# Arbitrage in Commodity Markets and the Dynamics of Storage*

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June 2017

**Abstract**

This paper studies inventory adjustments in response to arbitrage opportunities, using the U.S. crude oil market as the experimental setting. We extend the theory of storage by documenting that inventories respond to not only contemporaneous but also lagged futures spreads, due to arbitrageurs contracting ahead. Examining the dynamics of storage, we find evidence of sizable arbitrage-related inventory movements at the NYMEX futures contract delivery point, but no evidence of arbitrage-induced inventory changes at other U.S. storage locations where, instead, operational factors explain most inventory changes.

*JEL Classifications*: G13, G18, Q41.

*Keywords*: theory of storage, commodity markets, cash-and-carry arbitrage, financialization, spot oil markets, oil futures markets, oil storage.

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We thank Bruce Bawks, Hank Bessembinder, John Conti, Huseyin Gulen, Yeejin Jang, Lutz Kilian, Andrei Kirilenko, Yongjia Li, Anthony May, John McConnell, Stefano Rossi, Latha Shanker, Glen Sweetnam, Deniz Yavuz, Xiaoyan Zhang, John Zyren, and seminar participants at the U.S. Energy Information Administration, Financial Management Association annual meetings, Purdue University seminar, the Second IEA IEF OPEC Workshop on the Interactions Between Physical and Financial Energy Markets, the 2016 Energy & Commodity Finance Conference, and the 2016 Commodity Market Conference for valuable discussions and comments. We gratefully acknowledge financial support from the U.S. Department of Energy (EIA) and the University of Oklahoma Office of the Vice President for Research. The views expressed in this paper reflect the opinions of the authors only, and do not necessarily reflect the views of the Energy Information Administration or the U.S. Department of Energy. The authors are solely responsible for all errors and omissions.

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## Abstract

This paper studies inventory adjustments in response to arbitrage opportunities, using the U.S. crude oil market as the experimental setting. We extend the theory of storage by documenting that inventories respond to not only contemporaneous but also lagged futures spreads, due to arbitrageurs contracting ahead. Examining the dynamics of storage, we find evidence of sizable arbitrage-related inventory movements at the NYMEX futures contract delivery point, but no evidence of arbitrage-induced inventory changes at other U.S. storage locations where, instead, operational factors explain most inventory changes.



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**Arbitrage in Commodity Markets and the Dynamics of Storage**

"*U.S. oil tanks barely one-third full beckon crude contango play*" Jonathan Leff, Reuters, January 12, 2015.

## 1. Introduction

Futures markets are an integral part of the financial landscape and are widely used, both directly by companies for risk management purposes, and indirectly as a basis for over-the-counter swap or forward contracts (Wang, Wu, Yang, 2015). Futures markets also serve as sources of price signals for resource allocation decisions (Williams and Wright, 1991; Brennan, 2003). When distortions occur in the link between spot and futures prices, the potential for resource misallocation and mismanagement of risk emerges. Cash-and-carry 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 cash-and-carry arbitrage for the utility of futures prices in decision making is that the absence of arbitrage also implies informational market efficiency.[1] At the same time there is an intimate link between cash-and-carry arbitrage and the theory of storage as articulated by Kaldor (1939), Working (1949), Brennan (1958), and many others through the concept of the convenience yield. The size of the spread between futures and spot prices accounting for the convenience yield acts as a trigger for arbitrage trades. When an arbitrage opportunity presents itself, agents buy or sell the commodity and place opposing trades in the futures market.

An important but unanswered question that has emerged in the literature and as part of a public policy debate is whether and the extent to which temporary distortions in futures prices impact spot prices. Nowhere has this garnered greater interest and attention than in the U.S. crude oil market. The market for oil is enormous, and oil futures contracts represent one of the largest

[1] A fundamental principle that helps to insure that the futures and spot markets for a commodity gravitate to a competitive equilibrium is the execution of arbitrage trades (Williams and Wright, 1991; Pirrong, 2012).

such financial markets in terms of both activity and liquidity.[2] Theory tells us that arbitrageurs will take actions to exploit distortions by going short or long in futures contracts while simultaneously buying or selling the product, which translates into moving product into or out of storage (e.g., see Pirrong, 2012). While this hypothesis is well articulated in theory and has important implications for interpreting the informational efficiency of futures prices (Jarrow and Larsson, 2012), little actual empirical work exists confirming or disconfirming this prediction. We fill this gap in the literature through an examination of the U.S. crude oil market.

We present several primary results contributing to the understanding of the theory of storage as well as the dynamic relation between the futures and spot markets for oil. We show that changes in futures prices (which could be influenced by fundamentals or financial trading that is independent of fundamentals), are transmitted to spot prices through cash-and-carry arbitrage. Specifically, we document that inventory changes are a positive function of changes in futures-spot spreads and that cash-and-carry arbitrage occurs in crude oil markets when arbitrage opportunities arise. Moreover, we provide important new empirical evidence that extends the theory of storage by showing that inventory adjusts with a lag, and that such adjustments are concentrated at the primary storage hub for oil in Cushing, Oklahoma, which is also the delivery point for the NYMEX Crude Oil contract. While changes in stocks outside of Cushing are mostly explained by operational variables, such as refinery inputs, imports and production, changes in stocks at Cushing are primarily explained by changes in futures spreads. This suggests that the inventory changes we document are, indeed, related to cash-and-carry arbitrage.[3] Finally, we show

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[2] See the website of the CME Group, http://www.cmegroup.com/education/files/cme-group-leading-products-2017-q1.pdf.

[3] The U.S. Energy Information Administration reports that as of September 30, 2014 80% of storage capacity at Cushing, OK was leased to parties other than operating companies: .http://www.eia.gov/petroleum/storagecapacity/table3.pdf Considerable anecdotal evidence indicates that C&C arbitrage is common – several investment banks and trading companies reportedly rent oil storage space at Cushing, OK, for trading and arbitrage (Davis, Ann "Where Has All

that arbitrage-induced inventory movements are, on average, price stabilizing. Specifically, arbitrage generally leads to oil coming off the market when prices are relatively low and going back on the market when prices are relatively high.[4]

We provide an extension to the theory of storage (Kaldor, 1939; Working, 1949; Brennan, 1958; Deaton and Laroque, 1992) by showing that the relationship between inventories and spreads is not only contemporaneous, as predicted by the extant theory of storage, but also, that a lagged relation is present. Specifically, we document that inventories change in response to changes in both current and *past* futures price spreads. Profit driven arbitrageurs will 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 the net storage/transaction costs.[5] Additionally, suppose that in January the spread between the April and May *futures* contracts also exceeds the net storage/transaction costs. In this situation, arbitrageurs can make a riskless profit by contracting in January (1) to buy oil in February, store, and sell in March, causing inventories to rise in February and fall back to non-arbitrage levels in March, and (2) to buy oil in April, store, and make delivery in May, so that inventories increase in April and fall in May.[6] Therefore, because arbitrageurs contract ahead, inventories in any given month could be a function of *past futures-futures* spreads

the Oil Gone?," WSJ, October 6, 2007). Various reports suggest that additional storage capacity was added at Cushing, OK to support C&C arbitrage activities.

