affect the short end of the price curve and show that the volatility of spot prices is related to the level of inventories. Also, Reeve and Vigfusson (2011) and Knittel and Pindyck (2016) consider capacity limits theoretically.

[12] In addition to the aboveground storage figures compiled by the EIA, crude oil can be stored in oil tankers at sea; however, to our knowledge, no historical tanker inventory data exist for a period sufficient for analysis, so our analysis is restricted to the EIA data.

1,000 barrels. Prices for other grades of crude oil and for delivery at other locations are normally quoted as a premium or discount to this price.

A relevant characteristic of the crude-oil market is that it is almost exclusively a forward market. Physical crude-oil trading normally requires movement by pipeline (or rail), and pipeline transportation contracts are typically for delivery over a monthly period.[13] Thus, like the WTI futures contract, forward contracts commonly call for delivery over a calendar month, and the prices referred to as "spot prices" are generally forward prices for delivery in the next month. Because the price of the nearby futures contract represents the Cushing price for delivery of WTI-grade crude over the coming month, it is commonly used as a measure of the spot price because it is highly liquid and readily observable.[14] Following this convention, we measure the futures–spot spread as the difference between longer-term futures contracts and the nearby futures contract. Specifically, we use the second-month–nearby spread as our measure of the futures–spot spread. We justify this choice based on the empirical observation that the measured spreads at successively longer futures maturity dates tend to be highly correlated. For instance, over the longer 1982–2017 period, the correlation between the second-month–nearby spread and the third-month–nearby spread is 98%, and the correlation between their weekly changes is 95%.

In Section III.B, we show that past spreads can influence current inventory changes if arbitrage opportunities present themselves between two or more futures contracts with different expirations. For example, if in January, the futures price for delivery in April sufficiently exceeds the futures price for delivery in March, arbitrageurs should contract ahead to take delivery in March, store, and sell in April, so the inventory changes in March and April reflect the futures–futures spread observed in January. Moreover, as we discuss in Section III.C, such a spread arbitrage transaction might be unwound prior to March if it becomes profitable to do so. Consequently, inventory changes in March and April could potentially depend on the entire past history of futures–futures and futures–spot spreads.

To relate current inventories to all past spreads that are theoretically relevant leads to an unworkably large set of highly correlated independent variables and likely an underidentified model. To make the estimation tractable, our approach is to use a single futures–futures spread as a proxy for all potentially relevant spreads at that time. Specifically, we use the spread between the third-month contract and the second-month contract as our measure of the futures–futures spread. For example, for the futures–futures spread observed in January, we use the January price of the April contract minus the January price of the March contract. As with the futures–spot spread, this variable should be viewed as a proxy for numerous futures–futures spreads.

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[13] This is not the case if both traders have storage tanks at the same location (i.e., Cushing Oklahoma), but prices for such intra-location transfers are not readily observable.

[14] The "spot" price quote found on Bloomberg and some other sources sometimes differs from the price of the nearby futures contract as reported by NYMEX. It is our understanding that this is primarily because i) it is a forward rather than a futures contract; ii) they are quoting the forward price at noon Eastern time, whereas the NYMEX daily price is the settlement price; and iii) the nearby futures contract rolls over on the third business day prior to the 25th calendar day of the month while the forward continues trading.

Because inventory changes are observed weekly and the futures contracts call for delivery over a month, the second-month–nearby spread is expected to affect inventories for approximately 4 weeks, and the third-month–second-month spread is expected to affect inventories for approximately 4 weeks. Because the nearby contract is a forward contract for delivery in the next month, changes in the second-month–nearby spread should not affect inventories until the following month. In other words, if in January, the nearby contract is for February delivery (and the second for March delivery), arbitrage based on these futures contracts should not affect inventories until February. However, because it may be possible to conduct arbitrage based on forward or spot contracts for more immediate delivery, we use the second-month–nearby spread as a proxy for these possible spreads as well. This more immediate period until the second-month–nearby spread directly affects inventories lasts from 0 to 4 weeks for an average of 2 weeks.

Given this reasoning, we relate the current change in inventories to changes in the second-month–nearby spread over the current and most recent 6 weeks and to the third-month–second-month spread over the 4 prior weeks. Our results are only slightly affected if we instead use 4 or 6 prior weeks for either or both spreads.

C. The Main Regression Form

Our main interest is in estimating if and how current and past changes in the futures–spot and futures–futures spreads affect oil inventories. The estimated relationship is as follows:

$$(7)\qquad \Delta\text{STOCK}_\text{t} = \beta_0 + \sum_{j=0}^{5} \beta_j \Delta\text{SP(FUT\_SPOT)}_{t-j} + \sum_{j=6}^{9} \beta_j \Delta\text{SP(FUT\_FUT)}_{t-j} + \sum_{j=10}^{J} \beta_j \Delta Y_{j,t},$$

where ΔSTOCK_t is the change in inventories over week t; $\Delta\text{SP(FUT\_SPOT)}_{t-j}$ is the change in the futures–spot spread, specifically the second-month–nearby spread, over week $t-j$; ΔSP(FUT_FUT) is the change in the futures–futures spread, specifically the third-month–second-month spread, over week $t-j$; and $\Delta Y_{j,t}$ is the change in control variables, such as oil production, refinery inputs, net imports/exports, and controls for a spurious correlation. Note that ΔSTOCK_t could include changes in inventories due to the unwinding of existing positions triggered by changes in the spread.

Note that equation (7) relates changes in oil inventories to changes (ΔSP) in futures–spot and futures–futures spreads, whereas the discussions in Sections III.A and III.B predict that what matters is changes in the spreads *net of changes in carrying costs* (i.e., ΔSP − ΔSC) or, in the case of reverse C&C arbitrage, changes in the spreads net of changes in the returns from selling oil short (ΔSSC). We have been unable to obtain weekly measures of storage costs for our data period, and convenience yields are unobservable. Therefore, only the interest rate component of carrying costs is observable. Moreover, as discussed in Section III.C, storage costs and convenience yields basically represent opportunity costs that vary from trader to trader. Thus, the question arises as to how the failure to include changes in net carrying costs, ΔSC, in the estimation of equation (7) affects the estimation results.

First, we would note that convenience yields become most important when inventory approaches stock-out levels. Over our sample period, Cushing storage levels rarely fall below 40% of capacity. Consequently, convenience yields are likely small over our sample period. Likewise, changes in interest rates over short periods are also negligible.

Second, storage operators at Cushing with whom we communicated inform us that storage costs do not vary much from week to week. The largest Cushing storage operator, Plains All American Pipeline, provided us its proprietary data on maximum and minimum storage costs for each year from 2004 through 2017. The mean difference between the annual maximum and minimum storage costs over the 2004–2017 period is $0.175 per barrel. By way of comparison, the average annual futures–spot spread difference over the same period is $3.22 per barrel, or over 18 times the storage cost difference. Hence, futures–spot spread changes adjusted for carrying costs likely very closely proxy the unadjusted spread changes we use in the paper.

Third, in Appendix A.1 of the Supplementary Material, we show that if fluctuations in ΔSC are independent of ΔSP, the beta coefficients from our estimations are unbiased measures of how oil inventories react to changes in the spreads net of changes in net carrying costs, $\Delta SP - \Delta SC$. Furthermore, if ΔSC is positively correlated with ΔSP, as argued in Section III.D, then the coefficients are negatively biased; that is, they are biased against finding evidence that oil inventory changes are a positive function of spread changes. Thus, the actual relation including carrying costs is likely stronger than what we estimate.

Contemporaneous changes in the spot price and inventories may exhibit a spurious correlation that is independent of adjustments in inventories due to past spreads. For instance, if there is an unforeseen increase in current demand, it would tend to lead to a fall in crude-oil inventories and a simultaneous increase in spot prices, which would mean a decrease in the futures–spot spread. This would result in a positive contemporaneous correlation between changes in the futures–spot spread and inventories that is not due to C&C arbitrage. Likewise, a sudden unforeseen increase in supply would tend to cause a simultaneous increase in crude-oil inventories and the futures–spot spread. Note, however, that this applies only to contemporaneous changes in the spread and inventories, not lagged changes, because current unexpected changes in supply or demand would not affect past prices.

To control for potential contemporaneous correlation of the type just described, we include as independent variables the changes over the current week in i) U.S. levels of crude-oil production, ii) imports (overall net for the U.S. regressions and by PADD for the PADD and Cushing regressions), and iii) refinery inputs (overall and by PADD).[15] To understand how changes in these operational variables affect inventories, consider, for example, the weekly change

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[15] The EIA measures production, imports, and refinery inputs as thousands of barrels per day. Because our dependent variable is the change in crude oil inventories over a week (in thousands of barrels), we convert the EIA daily flow figures to a weekly basis by multiplying by 7.

in refinery inputs. The change from the previous week consists of a planned or expected change plus any unplanned or unexpected change. If refinery demand increases unexpectedly, this would lead to an unexpected decline in crude-oil inventories. Thus, to the extent that part of the change in refinery inputs is unexpected, we expect it to be negatively correlated with the change in crude-oil inventories. Similarly, to the extent that changes in U.S. crude-oil production and imports are unexpected, we expect them to be positively correlated with changes in crude-oil inventories. In addition, we include the contemporaneous change in the spot WTI price as an independent variable. If an unexpected change in demand or supply is viewed as temporary, it will tend to affect the spot price but not the futures price. Thus, the contemporaneous change in the spot WTI price should be negatively related to the change in inventory and pick up additional unforeseen shifts in supply and demand that affect both the spread and crude-oil inventories.

We also expect inventories to be held for operational purposes to buffer anticipated shifts in supply and demand. Suppose an increase in refinery demand for crude is forecast for the coming week. In this case, we would expect storage operators, which could include refiners, to increase oil inventories this week to meet the expected increase in demand next week. Similarly, if an increase in crude-oil production or increased imports are expected next week, less inventory is needed this week to meet next week's anticipated demand. Thus, we expect an anticipated future increase in demand to lead to an inventory increase now and an expected increase in supply to lead to a decrease in current inventories. Although we cannot observe expected changes in refinery inputs, crude-oil imports, and production, we posit that actual changes in these variables vary randomly around expected changes for short forecast horizons. Hence, we use actual future changes in these lead inventory variables as proxies for operator expectations.

Note that the expected signs for these lead variables are opposite to those for the current-week variables described in the prior paragraph. We expect a negative coefficient for the current-week change in refinery inputs and a positive coefficient for the change next week. We expect positive coefficients for current-week changes in imports and production and negative for the changes next week. The rationale for the current-week variables is to pick up the effect of *unexpected* supply-and-demand changes on actual inventories; the rationale for the lead variables is to pick up the effect of *expected* future changes in these variables on desired inventories.

Oil inventories also tend to vary seasonally. We control for seasonality with four seasonal variables, $z2$, $z3$, $z4$, and $z5$, which are polynomial functions of 52 zero–one (0–1) dummy independent variables representing each week of the year. A description of these seasonality variables is provided in Appendix A.2 of the Supplementary Material.

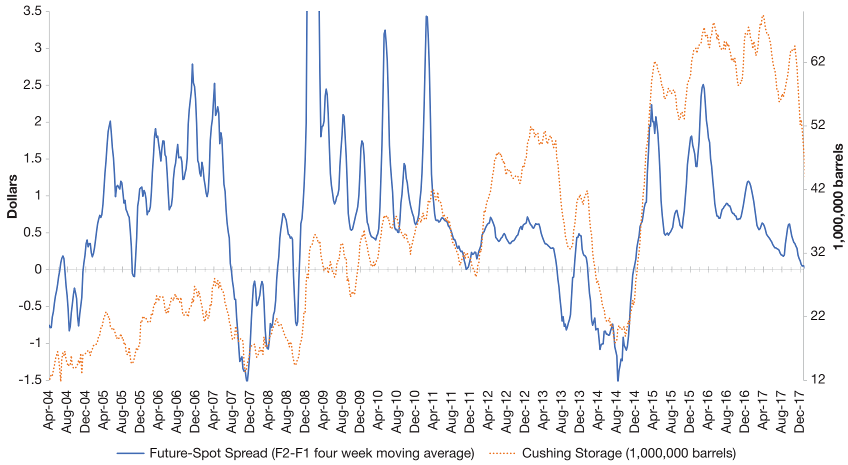
D. Descriptive Statistics

In Figure 1, we graph weekly levels of crude-oil storage (in millions of barrels) at Cushing from Sept. 11, 2004 through Dec. 29, 2017 (on the right axis) and a 4-week moving average of the futures–spot spread (in dollars) (on the left axis). Consistent with C&C arbitrage, the two series appear negatively correlated. In

FIGURE 1

Cushing Crude Inventory and the Spread Between the 2- and 1-Month NYMEX WTI Crude Futures

Figure 1 plots crude-oil inventories at Cushing, Oklahoma, and the spread between the 2- and 1-month New York Mercantile Exchange (NYMEX) West Texas Intermediate (WTI) crude futures, presented as a 4-week moving average, between Apr. 9, 2004 and Dec. 29, 2017.



addition, there is a secular upward trend due to the increase in storage capacity at Cushing that is widely attributed to arbitrage motives.

Figure 1 also shows that the market was in contango more often than in backwardation over our sample period. A closer look at the data reveals that the market was in contango 81.6% of the time over our sample period of 2004–2017. In contrast, the market was in contango only 44% of the time over the 1992–2004 period. Statistics for the weekly storage, spread, and other operational variables (refinery inputs, imports, production) are reported in Table 1 for both levels and weekly changes. The average (median) futures–spot spread of \$0.56 (\$0.47) reflects the predominance of contango over our sample period. Table 1 shows that the average change in Cushing storage is 52,000 barrels, whereas the average absolute change is 798,000 barrels.

V. Crude-Oil Inventories and Spreads

A. Regression Results: Spread Variables

Estimations for equation (7) are reported in Table 2 for weekly changes in crude-oil stocks (in thousands of barrels) for storage at Cushing, Oklahoma, in column 1; the United States (excluding Cushing and the SPR) in column 2; and PADD2 (excluding Cushing) in column 3. Standard errors are estimated using the Newey–West procedure to correct for heteroscedasticity and autocorrelation.

There is strong evidence that futures spreads affect crude-oil stocks, and thus the actual physical supply of crude oil, but that the relation is concentrated at the futures contract delivery point: Cushing, Oklahoma. For Cushing, coefficients are

TABLE 1

Descriptive Statistics

Table 1 presents weekly level and change statistics and augmented Dickey–Fuller (ADF) test *p*-values for crude-oil storage in thousands of barrels in Panel A, prices in dollars in Panel B, and other operational variables in thousands of barrels in Panel C. All data are from the U.S. Energy Information Administration (EIA) website from Apr. 9, 2004, to Dec. 29, 2017 (717 observations). SP(FUT_SPOT) is the futures–spot spread, measured as the difference between the second month and nearby futures contracts; SP(FUT_FUT) is the futures–futures spread, measured as the difference between the third- and second-month futures contracts.