[4] This is consistent with Brunetti and Buyuksahin (2009) and Brunetti, Buyuksahin, and Harris (2016) who conclude that trading by hedge funds and swap dealers does not destabilize oil markets.

[5] 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 EIA) is the forward market price for delivery over the next month.

[6] For simplicity and because our price data below are futures contract prices, we henceforth use the term "futures" but the model holds for forward contracts as well.

(as in the example above, the May-April spread) and of current and recent *futures-spot* spreads (as in the example above, the March-February spread).

Our finding of arbitrage activity due to past spreads provides an alternative explanation for the evidence underlying Singleton's (2014) argument (concerning index fund flows) that an increase in oil prices above levels consistent with market fundamentals need not lead to significant inventory changes – at least not in the short-run. We document an alternate channel that can explain the lack of immediate inventory buildup in response to changes in prices above the level that equates supply and demand. If it takes months for the full effect of a futures price change on inventories to be realized, the inventory changes due to past spreads may "mask" for a time the impact of current spread changes. This helps explain the lack of inventory buildup (shortfall) in periods when prices can deviate from fundamentals if supply exceeds (falls short of) demand.[7]

We control for various factors that may influence inventory changes in our analysis, but we acknowledge that endogeneity concerns remain, i.e., that inventory levels may impact oil price spreads rather than the reverse as presumed in our analysis, which takes prices as given. Two points are worth noting in this regard. First, we document a similar relation between past spreads and inventories and between current spreads and inventories. If reverse causation is present, its impact should be greatest on the contemporaneous relation. Second, and more importantly, reverse causation implies a negative relation between inventories and futures prices while 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

[7] Our finding that current inventories are a function of past spreads is relevant to the debate over whether financialization has impacted oil prices. The main argument of those who argue that spot (or physical) prices are solely determined by fundamentals is that if energy derivatives trading somehow pushed the spot price above the price equating supply and demand, then inventories should accumulate.

inventories are negatively related to future price spreads.[8] Thus, to the extent that some endogeneity remains after our controls, our results likely tend to understate the impact of futures price spreads on inventories.

To summarize, we find that via cash-and-carry arbitrage, crude oil inventories, and therefore physical supply and demand, vary substantially in response to changes in contemporaneous and *past* futures price spreads. We focus on the arbitrage channel through which trading in crude oil futures does impact physical supply and demand and thus spot prices.[9] Arbitrage-related crude oil inventory movements occurs primarily at Cushing, Oklahoma, the NYMEX futures delivery point, while at other U.S. storage locations inventories are explained principally by operational factors. Accordingly, we point out two important considerations for future research. First, it is important to differentiate between various storage locations when examining arbitrage-related activities. Second, future research should consider not only the contemporaneous inventory impact but also account for the delayed inventory responses to past spreads.

This paper contributes to the literature that examines factors through which futures prices can influence physical prices, and thereby contributes to the vast literature on the theory of storage (Kaldor, 1939; Working, 1949; Brennan, 1958; Deaton and Laroque, 1992) and the financialization of commodity markets. It also adds to the literature that examines the influence of various traders on the volatility in commodity markets (Bryant et al.,2006; Brunetti and

[8] Similarly, Halova, Kurov and Kutcher (2014) show that oil and gas inventory announcements have a significant effect on energy prices and suggest that past inventories could influence current spreads while we examine the influence of influence of past spreads on current inventories.

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

Büyükşahin, 2009; Gilbert, 2010; Aulerich et al. 2010; Büyükşahin and Harris, 2011; Sanders and Irwin, 2011; Irwin and Sanders, 2012; Hamilton and Wu, 2015). But while the majority of these papers use Granger causality tests to examine the relation between trader positions and prices, our approach differs, as we explore whether *arbitrage-induced* inventory movements in response to futures spreads tend to exacerbate or moderate crude oil price volatility. We add to this literature by showing that arbitrage-related inventory movements in crude oil, on average, stabilize prices, as inventories rise when prices are low and fall when prices are high.

Section 2 discusses the background and motivation for the paper and reviews the basic theory of cash-and-carry arbitrage. Section 3 discusses our data and methodology. Our results are presented in section 4, followed by robustness checks in section 5. Section 6 concludes.

## 2. Background

In this section, we first discuss the background and motivation for our paper and then review the basic theory of cash-and-carry arbitrage that we empirically examine in the paper.

### 2.1. Cash-and-carry arbitrage and crude oil inventories

The literature on the financialization of commodity markets suggests that changes in futures prices can be driven by changes in trader beliefs about fundamental supply and demand conditions as well as by noise traders whose activities are divorced from fundamentals. Distortions of the cash-and-carry relation caused by futures price changes, irrespective of the cause, can potentially influence spot prices. This paper does not examine whether and why the futures spread becomes distorted, a debate that has been dealt with extensively in the financialization literature.[10] Rather, our primary focus is on the implications of such distortions for fundamental effects in the spot market. An unresolved issue that lies at the heart of the debate over whether fundamentals or financialization impact spot prices is identification of the channel by which futures trading affects spot prices. If spot prices are determined by physical supply and demand, then futures trading can only impact spot (or physical) prices if it impacts physical supply or demand.

This paper explores how futures prices and spreads impact the supply of crude oil by stimulating inventory adjustments through cash-and-carry arbitrage activity. Arbitrage helps to ensure that futures and spot contracts are correctly priced relative to each other. Such arbitrage activity depends upon movements of physical product into and out of inventories in response to spreads that promise arbitrage profits; thus distortions in futures prices that affect spreads could impact spot prices through this channel.