Variables	Mean	Median	Std. Dev.	Maximum	Minimum	ADF *p*-Value
Panel A. Storage in Thousands of Barrels						
CUSHING_STORAGE	35,533	32,165	16,240	69,420	11,677	0.256
US_STORAGE (no SPR, no Cushing)	317,272	298,403	52,935	466,399	239,662	0.504
PADD2_STORAGE (no Cushing)	59,163	57,154	14,012	94,666	41,176	0.882
PADD1_STORAGE	13,789	14,044	2,437	20,315	8,882	0.007
PADD3_STORAGE	175,959	164,901	35,419	280,938	124,876	0.376
PADD4_STORAGE	15,137	13,958	3,582	25,833	10,013	0.816
PADD5_STORAGE	53,224	53,367	2,999	61,295	42,840	0.000
ΔCUSHING_STORAGE	52	47	1,058	4,737	−3,678	0.000
ΔUS_STORAGE (no SPR, no Cushing)	151	275	3,879	14,331	−14,079	0.000
ΔPADD2_STORAGE (no Cushing)	52	48	1,161	4,895	−6,625	0.000
ΔPADD1_STORAGE	−8	17	1,041	3,428	−4,006	0.000
ΔPADD3_STORAGE	92	252	3,330	10,913	−10,297	0.000
ΔPADD4_STORAGE	15	28	363	1,935	−1,482	0.000
ΔPADD5_STORAGE	0	83	1,472	4,649	−4,743	0.000
Panel B. Prices in Dollars						
SP(FUT_SPOT)	$0.56	$0.47	$0.93	$8.49	−$2.03	0.000
SP(FUT_FUT)	$0.40	$0.46	$0.71	$4.45	−$1.75	0.000
ΔSP(FUT_SPOT)	$0.00	$0.01	$0.52	$5.65	−$5.67	0.005
ΔSP(FUT_FUT)	$0.00	$0.01	$0.27	$1.41	−$2.90	0.000
Panel C. Other Operational Variables in Thousands of Barrels per Week						
IMPORTS_PADD1	7,939	7,833	2,713	16,632	1,673	
IMPORTS_PADD2	11,065	9,653	3,721	20,958	4,942	
IMPORTS_PADD3	33,100	34,678	9,120	50,484	10,332	
IMPORTS_PADD4	1,992	1,974	352	3,192	616	
IMPORTS_PADD5	7,892	7,903	1,450	12,740	3,619	
IMPORTS_US_NON_SPR	60,732	61,901	9,254	79,198	36,610	
REFINERY INPUTS_PADD1	8,641	8,162	1,637	12,530	4,347	
REFINERY INPUTS_PADD2	23,703	23,534	1,564	28,490	18,963	
REFINERY INPUTS_PADD3	53,686	52,983	5,241	66,304	24,276	
REFINERY INPUTS_PADD4	3,940	3,941	298	4,823	3,031	
REFINERY INPUTS_PADD5	17,291	17,199	1,178	19,922	14,112	
REFINERY INPUTS_US NON SPR	107,261	107,079	6,123	124,075	80,528	
US_PRODUCTION	46,071	39,151	11,855	68,523	26,691	
ΔIMPORTS_PADD1	−13	−91	2,047	5,943	−6,188	
ΔIMPORTS_PADD2	20	42	1,213	3,948	−4,270	
ΔIMPORTS_PADD3	−31	−112	3,641	18,277	−12,257	
ΔIMPORTS_PADD4	1	−7	397	1,876	−1,624	
ΔIMPORTS_PADD5	6	−14	1,911	8,008	−5,908	
ΔIMPORTS_US_NON_SPR	−32	−35	4,278	13,930	−15,771	
ΔREFINERY_INPUTS_PADD1	−6	7	511	1,988	−2,940	
ΔREFINERY_INPUTS_PADD2	11	42	706	2,254	−2,436	
ΔREFINERY_INPUTS_PADD3	21	91	2,098	11,200	−22,869	
ΔREFINERY_INPUTS_PADD4	1	0	175	826	−756	
ΔREFINERY_INPUTS_PADD5	0	0	585	2,156	−1,932	
Δ(REFINERY_INPUTS_US_NON_SPR)	27	140	2,381	11,004	−22,771	
ΔUS_PRODUCTION	40	42	959	7,707	−7,518	

consistently positive for all 10 spreads, and the majority of the lagged spreads are significantly different from 0 at the 1% level. In the final rows of Table 2, we present estimated cumulative effects of spread changes. For instance, the figure in the "Cumulative, 10 spreads" row for Cushing shows that the null that the 10 spreads combined have no effect on Cushing inventories is rejected at the 1% level. This implies significant economic effects, indicating that over a 10-week period, an increase in the futures spread of $1.00 leads to an increase in storage levels at

TABLE 2

Impact of Crude-Oil Futures Spreads on Inventory Changes at Cushing, Oklahoma, U.S., and PADD2

In Table 2 we report weekly changes in crude-oil storage for i) Cushing, ii) the United States excluding the Strategic Petroleum Reserve (SPR) and excluding Cushing, and iii) Petroleum Administration for Defense District 2 (PADD2) excluding Cushing, regressed on the current and five lagged values of the futures–spot spread and the futures–futures spread lagged from 6 to 9 weeks. Current-week changes in refinery inputs, imports, and U.S. production are included to proxy for the impact of unforeseen changes in crude-oil supply and demand, and 1-week lead values of these variables are included to proxy for inventory changes to meet expected future changes in supply and demand. In the Cushing and PADD2 regressions, the refinery input and import figures are for PADD2. *z*2–*z*5 are polynomial terms to measure normal calendar inventory patterns. In the final rows, we present the estimated cumulative impacts of the spread variables and their *p*-values. Standard errors are calculated using the Newey–West procedure. The regressions are estimated using weekly data from Apr. 9, 2004, to Dec. 29, 2017. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

	Cushing		U.S. (no SPR, no Cushing)		PADD2 (no Cushing)	
	1		2		3	
Variables	Coefficient	*p*-Value	Coefficient	*p*-Value	Coefficient	*p*-Value
ΔSP(FUT_SPOT)	380.21***	0.000	−60.78	0.787	−3.87	0.974
ΔSP(FUT_SPOT) – 1	222.19*	0.050	315.82	0.164	55.88	0.596
ΔSP(FUT_SPOT) – 2	501.03***	0.000	−65.57	0.760	−72.98	0.414
ΔSP(FUT_SPOT) – 3	474.69***	0.000	−203.68	0.411	−88.17	0.269
ΔSP(FUT_SPOT) – 4	329.37***	0.000	−198.68	0.296	68.92	0.672
ΔSP(FUT_SPOT) – 5	309.48***	0.000	18.95	0.910	−106.68	0.243
ΔSP(FUT_FUT) – 6	490.52***	0.000	536.89	0.202	124.06	0.443
ΔSP(FUT_FUT) – 7	170.47	0.218	238.79	0.537	−15.11	0.913
ΔSP(FUT_FUT) – 8	462.44***	0.001	−274.77	0.522	−76.24	0.688
ΔSP(FUT_FUT) – 9	277.63**	0.037	−195.54	0.599	8.55	0.955
ΔREFINERY_INPUT	−0.01	0.388	−0.04***	0.000	−0.03***	0.003
ΔREFINERY_INPUT + 1	0.01	0.130	0.05***	0.000	0.01	0.261
ΔIMPORTS	0.01	0.234	0.04***	0.000	0.02***	0.000
ΔIMPORTS + 1	0.00	0.990	−0.04***	0.000	−0.01	0.322
ΔUS_PRODUCTION	0.00	0.244	0.08***	0.000	0.01	0.351
ΔUS_PRODUCTION + 1	−0.01**	0.031	0.00	0.874	0.01***	0.009
ΔSPOT_PRICE	9.85	0.443	−63.17**	0.049	−15.88	0.202
*z*2	175.19***	0.009	1,127.42***	0.000	137.85**	0.012
*z*3	−14.98***	0.004	−110.76***	0.000	−12.44***	0.003
*z*4	0.41***	0.005	3.4***	0.000	0.37***	0.003
*z*5 × .01	−0.36**	0.010	−3.3***	0.000	−0.34***	0.004
Intercept	−295.22	0.260	−483.56	0.467	−209.80	0.315
Cumulative, 10 spreads	3,618.03***	0.000	111.79	0.947	−105.64	0.817
Cumulative, 6 futures–spot	2,216.98***	0.000	−193.72	0.809	−146.90	0.606
Cumulative, 4 futures–futures	1,401.05***	0.000	305.51	0.814	41.26	0.894
Adj. R^2	0.1558		0.5247		0.0521	

Cushing of about 3.6 million barrels. To put a $1.00 spread change in perspective, changes of $1.00 or greater are observed 4.67% of the time.

The results of column 1 in Table 2 support our hypothesis that the main impact of a change in the spread on inventories should be spread out over time because arbitrageurs tend to contract ahead. Dividing the six futures–spot spreads into two groups, lags 0–2 weeks and lags 3–5 weeks, both sets are significant, and the cumulative impact of the longer spreads does not differ significantly from that of the shorter spreads; in both cases, a $1 increase in the spread leads to an increase of approximately 1.1 million barrels in inventory. Similarly, the lagged futures–futures spreads are jointly significant, and a $1 increase in spreads several months out leads to an increase of approximately 1.4 million barrels in Cushing inventory.

Table 2 shows that although active arbitrage in response to futures spreads occurs at Cushing, the NYMEX futures contract delivery point, there is no evidence of such arbitrage at storage locations in the United States away from the futures delivery location. Specifically, outside of Cushing, crude-oil inventories are not significantly influenced by futures spreads, as in column 2 for the overall United States (excluding Cushing) and column 3 for PADD2 (excluding Cushing).

Table 2 further indicates that crude oil outside of Cushing is stored primarily for operational purposes. Whereas column 1 shows that, except for U.S. production levels, Cushing inventories are not significantly influenced by the operational variables, columns 2 and 3 show that U.S. and PADD2 inventories (excluding Cushing) are significant functions of refinery inputs, imports, and production. Unexpected increases in supply, such as imports and production, increase inventories in the United States and PADD2, and unexpected increases in demand, such as refinery draws, decrease inventories in those locations. Our estimates indicate that expected future supply-and-demand changes influence U.S. inventories but not PADD2 inventories. Column 2 documents a positive and significant coefficient on next week's refinery inputs and a negative and significant coefficient on next week's imports, consistent with operators increasing crude-oil stocks if either an increase in demand or a decrease in supply is expected in the future. However, changes in U.S. production do not seem to be anticipated because inventories are not significantly related to next week's production change. Finally, all four z variables that capture the seasonal pattern are statistically significant, reflecting the seasonal pattern in crude-oil storage.[16]

In summary, the results presented in Table 2 indicate that i) stocks at Cushing are held more for arbitrage purposes, and stocks away from Cushing are held primarily for operational purposes; ii) arbitrage-related inventories at Cushing are influenced by both current and past spreads; iii) unexpected changes in operational variables, such as refinery inputs, imports, and production, influence inventories outside of Cushing; and iv) changes in refinery inputs and imports are partially, but not totally, anticipated by storage operators in U.S. non-Cushing storage locations.

B. Subperiod and Area Results

The regression results presented in Table 2 are based on data commencing in Apr. 2004 because this was when the EIA began separately reporting Cushing inventories. Although it is not possible to break out Cushing inventories prior to Apr. 2004, inventory data for the United States and all PADDs are available since 1992. Therefore, it is possible to explore whether there is evidence that arbitrage activities occurred prior to 2004. In Table 3, we reestimate the U.S. and PADD2 regressions for i) the 2004–2017 subperiod with and without breaking out the Cushing inventories, ii) the full 1992–2017 period where the U.S. and PADD2 data include the Cushing inventories, and iii) the 1992–2004 subperiod. All regressions in Table 3 include the same set of variables as those in Table 2, but for brevity, we report only the cumulative impacts of the spreads.

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[16] As a final check that our results are not affected by the absence of carrying costs, we recalculated the Cushing results in Table 2 using spreads net of the annual average storage costs because the annual maximum and minimum storage cost data we received are obviously not granular enough to calculate spreads net of storage costs on a weekly basis. We use the 1-month London Interbank Offered Rates (LIBORs) to proxy for interest costs. The results, which are not reported but available from the authors, are substantively identical to those in Table 2.

TABLE 3

Subperiod and Area Results

Table 3 presents results for variations of the Table 2 regressions. We examine the following subperiods: i) the Apr. 9, 2004–Dec. 29, 2017, subperiod for which Cushing data are available and over which the Cushing inventories can be separated out; ii) the full period for which U.S. Energy Information Administration (EIA) data are available from Sept. 11, 1992, to Dec. 29, 2017; and iii) the prior Sept. 11, 1992–Apr. 8, 2004, subperiod. All regressions include controls as in Table 2, but for brevity, we only report the estimated cumulative impacts of the lagged spread variables, their *p*-values, and the adjusted R^2s. The *p*-values are for Wald tests based on the variance-covariance matrix estimated using the Newey–West procedure. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

	All 10 Spreads		6 Future–Spot Spreads		4 Futures–Futures Spreads		
	Estimated Cumulative Impact	*p*-Value	Estimated Cumulative Impact	*p*-Value	Estimated Cumulative Impact	*p*-Value	Adj. R^2
1. Apr. 9, 2004–Dec. 29, 2017							
Cushing	3,618.03***	0.000	2,216.98***	0.000	1,401.05***	0.000	0.156
U.S. (no Cushing)	111.79	0.947	−193.72	0.809	305.51	0.814	0.525
PADD2 (no Cushing)	−105.64	0.817	−146.90	0.606	41.26	0.894	0.052
U.S. (with Cushing)	3,723.90**	0.030	2,029.23**	0.017	1,694.67	0.18	0.560
PADD2 (with Cushing)	3,520.35***	0.000	2,076.78***	0.000	1,443.57***	0.004	0.146
2. Sept. 11, 1992–Dec. 29, 2017							
U.S. (with Cushing)	5,050.26***	0.002	2,663.7***	0.001	2,386.56*	0.056	0.336
PADD2 (with Cushing)	4,150.32***	0.000	2,370.25***	0.000	1,780.07***	0.000	0.136
3. Sept. 11, 1992–Apr. 9, 2004							
U.S. (with Cushing)	8,159.06***	0.006	4,512.9**	0.019	3,646.16	0.116	0.185
PADD2 (with Cushing)	5,414.57***	0.000	2,969.24***	0.000	2,445.34***	0.004	0.111
Difference: 3 vs. 1							
U.S. (with Cushing)	4,435.16	0.376	2,483.67	0.274	1,951.49	0.776	
PADD2 (with Cushing)	1,894.22	0.181	892.46	0.278	1001.76	0.306	
Other PADDs: *Sept. 11, 1992–Dec. 29, 2017*							
PADD1	312.13	0.593	16.93	0.560	295.21	0.307	0.132
PADD3	214.23	0.864	198.40	0.767	15.83	0.987	0.257
PADD4	−39.79	0.776	72.69	0.343	−112.47	0.257	0.056
PADD5	585.78	0.246	252.15	0.416	333.63	0.414	0.077