In extant research, some studies show that positions of various traders (speculators, index funds, hedge funds, etc.) are correlated with spot crude oil prices while in other studies no such

[10] Specifically within the context of the oil market that we study, there are now numerous recent studies which have addressed the distortion issue, largely under the rubric of the debate concerning whether fundamental supply and demand conditions drive spot physical prices or whether the drivers emerge from futures prices being influenced by the financialization of commodity markets. The latter being driven by financial speculators and index investors. One side of the debate concludes that trading in energy financial instruments does not impacts spot (or physical) energy prices and includes Interagency Task Force on Commodity Markets (2008), Gilbert (2010), International Energy Agency (July 2008), Brunetti and Büyükşahin (2009), Büyükşahin and Harris (2011), Hamilton (2009), Kilian (2009), Stroll and Whaley (2010), Sanders and Irwin (2010 and 2011), Irwin and Sanders (2012), Kilian and Hicks (2013), Fattouh, Kilian, and Mahadeva (2013), Kilian and Murphy (2014), Hamilton and Wu (2014, 2015).

On the other side of the debate are studies concluding that financial inflows from various speculative and index fund investors have caused systematic deviations of commodity prices away from fundamental values determined by physical supply and demand: Staff Report of US Senate Permanent Subcommittee on Investigations (2006), Masters (2008), Einloth (2009), Kaufmann and Ullman (2009), Sornette et al. (2009), Phillips and Yu (2010), Parsons (2010), Tang and Xiong (2012), Buyuksahin and Robe (2014), Singleton (2014), Henderson, Pearson and Wang (2015), Baker (2016), Basak and Pavlova (2016), and Sockin and Xiong (2015).

Manera, Nicolini, and Vignati (2016) test whether speculation affects energy futures price volatility in GARCH-type models and shows that higher speculation is, in fact, associated with lower volatility.

correlation exists (Sanders and Irwin, 2010 and 2011; Irwin and Sanders, 2012; Tang and Xiong, 2012; Singleton, 2014; Hamilton and Wu, 2015; Brunetti and Buyuksahin, 2009; Brunetti, Buyuksahin and Harris, 2016). However, the finding that 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. However, their trading could still impact prices, since the impact of trades on prices should occur at the time of the trade and not later. Indeed, while they find no evidence that hedge fund positions lead prices, Büyükşahin and Harris (2011) and Brunetti, Buyuksahin, and Harris (2016) report significant positive correlations between hedge fund position changes and same day changes in the futures price, which would be consistent with hedge fund and swap dealer trading impacting 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, while 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.

There has been no substantive research on how changes in inventories and storage respond to the futures-spot price spread. In principle, if spot prices are influenced by supply and demand changes, then changes in inventories through product either being taken off the market or added to the market is a fundamental channel through which distortions in the futures-spot spread are corrected. While this relationship is theoretically implied by the dynamics associated with arbitrageurs taking actions that restore the cash-and-carry relationship when it becomes distorted, it has not been rigorously examined empirically despite the apparent support from abundant anecdotal evidence. Smith (2009) argues that, **"***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.

According to standard financial market theory, arbitrageurs have an incentive to buy oil in the spot market and put it in storage when the futures price exceeds the spot price by enough to cover storage costs, and to sell oil from inventories when the futures price is below the spot price. This provides an avenue for futures prices to impact supply and demand and thus physical oil prices. This study tests whether the influence of the financial futures market on physical spot prices can be traced through inventories via cash-and-carry arbitrage. Our choice of the crude oil market is based upon two important criteria: first, the availability of inventory information at a weekly frequency, and second, the availability of futures contract prices for highly liquid, actively traded, contracts.

We examine whether inventories respond to spreads as would be expected if arbitrage activity is present. The answer to this question adds to our understanding of the link between futures prices and spot prices. We first test for evidence consistent with the exploitation of arbitrage opportunities. Taking futures prices as given, we examine whether arbitrageurs respond to changes in spreads and whether the influence of financial prices is transmitted to spot prices through inventories.[11] Specifically, we analyze the relationship between price spreads and inventory

[11] Given the lack of agreement on whether financialization affects commodity futures prices directly, we take the price as given and do not aim to establish a model for the real price of oil. We examine how the futures price, or more specifically the spread relative to the spot price, influences the storage decision. Our examination of factors that influence the storage decision is related to, but differs from, that of Kilian and Murphy (2014), where the authors consider changes to inventory due to anticipation of future events related to supply and demand in a Vector Autoregression (VAR) estimation showing 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) impact current supply and demand and hence spot prices.

changes, controlling for operational factors influencing inventories while also addressing possible spurious correlation issues. While Singleton (2014) calculates simple correlations between the futures-spot spread and inventories, no study, to our knowledge, controls for other factors that impact inventories in the short-term, especially supply and demand shocks (specifically production, exports and refinery demand), nor tests for the impact of past futures-futures spreads.

## 2.2. Basic cash-and-carry theory

Inventories are connected to the futures-spot and futures-futures spreads through cash-and-carry (C&C) arbitrage. If the current (time t) futures price for delivery at time t+s, $F_{t,t+s}$, exceeds the current spot price, $S_t$, by more than the cost of storing oil from t to t+s (including transaction and transportation costs and net of any convenience yield) which we designate, $SC_{t,t+s}$, plus interest, arbitrageurs can earn a riskless profit by buying oil in the spot market for $S_t$, simultaneously shorting the futures contract at price $F_{t,t+s}$ and storing the oil (storage costs are assumed to be paid at time t). At time t+s, they can deliver on the futures contract collecting $F_{t, t+s.}$ Their time t+s profits adjusted for interest costs are $F_{t,t+s} – [S_t+SC_{t,t+s}](1+r)^s$ where r is the interest rate. Thus, such arbitrage is profitable when $F_{t,t+s} > [S_t+SC_{t,t+s}](1+r)^s$.

Hence, if foreseeing a future shortage, speculators bid up the futures price or the futures price is pushed up by flows into index funds or similar price pressure to a level above $[S_t+SC_{t,t+s}](1+r)^s$, this sets off arbitrage 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. Conversely, if the expected future shortage does not materialize, the C&C arbitrage-induced inventory changes may exacerbate price volatility.

Opportunity for profitable arbitrage, similar to the one described above if $F_{t,t+s} > [S_t+SC_{t,t+s}](1+r)^s$, can also arise through reverse C&C if $F_{t,t+s} < [S_t-SSC_{t,t+s}](1+r)^s$, where $SSC_{t,t+s}$ is the net transaction cost of selling oil from inventory at time t (or borrowing to short-sell) and replenishing at time t+s.[12] In this case, where spot prices exceed futures prices along with related transaction costs, holders of crude oil inventories, such as refiners and storage companies, can profit by drawing down inventories and selling in the spot market at time t and simultaneously contracting for repurchase of the oil at time t+s at price $F_{t,t+s}$. Again, these arbitrage-induced inventory movements may stabilize oil prices, if the future spot price at time t+s, $S_{t+s}$, does decline as the lower $F_{t+s}$ anticipates, as oil would be brought to the market at time t, thus lowering $S_t$, and replenished back into storage at time t+s, thus increasing $S_{t+s}$.

## 3. Data and methodology

The main crude oil futures contract in the U.S. is the NYMEX West Texas Intermediate (WTI) contract for delivery at Cushing, Oklahoma (OK). Prices are quoted in U.S. dollars per barrel and each contract is for 1000 barrels. This is a heavily traded futures contract; according to Bloomberg, the trading volume in 2014 alone was over 133 million contracts for maturities from one to 12 months. Prices for other grades of crude oil and for delivery at other locations are normally quoted as a premium or discount to this price.

[12] SSCt,t+s consists of any transaction and transportation costs plus the convenience yield minus any savings on storage costs.

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 what are referred to as "spot prices" are generally forward prices for delivery in the next month. Hence, the term "spot price" normally refers to contracts calling for delivery over the next calendar month. Since the price of the nearby futures contract represents the Cushing price for delivery of WTI grade crude over the coming month, is highly liquid and readily observable, it is commonly used as a measure of the spot price.[14] Following this convention, in the present paper we measure the "futures-spot spread" as the difference between a longer term futures contract and a nearby futures contract. We utilize daily settlement futures prices from NYMEX as reported on the Energy Information Administration (EIA) website from 4/9/2004 to 5/1/2015.

Our oil inventory data are also from the EIA and our sample start date of April 2004 is because that is when the EIA began reporting separately report storage levels at Cushing, Oklahoma, the delivery point for the NYMEX WTI crude oil futures contract. Each Wednesday the EIA releases figures on crude storage in the U.S. as of the previous Friday. The inventory data released by EIA is further broken down by region or PADD district.[15]

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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 because: (1) it is a forward rather than a futures contracts, (2) they are quoting the forward price at noon Eastern time whereas the NYMEX daily price is the settlement price, and (3) 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.

[15] In addition to the above ground 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 exists for a period sufficient for analysis so our analysis is restricted to the EIA data.

While it is possible to conduct cash-and-carry 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 with storage at Cushing offers lower cost and/or risk. If an arbitrageur is conducting arbitrage based on the WTI futures contract, storage away from Cushing (the futures delivery point) 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 she 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. Consistent with WTI storage at Cushing affording the arbitrageur a liquid market with minimal transportation costs, it is well-known in the industry that a number of financial firms lease storage at Cushing.

### 3.1. The WTI futures contact and futures-spot and futures-futures spreads

In our empirical analysis below, we use the second-month-nearby spread as our measure of the *futures-spot* spread so it should be kept in mind that the second-month-nearby spread is serving as a proxy for all relevant futures-spot spreads. However, these spreads tend to be highly correlated. For instance, in our 1992-2013 dataset, the correlation between the second-month-nearby spread and the third-month-nearby spread is .984 and the correlation between weekly changes in the two spreads is 0.956.

While discussions of cash-and-carry arbitrage in the finance literature invariably focus on the futures-spot spread, speculative inventory levels could be related to past spreads between longer-term and shorter-term futures as well as the current futures-spot spread 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. In this case, arbitrageurs could make a riskless profit by (in January) buying the March contract, shorting the April contact, and arranging future storage. In March they could take delivery on the March contract, store the oil, and make delivery on the April contract in April. 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.

More generally, if the time t futures price for delivery at time t+s, $F_{t,t+s}$, exceeds the time t futures price for delivery at time t+v, $F_{t,t+v}$, where s > v, by more than the net cost of storage from v to s, $SC_{t+v,t+s}$, plus interest, arbitrageurs can make a riskless profit by simultaneously (at time t) buying the t+v futures contact at price $F_{t,t+v}$ and shorting the t+s futures contract at price $F_{t,t+s}$. At time t+v, they would take delivery on the t+v contract paying $F_{t,t+v}$ and store. At time t+s, they would deliver on the t+s contract receiving $F_{t, t+s}$. Such arbitrage is profitable and oil inventories should tend to rise at time t+v and fall at time t+s when $F_{t,t+s} > [F_{t,t+v}+SC_{t+v,t+s}](1+r)^{s-v}$. In this case, spot prices tend to be pushed up at future time t+v when the oil is taken off the market and placed in storage and pushed down at time t+s when the oil comes out of storage and back on the market. Similarly, reverse C&C arbitrage is profitable when $F_{t,t+s} < [F_{t,t+v}-SSC_{t+v,t+s}](1+r)^{s-v}$ where $SSC_{t+v,t+s}$ is the net cost of selling oil from inventory at time t+v and replenishing at time t+s.

Note that this implies that the current inventory level can be a function of numerous past spreads between long and short futures prices where the long futures contract maturities are after the current month and the maturities of the short futures contracts are prior to the current month. Specifically, the level of 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 $s \geq w$. 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 under-identified model. To make the estimation tractable, our approach is to use one time t-s 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.

Furthermore, an increase in the spread between April (or any month after March) and March futures contracts in months prior to March are expected to lead to an increase in oil inventories in March. Since inventory changes are observed weekly and the futures contracts call for delivery over a month, the second-month-nearby spread is expected to impact inventories for approximately four weeks and the third-month-second-month spread for about four weeks. [16] Since the nearby contract is a forward contract for delivery in the next month, if all arbitrage involves these futures contracts, changes in the second-month-nearby spread should not impact 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 impact inventories until February. However, since 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 impacts inventories lasts from zero to four weeks for an average of two weeks. We relate the current change in inventories to changes in the second-

[16] "Delivery shall take place no earlier than the first calendar day of the delivery month and no later than the last calendar day of the delivery month." http://www.cmegroup.com/trading/energy/crude-oil/light-sweet-crude_contract_specifications.html

month-nearby spread over six weeks and to the third-month-second-month spread over the four prior weeks.

### 3.2. Storage costs and the convenience yield

We have noted above that cash-and-carry arbitrage is profitable when $F_{t,t+s} > [S_t+SC_{t,t+s}](1+r)^s$. Where $SC_{t,t+s}$ is the net cost of storing the oil from t to t+s (assumed in this formulation to be paid at time t) including any transaction and storage costs and net of the convenience yield[17]. Similarly, reverse-cash-and-carry is profitable if $F_{t,t+s} < [S_t-SSC_{t,t+s}](1+r)^s$ where $SSC_{t,t+s}$ consists of any transaction and transportation costs plus the convenience yield minus any savings on storage costs. Note that SC is a positive function of storage costs and a negative function of the convenience yield. SSC is a negative function of storage costs and a positive function of the convenience yield. SC (SSC) can conceivably be negative if the convenience yield (storage cost saving) is high.