Several Table 3 statistics are noteworthy. First, there is strong evidence of futures spread–induced arbitrage over the 1992–2004 period prior to the start of our Cushing data in that the futures–spot spreads are significant in all regressions, and the futures–futures spreads are significant in the PADD2 regressions when the data include the Cushing inventories. Second, based on the 2004–2017 data, when we separate the Cushing inventories from the U.S. and PADD2 inventories, there is no evidence of arbitrage outside of Cushing. Also, there is no evidence of spread-induced arbitrage in PADDs 1, 3, 4, and 5, as shown in the final rows of Table 3. It is clear, therefore, that C&C arbitrage is not just a recent phenomenon but was prevalent for the full period and that the C&C arbitrage was largely confined to Cushing. Further evidence of this is presented in Appendix A.3 in the Supplementary Material, in which we report complete estimation results, including the operational variables, for Cushing and PADDs 1, 2, 3, 4, and 5 for the 2004–2017 subperiod. There the futures spread variables are highly significant in the Cushing regression but only in the Cushing regression. The operational variables are insignificant in the Cushing regression (except for U.S. production, which has the wrong sign), but in the PADD regressions, most are significant, with the hypothesized signs.

VI. The Effect of Physical and Financial Arbitrage Constraints

A. Physical Storage Constraints

We next examine the impact of possible physical and financial constraints on arbitrage, studying the effect of physical constraints in this section, followed by financial constraints in Section VI.B. Once storage tanks are completely full, the arbitrage we have described and documented previously obviously cannot occur because the required physical storage capacity is not available. To test the impact of possible physical constraints, we need measures of storage capacity at Cushing that the EIA only began reporting in Sept. 2010.[17] Because the EIA's capacity figures cover only the latter half of our data period, we develop a proxy for effective capacity over the pre-2010 period based on historical peaks in actual storage. In order to create this capacity proxy, we search for the fewest peaks or inflection points for a log-linear spline function, identifying peaks at Apr. 22, 2005; Feb. 6, 2009; and Jan. 11, 2013. Cushing estimated capacities using this spline function are graphed from Apr. 2004 to Sept. 2010 in Figure A.2 of the Supplementary Material.

For the period prior to Sept. 2010, capacity utilization is measured as the ratio of the actual level of crude-oil stocks, as reported by the EIA, to our estimated capacity proxy. For the period after Sept. 2010, it is measured as the ratio of the actual level of crude oil stocks to the capacity figures reported by the EIA. Because our data are weekly but the EIA capacity figures are semiannual, we assume capacity grows at a constant rate between EIA announcements.

The two capacity-utilization measures (our estimate and EIA capacity) are not equivalent because the EIA capacity figures after Sept. 2010 (which the EIA says exceed effective capacity) generally exceed the proxy based on storage peaks. To obtain comparable measures for the two periods and test whether arbitrage is constrained as storage levels approach capacity, we define a 0–1 dummy variable $\text{STORAGE\_CONSTRAINT}_t$, which, for the period of Apr. 9, 2004–Sept. 24, 2010, is equal to 1 if the ratio of actual Cushing storage levels announced by the EIA for that week divided by our estimate of capacity is in the top 10% of observed levels of capacity utilization for that period (which translates to capacity utilization above 95%), and 0 otherwise. For the post–Sept. 24, 2010, period, $\text{STORAGE\_CONSTRAINT}_t = 1$ if capacity utilization based on the EIA capacity figure is in the top 10% for that period (which translates to capacity utilization above 86.2% by that measure).[18]

The hypothesis that arbitrage is restricted as storage approaches capacity implies that the coefficients of the ΔSP variables in our arbitrage regressions should be lower when $\text{STORAGE\_CONSTRAINT}_{t-1} = 1$, which we test by interacting

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[17] The EIA reports both shell capacity and working capacity semiannually, where the latter, lower figure adjusts for the fact that oil at the bottom of the tank is not obtainable and that the tanks cannot be filled to the very top. Both the EIA and others stress that the unknown effective capacity is less than either figure because some space is required for effective operation.

[18] According to the EIA, its measure exceeds effective capacity, so effective utilization rates are higher.

$\text{STORAGE\_CONSTRAINT}_{t-1}$ with the lagged ΔSP variables. Interacting $\text{STORAGE\_CONSTRAINT}_{t-1}$ with each of the 10 ΔSP variables separately would result in 20 highly correlated variables. To reduce multicollinearity and construct an interpretable regression equation, we condense the 10 lagged ΔSP variables in Table 2 into a weighted index, INDEX_ΔSP, using the coefficients from Table 2 (see Appendix A.4 in the Supplementary Material), and interact $\text{STORAGE\_CONSTRAINT}_{t-1}$ with this index. The hypothesis that C&C arbitrage is constrained by a shortage of storage capacity when capacity utilization rates are very high implies a negative value for the estimated coefficient multiplying this interaction variable.

Because reverse C&C arbitrage involves selling oil for replenishment at a later date, it is possible that reverse C&C arbitrage is constrained by very low levels of crude-oil inventory if those levels are near the minimum needed for operational purposes. To test this, in a manner similar to that described for $\text{STORAGE\_CONSTRAINT}_t$, we also define $\text{INVENTORY\_CONSTRAINT}_t = 1$ if capacity utilization is in the bottom 10% for that period using our measure of storage capacity for the Apr. 9, 2004–Sept. 24, 2010, period and the EIA measure for the period after Sept. 24, 2010, and 0 otherwise. We interact $\text{INVENTORY\_CONSTRAINT}_t$ with INDEX_ΔSP. The hypothesis that reverse C&C arbitrage is constrained by a shortage of available spot oil for arbitrage when oil storage levels are low implies a negative value for the estimated coefficient of this interaction variable.