The convenience yield reflects the fact that by drawing down inventory the seller risks a stock-out. For example if a refiner reduces its inventory and expected future crude oil deliveries are less than expected, then the refinery may have to reduce production or shut down. Thus owners of inventories may receive an added benefit or “convenience” when inventories in general are low because holding the commodity allows them to avoid stock-outs.[18] The refinery also loses the opportunity to respond to unexpected increases in demand. When inventory levels are low, producers, refiners, and marketers run the risk of a stop-out or shortage. As inventories increase,

[17] Since the implied cost of storage is net of the unobservable convenience yield, which can vary through time, we cannot directly measure the cost of storage and acknowledge the possible measurement error this would introduce for our analysis.

[18] Convenience yield as defined by Brennan and Schwartz (1985) is “…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.”

the risk of a stop-out falls, lowering the convenience yield as Einloth (2009) and others point out. Conversely as inventory levels approach capacity, storage costs likely rise. Storage operators at Cushing have informed us that storage rates average about $0.40 to $0.50 a barrel a month but vary with capacity utilization. Thus $SC_{t,t+s}$ likely varies positively with inventory levels and $SSC_{t,t+s}$ negatively.

We expect SC and SSC to vary from trader to trader as well as over time. What matters for arbitrage are storage opportunity costs and these likely vary by trader. Consider, for instance, a trader who has leased storage capacity for a year at $0.40 a barrel/month. Since the $0.40 is a sunk cost, what matters is the marginal opportunity cost. Depending on whether it is possible to re-lease the storage capacity, this marginal opportunity cost may vary from zero to the re-lease rate. Moreover any excess storage capacity has an option value[19]. If the trader institutes a cash and carry arbitrage as soon as the spread widens sufficiently to make the arbitrage profitable and hence fills his storage units to capacity, he loses the option to conduct the arbitrage on even more favorable terms in the future if spreads should widen further. Thus each arbitrage opportunity is in competition with possible future arbitrage possibilities and the timing of an arbitrage is more complicated than the $F_{t,t+s} > [S_t+SC_{t,t+s}](1+r)^s$ formula suggests. Convenience yields also likely differ by trader. Consequently, we expect aggregate storage levels and changes to be continuous functions of the futures-spot and futures-futures spreads.

### 3.3 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 impact oil inventories. The estimated relationship is:

[19] Jarrow (2010) and Aulerich, Fishe and Harris (2011) discuss option values embedded in futures markets.

$$\Delta STOCK_t = \beta_0 + \sum_{j=0}^{5} \beta_j \, \Delta SP(fut - spot)_{t-j} + \sum_{j=6}^{9} \beta_j \, \Delta SP(fut - fut)_{t-j} + \sum_{j=10}^{J} \beta_j \, \Delta Y_{j,t} \quad (1)$$

where $\Delta STOCK_t$ is the change in inventories over week t , $\Delta SP(fut\text{-}spot)_{t\text{-}j}$ 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 variable $Y_j$ over week t.[20] The choice of spreads and lags is explained in section 3.1, while the variables included in $Y_j$ are detailed in section 3.4. The above relation is estimated for inventories at Cushing, Oklahoma, U.S. crude oil inventories excluding the Strategic Petroleum Reserve (SPR) and excluding Cushing, PADD2 or Midwest PAD district (which includes Cushing) excluding Cushing, PADD1, PADD3-5. We exclude Cushing from the locations that include storage in that location to prevent double counting crude inventories and to examine the relationship between futures spread and specific inventories.

### 3.4. Spurious correlation and operational control variables

Certainly crude oil inventories are held for operational as well as arbitrage purposes so it is necessary to control for these factors. There is also a spurious correlation issue. For instance, if there is an unforeseen increase in demand, it would tend to lead to a fall in crude oil inventories and at the same time an increase in spot prices, which would mean a fall in the spread.  Hence a positive correlation between contemporaneous changes in the futures-spot spread and in inventories would be observed but due to the impact of the demand shift on both prices and

[20] As explained below, we estimate the spreads-inventories relation in change rather than level form partially because we cannot reject the null that inventory levels have a unit root.

inventories - not to C&C arbitrage. Likewise a sudden unforeseen increase in supply would tend to cause a simultaneous increase in crude oil inventories and in the futures-spot spread. Note that this applies only to contemporaneous changes in the spread, $\Delta SP(\text{fut-spot})_t$, not lagged changes $\Delta SP(\text{fut-spot})_{t-j}$ for j>0, since current unexpected changes in supply or demand could not impact past prices.

To control for this spurious correlation, we include as independent variables the changes over the current week in: 1) U.S. crude oil production levels, 2) imports (overall net and by PADD), and 3) refinery inputs (overall and by PADD). To understand how changes in supply and demand fundamentals affect inventories, consider, for example, the change in refinery inputs. The change from the previous week consists of a planned or expected change plus the unplanned or unexpected change. If refinery demand increases unexpectedly, this would lead to an unexpected decline in crude oil inventories. Thus, to the extent 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 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 impact the spot price but not the futures price. Thus this variable should have a negative coefficient and pick up additional unforeseen shifts in supply and demand which impact both the spread and crude oil inventories.[21]

[21] While including current week changes in refinery inputs, imports, and production as independent variables helps control for correlation between changes in the spread and changes in inventory induced by unforeseen shifts in supply and demand, coefficients of these variables must be interpreted with caution. We cannot distinguish between expected and unexpected changes in these variables. By definition, if the data is perfect, the change in inventories this week is equal to the level of imports plus the level of production minus the level of refinery inputs. Since the levels of imports, production, and refinery inputs are by definition equal to the sum of all current and past changes in these variables, there is a small built-in positive correlation between current changes in imports and production and the change in inventories and a small built-in negative correlation between change in refinery inputs and the change in inventories.

We also expect inventories to be held to buffer anticipated shifts in supply or demand. Suppose, an increase in refinery demand for crude is foreseen. In this case, we would expect storage operators 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. 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. While 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, which in our formulation amounts to only one week, an assumption we feel is reasonable. Hence we use actual future changes in these lead variables as proxies for operator expectations. Note that the expected signs for these lead variables are opposite to those for the current week variables. 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 this with dummy independent variables. With monthly dummies, all seasonal changes from one month to the next are forced to occur in the first week of the month, so weekly dummies are more appropriate.[22] Since 52 separate weekly dummy variables are neither feasible nor appropriate, we assume that any seasonality can

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Thus positive coefficients for current week changes in production and imports and negative coefficients for refinery inputs need not necessarily indicate an effect of unforeseen changes in supply and demand on inventories.