Estimation results with these added variables are reported in Table 4, with results for the 2004–2017 period using the combined measure of capacity utilization in column 1 and results for 2010–2017 based on just the EIA capacity utilization figures in column 2. The hypothesis that C&C arbitrage is constrained when there is little unused storage capacity is confirmed in that the coefficient of the interaction variable $\text{STORAGE\_CONSTRAINT}_{t-1} \times \text{INDEX\_}\Delta\text{SP}$ is negative and significant with a p-value of 0.011 in the 2004–2017 estimation and 0.010 in the 2010–2017 estimation. Together, the coefficients of INDEX_ΔSP and $\text{STORAGE\_CONSTRAINT}_{t-1} \times \text{INDEX\_}\Delta\text{SP}$ in the 2004–2017 estimation imply that the sensitivity of oil storage stocks to changes in the spreads is reduced by approximately (0.523/1.0705) = 48.9% when actual storage approaches capacity. The coefficients in the 2010–2017 estimation imply a reduction in this sensitivity of approximately 79.0%.[19]

Although there is strong evidence that C&C arbitrage is constrained when there is little unused oil storage capacity at Cushing, we find no evidence that reverse C&C arbitrage has been constrained by low oil inventory levels in that the coefficient of the $\text{INVENTORY\_CONSTRAINT}_{t-1} \times \text{INDEX\_}\Delta\text{SP}$ interaction

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[19] It is possible that when storage at Cushing is constrained, arbitrageurs might switch to using on-storage sites nearby, but outside of, Cushing for C&C arbitrage. To test this, in unreported work, we reestimate the model in column 2 of Table 4, changing the dependent variable from the change in Cushing inventories to the change in PADD2 inventories (excluding Cushing). The hypothesis that arbitrageurs switch to using storage sites outside of Cushing for C&C arbitrage when storage at Cushing is constrained implies a positive coefficient for the interaction variable, (STORAGE_CONSTRAINT – 1) × INDEX_ΔSP. However, the estimated coefficient is insignificant and negative, leading us to reject this hypothesis.

TABLE 4

The Effect of Physical Storage Constraints

In Table 4, we estimate the effect of possible storage constraints on the sensitivity of levels of crude-oil storage to changes in futures–spot and futures–futures spreads. The dependent variable is the change in Cushing, Oklahoma, storage. The 10 lagged ΔSP variables from previous tables are reduced to a single index, INDEX_ΔSP, and a 0–1 dummy for the possible presence of storage constraints is interacted with this spread index. In column 1, STORAGE_CONSTRAINT = 1 if capacity utilization is in the top 10% of weekly capacity-utilization figures, and INVENTORY_CONSTRAINT = 1 if capacity utilization is in the bottom 10% of weekly capacity-utilization figures using the U.S. Energy Information Administration (EIA) capacity figures after Sept. 2010 and our proxy before Sept. 2010. In column 2, STORAGE_CONSTRAINT = 1 if capacity utilization is in the top 10% of EIA weekly capacity-utilization figures, and INVENTORY_CONSTRAINT = 1 if capacity utilization is in the bottom 10% of EIA weekly capacity-utilization figures estimated over 2010–2017. *p*-values based on Newey–West standard errors are shown in parentheses. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

	2004–2017	EIA 2010–2017
Variables	1	2
INDEX_ΔSP	1.0705*** (0.000)	1.1365*** (0.001)
STORAGE_CONSTRAINT – 1	−397.8549*** (0.000)	−306.1902* (0.087)
(STORAGE_CONSTRAINT – 1) × INDEX_ΔSP	−0.523** (0.011)	−0.8977** (0.010)
INVENTORY_CONSTRAINT – 1	25.3842 (0.852)	−16.9642 (0.941)
(INVENTORY_CONSTRAINT – 1) × INDEX ΔSP	0.1421 (0.758)	−0.085 (0.899)
ΔREFINERY_INPUT	−0.0452 (0.415)	−0.0364 (0.599)
ΔREFINERY_INPUT + 1	0.0988* (0.08)	0.1361* (0.053)
ΔIMPORTS	0.0346 (0.302)	0.0072 (0.881)
ΔIMPORTS + 1	−0.0105 (0.739)	0.0173 (0.652)
ΔUS_PRODUCTION	0.0394 (0.186)	−0.0169 (0.56)
ΔUS_PRODUCTION + 1	−0.0519** (0.026)	−0.0324 (0.372)
ΔSPOT_PRICE	10.4798 (0.414)	−21.6709 (0.247)
*z*2	183.0943*** (0.007)	145.7746 (0.151)
*z*3	−15.1629*** (0.004)	−13.5544* (0.088)
*z*4	0.4079*** (0.007)	0.3777* (0.094)
*z*5 × .01	−0.3467** (0.015)	−0.3255 (0.122)
Intercept	−277.4291 (0.277)	−20.3502 (0.957)
No. of obs.	715	378
Adj. R^2	0.177	0.174

variable is insignificant and even positive in the 2004–2017 estimation. This is likely because extremely low levels of oil inventory at Cushing were observed only rarely during our data period. From 2010 to 2017, INVENTORY_CONSTRAINT$_t$ = 1 (i.e., capacity utilization is in the bottom 10%) when capacity utilization is below 40.8%, and from 2004 to 2019, when capacity utilization is below 54.5% (i.e., far from stock-out levels).

In summary, we find strong evidence that as storage at Cushing approaches capacity, the C&C arbitrage that normally maintains the relation between futures and spot prices is hindered or constrained by the lack of available storage. But we find no evidence that reverse C&C arbitrage is hindered by low inventory levels during our sample period.

B. Financial Constraints

In C&C arbitrage, the arbitrageur must finance both the spot market purchase and storage as well as post margin for the futures sale. Thus, as Brunnermeier and Pedersen (2009) note, any financial constraints faced by the arbitrageur could impede the arbitrage. In this subsection, we present tests of whether C&C arbitrage in the oil market was inhibited during periods of financial constraint or stress, utilizing several measures of financial constraints that have been employed in the literature. Our first financial constraint measure is the level of the Volatility Index (VIX). We reason that even though the arbitrage we explore is relatively riskless, traders may be constrained in their access to capital when market uncertainty is high. If so, storage levels should be less sensitive to changes in futures–spot and futures–futures spreads when VIX rates are high, which we test by interacting the standardized VIX level with INDEX_ΔSP.

For our second financial constraint measure, we follow Acharya et al. (2013) and use the financial sector's expected default frequency (EDF) computed by Moody's. According to Moody's, EDF measures the probability that a firm will default over a specified period of time (typically 1 year) (Chen, Dehghan, Ding, Du, Dwyer, Edwards, Ferry, Nazaren, Sun, Zhang, and Zhang (2015)). The source for the measure is the distance-to-default as defined by Merton (1974), which depends on three key drivers (asset value, asset volatility, and default point). Viewed from the perspective of a firm seeking to borrow to fund an arbitrage, EDF is an indicator of creditworthiness. When applied as an indicator of the credit stress faced by a potential lender, it serves as an indicator of credit tightness. We compute EDF_USFIN as the average over all U.S. financial firms and use this as an indicator of the reluctance of lenders to fund arbitrage transactions.[20] As with the VIX measure, we construct an interaction variable by multiplying the standardized EDF_USFIN by INDEX_ΔSP.

For our third financial constraint measure, we follow Matvos, Seru, and Silva (2018) and use the TED spread, that is, the difference between the 3-month LIBOR rate and the rate on 3-month Treasury bills. The TED spread is often used as a measure of credit risk. Again, we construct an interaction variable between the standardized TED − 1 and INDEX_ΔSP. Our final financial constraint interaction variable is $\text{LIBOR}_{t-1} \times$ INDEX_ΔSP, where LIBOR is the standardized 3-month LIBOR rate. As with physical constraints, the hypothesis that arbitrage is constrained in the presence of financial constraints implies a negative relation between inventory changes and our interaction variables.

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[20] A list of the specific Standard Industrial Classification (SIC) codes is available from the authors. This variable is only available through 2016.