[22] As a robustness test, we repeat our analysis with monthly seasonal dummies and our results remain unchanged.

be captured by a polynomial form. First, we define weekly dummy variables as follows: w1=1 if the observation is the first week in January and 0 otherwise, w2 =1 if the observation is for the second week in January and 0 otherwise, and so forth through w52 = 1 the last week in December and 0 otherwise. We then specify five dummy variables, zk, where z1 is a zero-degree polynomial of the wi's, z2 is a first degree polynomial, z3 is a second degree polynomial, z4 is a third degree polynomial, and z5 a fourth degree polynomial. Specifically,

$z_1 = w_1 + w_2 + w_3 + \cdots + w_{52}$ (picked up by the intercept)

$z_2 = w_1 + 2 \cdot w_2 + 3 \cdot w_3 + \cdots + 52 \cdot w_{52}$

$z_3 = w_1 + 2^2 \cdot w_2 + 3^2 \cdot w_3 + \cdots + 52^2 \cdot w_{52}$

$z_4 = w_1 + 2^3 \cdot w_2 + 3^3 \cdot w_3 + \cdots + 52^3 \cdot w_{52}$

$z_5 = w_1 + 2^4 \cdot w_2 + 3^4 \cdot w_3 + \cdots + 52^4 \cdot w_{52}$

The seasonal pattern over 52 weeks of the year implied by our estimates of the coefficients of the z variables in Table 2 is graphed in Figure 1(a) for total U.S. stocks and in Figure 1(b) for Cushing.

***** Insert Figure 1 about here*****

Figures 1(a) and 1(b) show similar seasonal patterns for crude oil inventories. Specifically, crude oil inventories tend to increase from the beginning of the year until about mid-May (week 20-22). This is followed by a period of withdrawals that goes to about the end of September - beginning of October (week 40-42). The seasonal build-up in crude inventories resumes from mid-October onwards with a brief withdrawal period around the holiday season at the end of December and the beginning of January.[23] In a series of robustness tests discussed later, we estimate the

[23] Note that while the year ending inventory level in Figure 1(a) (total U.S.) is approximately the same as the level at the beginning of the year, it is considerably higher in Figure 1(b) (Cushing). This is because, as documented in Figure 2, Cushing inventories increased sharply over the data period while inventories in the rest of the U.S. did not. When

model using monthly dummies and find the results are insensitive to which time control is employed.

### 3.5. Descriptive Statistics

In Figure 2, we graph weekly crude oil storage levels (in millions of barrels) at Cushing from September 11, 2004 through May 1, 2015 (on the right axis) and a four week moving average of the futures-spot spread (in dollars points) (on the left axis). Consistent with cash-and-carry arbitrage, the two series appear correlated. Specifically, storage levels are high (low) when the spread is high (low). In addition, there is a secular upward trend as storage capacity at Cushing grows which reports tie to adding storage capacity for arbitrage purposes.

*****Insert Figure 2 about here*****

Statistics for the weekly storage, spread, and other operational variables (refinery inputs, imports, production) series are reported in Table 1.

*****Insert Table 1 about here*****

We report statistics for both levels and weekly changes. Using an augmented Dickey-Fuller test, we cannot reject the unit root null for any of the U.S. storage locations, except PADD5. Hence, as reflected in our specification of equation (1), we use first differenced series for our further econometric tests.

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we re-estimate using detrended data implied beginning and ending inventory levels for Cushing are approximately the same.

## 4. Results

### 4.1. Regression results – spread variables

Estimations of equation (1) are reported in Table 2 for weekly changes in crude oil storage stocks (in thousands of barrels) for storage at Cushing, Oklahoma in Model 1, U.S. (excluding Cushing and excluding the SPR) in Model 2, and PADD2 (excluding Cushing) in Model 3. Standard errors are estimated using the Newey-West procedure to correct for heteroskedasticity and autocorrelation.

*****Insert Table 2 about here*****

There is strong evidence that futures prices, specifically futures spreads, impact crude oil stocks and thus the actual physical supply of crude oil but concentrated at the futures contract delivery point: Cushing, Oklahoma. For Cushing, coefficients are consistently positive for all ten spreads and the majority of the lagged spreads are significantly different from zero 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 ten spreads combined have no effect on Cushing inventories is rejected at the 1% level. It implies significant economic effects indicating that over a ten week period an increase in the futures spread of $1.00 leads to an increase in storage levels at Cushing of about 3.55 million barrels.

Also, Table 2 Model 1 results support our hypothesis above that the main impact of a change in the spread on inventories should be spread out over time, as arbitrageurs tend to contract ahead. Dividing the six futures-spot spreads into two groups: lags 0 to 2 weeks, and lags 3 to 5 weeks, both sets are significant, and the cumulative impact of the longer spreads ($1 increase in spread leads to an increase of 1.04 million barrel in inventory) does not differ significantly from that of the shorter spreads ($1 increase in spread leads to an increase of 1.02 million barrel in inventory). Similarly, the lagged futures-futures spreads are jointly significant and $1 increase in spreads several month out leads to an increase of 1.49 million barrel in Cushing inventory.

Table 2 shows that while active arbitrage in response to futures spread occurs at Cushing, the futures contract delivery point, there is no evidence of such arbitrage at storage locations in the US which are further from the futures delivery location. Specifically, outside of Cushing crude oil inventories are not significantly influenced by futures spreads, as in Model 2, for the overall U.S. (excluding Cushing) and PADD2 (excluding Cushing). [24]

Evidence in Table 2 indicates that crude oil outside of Cushing is stored primarily for operational purposes. Model 1 shows that Cushing inventories are not significantly influenced by operational variables. On the contrary, Models 2 and 3 show that U.S. and PADD 2 inventories (excluding Cushing) are used primarily for operational purposes, as inventories are a function of refinery inputs, imports and production. Unexpected increases in supply, such as imports and production, increase inventories in the U.S. and PADD2, and unexpected increases in demand, such as refinery draws, decrease inventories in those locations. Supply and demand changes that are expected in the future influence U.S. inventories but not PADD 2 inventories. Model 2 documents a positive significant coefficient on next week's refinery inputs and a negative significant coefficient on next week's imports, consistent with operators increasing crude oil stocks if either an increase in demand or decrease in supply was expected in the future. However, changes in the U.S. production seem to not be well anticipated, as inventories do not significantly change in expectation of next week's production. Finally, all four Z variables that capture the seasonal pattern are significant indicating a definite seasonal pattern in crude oil storage. Future research

[24] Appendix A shows that inventories are not influenced by futures spreads in PADD 1, 3-5 suggesting that arbitrage-related inventory movements do not occur in these storage locations. However, inventories in PADD 1, 3-5 are influenced by operational factors.

should differentiate between storage locations used only for operational uses and those that are used for arbitrage related activities.