TABLE 5

Financial, Storage, and Inventory Constraints

In Table 5, various financial constraint variables are added to the model in column 2 of Table 4: in column 1, the Volatility Index (VIX); in column 2, average expected default frequency (EDF) scores for U.S. financial firms; in column 3, the TED spread; and in column 4, the London Interbank Offered Rate (LIBOR) rate. STORAGE_CONSTRAINT is a 0–1 dummy based on the top 10% of U.S. Energy Information Administration (EIA) storage-capacity-utilization figures. INVENTORY_CONSTRAINT is based on the bottom 10% of EIA storage-capacity-utilization figures. The operational and seasonal variables from previous tables are included in the regressions, but their coefficients are not reported. The regressions are estimated over the 2010–2017 period for which EIA reports Cushing capacity figures. *p*-values based on Newey–West standard errors are shown in parentheses. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Variables	1	2	3	4
INDEX_ΔSP	1.098*** (0.001)	1.105*** (0.000)	1.2819*** (0.000)	1.372*** (0.001)
STORAGE_CONSTRAINT – 1	−294.2869 (0.109)	−396.3775* (0.076)	−359.1153** (0.035)	−268.093 (0.196)
(STORAGE_CONSTRAINT – 1) × INDEX_ΔSP	−0.7545** (0.04)	−0.7276*** (0.006)	−1.0654*** (0.002)	−1.0222** (0.011)
INVENTORY_CONSTRAINT – 1	−27.0206 (0.913)	−157.0262 (0.518)	39.4387 (0.868)	−109.9482 (0.641)
(INVENTORY_CONSTRAINT – 1) × INDEX_ΔSP	0.1099 (0.908)	−0.5743 (0.345)	−0.0788 (0.908)	0.6712 (0.446)
Financial constraint: VIX – 1	22.7196 (0.754)			
(VIX – 1) × INDEX_ΔSP	−0.5746 (0.130)			
Financial constraint: EDF_USFIN – 1		−104.2147 (0.128)		
(EDF_USFIN – 1) × INDEX_ΔSP		−0.7913*** (0.000)		
Financial constraint: TED – 1			78.8752 (0.318)	
(TED – 1) × INDEX_ΔSP			0.3371 (0.459)	
Financial constraint: LIBOR – 1				−61.0748 (0.513)
(LIBOR – 1) × INDEX_ΔSP				1.0885 (0.174)
Control variables and intercept	Yes	Yes	Yes	Yes
Seasonal adjustment	Yes	Yes	Yes	Yes
No. of obs.	378	322	378	378
Adj. R^2	0.178	0.262	0.177	0.19

In Table 5, the various financial constraint interaction variables are added to the model in column 2 of Table 4.[21] To focus attention on the financial and physical constraints, the coefficients of the operational and seasonal variables are not reported because they are little changed from Table 4. To make the results comparable across our different financial constraint measures, we standardized each to a mean of 0 and variance of 1 by subtracting the variable mean and dividing by its standard deviation.

Of the four financial constraint measures, the interaction variable (EDF_USFIN − 1) × INDEX_ΔSP based on Moody's EDF is negative and highly significant with a *p*-value of 0.0002. The coefficient of −0.7913 implies that a 1-standard-deviation increase in EDF_USFIN − 1 is associated with a decline of

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[21] We also estimated regressions with the financial constraint variables for the 2004–2017 period using the model in column 1 of Table 4 and capacity-utilization measures based on our estimates of storage capacity for the 2004–2010 period. The results are roughly the same as in Table 4.

approximately (0.7913/1.105) = 71.6% in the sensitivity of storage to changes in the futures–spot spread. None of the other financial constraint measures is significant at the 10% level. Note that the variable for physical storage constraints remains highly significant in the presence of financial constraint variables.

In summary, our results on whether crude-oil arbitrage is hindered by financial constraints are mixed, but we do find that arbitrage is hindered when the financial sector's EDF is high.

VII. Is Arbitrage Stabilizing or Destabilizing?

Our previous results show that inventory changes at Cushing, Oklahoma, are strongly affected by changes in futures spreads. We next explore whether these arbitrage-induced inventory movements at Cushing tend to increase or decrease spot price volatility. Because this partially depends on whether the futures–spot spread correctly foresees future spot price changes, we first examine how often spot prices move in the direction the futures market predicts. For example, if the futures price is pushed up due to price pressure from index funds or from traders who bid up the futures price to a level sufficient to create a profitable arbitrage opportunity because they foresee a higher future spot price, arbitrageurs will pull oil off the market now, raising the current spot price, and release it later, lowering the future spot price. If indeed spot prices rise in the future as the futures–spot spread predicted, this arbitrage-related inventory movement will tend to dampen the price swing. But if future spot prices fall instead, then the inventory movement will tend to exacerbate the price swing.

Accordingly, we examine the percentage of times the direction of the change in the spot price over 1 month matches the prediction of the futures–spot spread.[22] The results are reported in Table 6, and because we are especially interested in cases when the spread is large enough to set off C&C arbitrage, the results are separately reported for cases when the absolute spread exceeds \$0.50 and \$1.00. Because this test does not require Cushing storage figures, we are able to extend the data back to 1983.

Interestingly, over the full 1983–2017 sample, the subsequent change in the spot price matches the sign of the futures–spot spread only a little over 50% of the time, but that matched movement increases to 71.43% (which is significantly different from 50% at the .01 level) when the absolute 1-month futures–spot spread exceeds \$1 (2-month results are similar and available from the authors). Thus, for those cases in which the impact of arbitrage should be greatest, these results indicate

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[22] In addition, we estimate the predictive ability of the futures–spot spread using the approach of Abosedra and Baghestani (2004), Chinn, LeBlanc, and Coibion (2005), and Alquist and Kilian (2010). These studies examine how well futures prices anticipate future spot prices, generally by regressing the actual change in spot prices on the change forecast by futures prices. Specifically, $S_{t+i} - S_t = \alpha + \beta(F_{t+i,t} - S_t)$, where S_t is the spot price at time t (generally measured as the nearby futures contract), and $F_{t+i,t}$ is the price at time t of a futures contract maturing at time $t + i$. A forecast is said to be unbiased if $\alpha = 0$ and $\beta = 1$. Using this procedure, Abosedra and Baghestani and Chinn et al. find that the crude-oil futures–spot spread is an unbiased predictor of the future change in the spot price but that its predictive ability is low. Using a variation on the standard approach, Alquist and Kilian find some evidence of bias. In unreported regressions, we find that the spread has statistically significant but weak predictive ability.

TABLE 6

Future Changes in the Spot Price and the Futures Market Prediction

Table 6 shows the percentage of times the direction of the change in the spot price over 1 month matches the sign of the predicted change based on the futures–spot spread observed at time t. The predicted change based on the future–spot spread is estimated using $S_{t+1} - S_t = \alpha + \beta(F_{t+1,t} - S_t)$, where S_t is the spot price measured as the nearby futures over the 5 days just before expiration, and $F_{t+1,t}$ is the futures price of the futures contract expiring at month $t+1$ observed at time t. Data are monthly over the 1983–2017 period. Results are separately reported for cases when the absolute value of the spread exceeds \$0.50 and \$1.00 as well as the entire sample. *, **, and *** denote percentages significantly different from 50% at the 10%, 5%, and 1% levels, respectively, based on binomial tests.

	2004–2017	1983–2017	1983–2004
Full sample			
Percentage	55.76%*	52.15%	49.57%
No. of obs.	165	395	230
|Spread| > \$0.50			
Percentage	59.09%**	54.94%*	50.00%
No. of obs.	88	162	74
|Spread|> \$1.00			
Percentage	69.23%***	71.43%***	75%***
No. of obs.	39	63	24

TABLE 7

Relative Prices Around Cash-and-Carry Arbitrage–Related Storage Changes at Cushing, Oklahoma

The two-way tables in Table 7 present increasing (decreasing) prices and increasing (decreasing) forecast changes in crude-oil storage due to cash-and-carry (C&C) arbitrage. The relative price level is the price level during the week of the storage change divided by the average of the prices j weeks before and after it ($j = 2, 4$). The forecast change in storage due to C&C arbitrage is calculated by first estimating coefficients of both operational and spread factors that influence storage changes and then forecasting the storage changes based only on spread factors associated with C&C arbitrage. Data are weekly from Apr. 9, 2004, to Dec. 29, 2017.

		Forecast Storage Positive	Forecast Storage Negative	Total
	Relative price ($j = 2$) >1	164	208	372
	Relative price ($j = 2$) < 1	177	167	344
		341	375	716
χ^2	3.889			
p-value	0.049			
	Relative price ($j = 4$) >1	147	211	358
	Relative price ($j = 4$) < 1	194	164	358
		341	375	716
χ^2	12.369			
p-value	0.000			

that the futures market generally correctly anticipates future spot price changes. This implies that arbitrage resulting from the opportunities provided by the futures spreads moderates the price swings, on average.

To further address the question of whether C&C arbitrage tends to moderate or increase crude-oil price swings, in Table 7, we examine the direction of arbitrage-related changes in inventories. Specifically, we evaluate the relationship between changes in crude-oil storage due to C&C arbitrage and the relative level of crude prices during the time of the storage change. Although we cannot directly observe changes in oil storage due to C&C arbitrage, we can estimate them using the $\beta_{i,j}$ coefficients for the ΔSP variables in Table 2 and the observed ΔSP values. First, we estimate changes in crude-oil arbitrage inventories only for Cushing because we show in Table 2 that most arbitrage-related storage changes occur in that location.

Next, we relate this forecast change in storage due to C&C arbitrage to a measure of relative prices. We calculate the relative price $R_{j,t}$ as

$$R_{t,j} = \frac{S_t}{\frac{1}{2} \times \left(S_{t-j} + S_{t+j}\right)}, \tag{8}$$

where S_{t-j} and S_{t+j} are the crude-oil spot prices j weeks before and after date t, where S is measured as the price of the nearby futures contract. We evaluate equation (8) for $j = 2$ and 4 weeks.

C&C arbitrage will tend to moderate swings in oil prices and stabilize the market if oil is going into storage when prices are relatively low compared with prices before and after (i.e., $R_{t,j} < 1$) and coming out when prices are relatively high (i.e., $R_{t,j} > 1$). To test this, we form a 2 × 2 contingency table, as reported in Table 7. We separate the weeks in our sample into two groups depending on whether C&C arbitrage is causing oil to be stored or taken out of storage: i) weeks when oil is going into storage (column 2) and ii) weeks when oil is coming out of storage (column 3). The hypothesis that C&C arbitrage tends to moderate oil price swings implies that there should be more observations in the bottom-left cell (price below average and oil going into storage) and top-right cell (price above average and oil coming out of storage) than in the other two cells.

The evidence indicates that C&C arbitrage tends to result in oil going into storage in Cushing when prices are relatively low and coming out when prices are relatively high, thus tending to moderate price swings. For $j = 2$, there are 385 weeks when either i) prices are relatively low and arbitrageurs are storing oil or ii) prices are relatively high and arbitrageurs are bringing oil out of storage (along the upward-sloping diagonal), versus 331 weeks when either i) prices are relatively high but arbitrageurs are storing oil or ii) prices are relatively low but arbitrageurs are bringing oil out of storage. The null that arbitrage storage flows are uncorrelated with relative price levels is rejected at the 5% level by a χ^2 test. In other words, in most weeks, the actions of arbitrageurs tend to moderate price swings. For $j = 4$, there are 405 weeks when arbitrageur actions are tending to smooth price changes, versus 311 when they are not, and the no-relation null is rejected at the 1% level. In summary, the evidence in Table 7 indicates that, on average, C&C arbitrage at Cushing has a stabilizing effect on prices.[23]

VIII. Robustness Checks

We conduct a number of robustness checks, with results for several reported in Appendix A.6 of the Supplementary Material. First, to confirm that our results are not driven by large increases in the capacity for crude-oil storage specific to Cushing, Oklahoma, we reestimate the Table 2 Cushing regression with changes

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[23] In Appendix A.5 of the Supplementary Material, we consider whether arbitrage was stabilizing or destabilizing in particular periods, such as during the sharp run-up in oil prices from 2007–2008 or during the financial crisis. We find no significant evidence that C&C arbitrage tended to be destabilizing in any particular period. The cases where arbitrage leads to oil coming off the market when prices are relatively high and on when prices are relatively low are spread over our data period, not concentrated in any particular subperiod.

in storage, refinery inputs, imports, and production measured in percentages instead of barrels. Second, we reestimate the PADD3 regression controlling for crude-oil flows between PADDs. Third, we explore whether our results are possibly affected by pipeline bottlenecks and constraints in 2012. Finally, to improve efficiency and impose some structure on spread coefficients, we reestimate our main regressions expressing the spread lags in a fourth-degree polynomial distributed lag (PDL) model. As reported in Appendix A.6 of the Supplementary Material, our results remain robust in these alternative specifications.

IX. Conclusions

Profit-driven arbitrageurs move oil into and out of storage when futures–spot and futures–futures spreads create arbitrage opportunities. We study the relationship between changes in the futures–spot spread and changes in oil inventories to understand how *arbitrage actually works* and show that changes in futures–spot spreads affect the physical supply and demand for crude oil through changes in inventories. Our evidence indicates that such arbitrage activity is concentrated at Cushing, Oklahoma, the delivery point for the WTI futures contract, but not in other U.S. locations for crude-oil storage (which are used predominantly for operational storage). We show that because arbitrageurs contract ahead, arbitrage-related inventory movements reflect *past* as well as contemporaneous changes in futures spreads and are, on average, stabilizing. Finally, we find that as Cushing storage levels approach capacity, the responsiveness of oil storage levels to changes in futures spreads is reduced, indicating that arbitrage is impeded.

Our results point to several important directions for future research. First, not all storage locations are arbitrage hubs. This has important implications for tests of arbitrage activity, and this finding may have implications for other commodity markets as well. Second, not only contemporaneous but also past spreads must be considered in studies of inventory adjustments because changes in current inventories are partially due to spread changes several months in the past, implying the possible absence of an immediate change in crude-oil inventories when crude-oil prices change. Finally, we find that C&C arbitrage generally, but not always, leads to oil being taken off the market when crude-oil prices are relatively low and put back on the market when crude prices are relatively high. Although we point out several channels that explain the lack of immediate adjustment between futures spreads and inventories by highlighting the importance of past spreads and capacity limits for the inventory decision, future research should look to examine other factors, including shocks and possible frictions, which may limit arbitrage activity.

Supplementary Material

To view supplementary material for this article, please visit http://dx.doi.org/10.1017/S0022109020000204.

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