In summary, results in Tables 2 indicate: (1) that stocks at Cushing are held more for arbitrage purposes and stocks away from Cushing primarily for operational purposes, (2) arbitrage-related inventories at Cushing are influenced by both current and past spreads, (3) unexpected changes in operational variables, such as refinery inputs, imports and production, influence inventories outside of Cushing, (4) changes in refinery inputs and imports are partially, but not totally, anticipated by storage operators in U.S. non-Cushing storage locations (5) most changes in U.S. production are not anticipated.

**4.2. Sub-period results**

Due to data limitations, in Table 2 regressions were estimated using data from April 2004, as this was the time when EIA started separate reporting of Cushing inventories, which allowed us to examine inventories specific to Cushing and those outside of Cushing. While it is not possible to break out Cushing inventories prior to April 2004, inventory data for the U.S. and all PADDs is available since 1992. Therefore, it is possible to explore whether arbitrage activities occurred prior to 2004 by examining the aggregate data for the U.S. and PADD 2, territories that include Cushing storage, prior to 2004.

Hence, we re-estimated the U.S. and PADD2 regressions, without breaking out Cushing inventories, over several sub-periods: the Cushing sub-period beginning April 2004, the full time period starting in 1992, and the prior sub-period from September 1992 to April 2004. The results are reported in Table 3. In order to make the comparisons easier we include results for Cushing as well as U.S. and PADD 2 excluding Cushing in Table 3, replicating Table 2 results.

*****Insert Table 3 about here*****

Several Table 3 statistics are noteworthy. First, given the coefficients for the sub-period starting 4/9/2004, our evidence indicates spread induced changes in U.S. and PADD2 inventories (when they include Cushing) primarily reflect arbitrage at Cushing. According to the 2004-2015 sub-period results, the estimated cumulative impact on storage levels over the ten week period at Cushing is 3.6 million barrels, in PADD2 is 3.5 million barrels, and in total U.S. is 3.7 million barrels. The three figures are roughly the same implying that virtually all the effect on crude oil storage stocks occurs at Cushing. In other words, after 2004 arbitrage occurred primarily at Cushing.

Second, results in Table 3 indicate that C&C arbitrage occurred prior to 2004, as inventories are a significant positive function of the spread in the 1992-2004 subperiod. Interestingly, changes in the spreads appear to have a greater impact on crude oil stocks in the earlier sub-period, that is from 1992 to 2004. According to the results in Table 3, over a ten week period, an increase in the spread of $1.00 led to an increase in U.S. crude oil stocks of 8.26 million barrels in the 1992-2004 sub-period but only 3.7 million (m) in the 2004-2013 period. In PADD2, the estimated ten week cumulative effects are an increase of 5.41m barrels in 1992-2004 and 3.5 m in 2004-2013. However, when we test for the significance of the differences between the pre- and post-2004 periods, the differences are insignificant. It is clear that C&C arbitrage is not just a recent phenomenon.

In summary, our evidence indicates that storage for C&C arbitrage purposes was mostly limited to Cushing after 2004 and that both contemporaneous and past spreads influence current inventory levels in locations where C&C arbitrage occurs, that is at Cushing.

### 4.3. Inventories and operational factors

Since Table 3 indicates that price spreads influence inventories mainly at Cushing, we next examine how other factors, mainly operating factors, influence inventories at Cushing and other storage districts. Results for all PADD districts (1, and 3-5) are presented in Table 4. Results for Cushing and PADD2 (excluding Cushing) are replicated from Table 2 and presented in Table 4 for convenience. Also, since Table 3 presents evidence on the influence of spread on inventories in all PADD districts and we now want to focus on the influence of operational factors on inventories, future spread estimates are presented as a cumulative of the 10 past and contemporaneous spreads for brevity.

*****Insert Table 4 about here*****

Inventory changes in most PADD districts are a negative function of recent changes in refinery inputs (which is what we would expect if the changes were partially unexpected) and a positive function of the change in refinery inputs over the coming week (which if what we expect if the refinery demand is partially anticipated). Similarly, they are a positive function of recent changes in imports and a negative function of imports over the coming week. Also, changes in U.S. oil production influence inventories but only in PADD1 and PADD2, excluding Cushing. Overall, Table 4 indicates that over the 2004-2011 period, inventories outside of Cushing responded strongly to operating factors but Cushing inventories did not.

### 4.4. Is arbitrage stabilizing or destabilizing?

Our results show that inventory changes at Cushing, Oklahoma, unlike in other U.S. crude oil storage locations, are strongly impacted by changes in futures spreads but not by changes in operating factors. We next examine whether these arbitrage-induced inventory movements at

Cushing tend to increase or decrease spot price volatility. Since, partially, this 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.

If the futures price is pushed up (can be due to price pressure from index funds or from speculators who bid up the futures price because they foresee higher future spot price), this tends to cause arbitrageurs to pull oil off the market now, raising current spot prices, and release it later, lowering future spot prices. 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 spot prices fall instead, then the inventory movement will tend to exacerbate the price swing. Accordingly, we examine how often spot prices move in the direction the futures market predicts. We first follow the approach similar to the one from Abosedra and Baghestani (2004), Chinn, LeBlanc, and Coibion (2005) and Alquist and Kilian (2010).[25] We find that the spread has predictive ability but the predicting power is small (regressions available on request). Next, we report the percentage of times the direction of the change in the spot price from month t to month t+i matches the prediction of the futures-spot spread. Results are reported in Table 5; Panel A for i=1, i.e., the price change over 1-month, and in Panel B for i=2. Since we are especially interested in cases when the spread is large enough to set off C&C arbitrage, results are separately reported for cases when the absolute spread exceeds \$0.50 and \$1.00 for i=1 and \$1 and \$1.50 for i=2.

[25] These studies examine how well futures prices anticipate future spot prices and generally regress 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 (2004), and Chinn, LeBlanc, and Coibion (2005) 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 (2010) find some evidence of bias. While those studies examine whether the future-spot spread is an unbiased predictor of the future change in the spot price, our focus is on whether on average the futures-spot spread tends to correctly foresee the direction of change in spot prices.

*****Insert Table 5 about here*****

Interestingly, over the full sample, the subsequent change in the spot price matches the sign of the time t spread only about 50% of the time. However, when the absolute one or two month basis exceeds $1, the percentage of times the spot price changes in the same direction is significantly greater than 50%. Thus for those cases in which the impact of arbitrage on inventories and spot oil prices should be greatest, these results indicate the futures market generally correctly anticipates future spot price changes. This implies that arbitrage resulting from the opportunities provided by the spread on average moderates the price swings.

To further address the question of whether C&C arbitrage tends to moderate or increase crude oil price swings, we examine the direction of arbitrage related changes in inventories. If C&C arbitrageurs withdraw oil from the market during a time of relative plenty and low prices and then bring the oil back onto the market during a time of relative scarcity and higher prices (as the futures market anticipates), their actions will tend to stabilize the market, moderate oil price swings, and allocate oil to the periods when it is most needed. If, on the other hand, the oil comes back on the market during a time of relative plenty and low prices, their actions will tend to add volatility. In other words, C&C arbitrage is considered to be stabilizing (destabilizing) if it leads to oil going into storage when prices are relatively low (high), and coming out of storage when prices are relatively high (low). We examine whether arbitrage related changes in inventories are in directions that moderate or increase crude oil price swings by evaluating the relationship between crude oil storage changes due to C&C arbitrage and the relative level of crude prices during the time of the storage change.

While we cannot directly observe oil storage changes due to C&C arbitrage, we can estimate them using the $\beta_{i,j}$ coefficients for the $\Delta$SP variables in Table 2 and the observed $\Delta$SP values. We estimate changes in crude oil arbitrage inventories both at Cushing and in the US, excluding Cushing, over the 2004-2015 period and in the entire US over several periods, including 1992-2013, as well as the 1992-2004 and 2005-2013 periods. In our final step, 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

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

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

C&C arbitrage will tend to smooth or moderate swings in oil prices if oil is going into storage when prices are relatively low, 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 2x2 contingency table as reported in Table 6. 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: (1) weeks when oil is going into storage (column 2), and (2) weeks when oil is coming out of storage (column 3). We also separate the weeks into: (1) weeks when the crude oil price exceeds the average of prices before and after (top row) and (2) weeks when the crude oil price is lower than the average of prices before and after (second row). Thus 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.

*****Insert Table 6 about here*****

Results for storage flows at Cushing, where most C&C arbitrage occurs, are reported in Panel A of Table 5 for the 2005-2013 period. The evidence indicates that C&C arbitrage tends to result in oil going into storage when prices are relatively low and coming out when prices are relatively high, thus tending to moderate price swings. For j=2 there are 309 weeks when either (1) prices are relatively low and arbitrageurs are storing oil or (2) prices are relatively high and arbitrageurs are bringing oil out of storage (along the upward sloping diagonal) versus 266 when either (1) prices are relatively high but arbitrageurs are storing oil or (2) prices are relatively low but arbitrageurs are bringing oil out of storage. The no-relation null is rejected at the 10% level. Accordingly, in most weeks the actions of arbitrageurs tend to moderate price swings. For j=4, there are 311 weeks when arbitrageur actions are tending to smooth price changes versus 262 when they are not and the no-relation null is rejected at the 5% level.

Results for other US inventories, excluding Cushing, over the 2005-2013 period are reported in Panel B of Table 6. The results indicate that C&C arbitrage happens primarily at Cushing and there is no significant stabilizing effect from other crude oil inventories, as the null that prices and inventory flows outside of Cushing are unrelated cannot be rejected.

In summary, the evidence in Table 6 indicates that on average, C&C arbitrage at Cushing has a stabilizing effect on prices. Crude oil tends to be usually taken into storage during periods of low prices and returned to the market during periods of high prices though this is not always the case. However, there is no evidence that inventory withdrawals and additions at other storage locations outside of Cushing are price stabilizing.

One additional issue, we consider is whether arbitrage was stabilizing or destabilizing in particular periods, such as during the sharp run-up in oil prices 2007-2008 or during the financial crisis. Accordingly, we take a closer look at weeks when C&C arbitrage did not tend to stabilize prices in that arbitrage tended to reduce the oil supply when prices were relatively high or added to supply when prices were relatively low. Table 7 Panel A presents the number of weeks each year where estimated arbitrage inventories tended to increase (thus reducing supply) when oil prices were relatively high. Panel B presents the number of weeks where inventories tended to decrease when prices were relatively low.

*****Insert Table 7 about here*****

No consistent seasonal patterns are documented for periods when C&C arbitrage did not tend to stabilize prices. Weeks with destabilizing additions to arbitrage inventories are somewhat higher than average in 2005, 2006, 2008, and 2012. However, the null that destabilizing additions do not differ by year cannot be rejected at the 10% level.[26] Weeks with destabilizing withdrawals are somewhat higher 2007, 2009, 2010, 2011, and 2013 but again the null that these do not differ by year cannot be rejected at the 10% level. In summary, we find no significant evidence that cash-and-carry arbitrage tended to be destabilizing in any particular periods. 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.

## 5. Robustness checks

We next check the robustness of these results by exploring several alternative regression specifications. First, it is important to confirm that our results are not driven by large increases in crude oil storage capacity specific to Cushing, OK (see Figure 2), accordingly we examine percentage changes, as opposed to barrel changes, in storage and for consistency use percentage changes for refinery inputs, imports, and production. Second, we control for crude oil flows between PADDs. Since according to personnel at the EIA and confirmed in our data, we find that

[26] We conducted a chi-square test using data for 2005-2014. Years 2004 and 2015 were excluded since, we have only partial weeks for these years.

the major inter-PADD flows are between PADD2 (Midwest) and PADD3 (Gulf Coast), we add the lagged changes in PADD3 stocks and PADD3 imports as controls expecting positive coefficients for both.

Finally, we control for possible persistent changes to crude oil inventories caused by forces not captured by our regression specification. In 2012 inventories at Cushing rose as oil flowed in from the Bakken and other fields but could not leave, as the available pipelines were configured to flow from the Gulf to Cushing and not the reverse. This problem was largely resolved as flows were reversed on the Seaway pipeline in May 2012 and new pipelines completed. Dating this phenomenon is difficult because there were no sharp time demarcations, but in a rough attempt to control for the impact of this transport bottleneck we include a zero-one dummy for 2012 observations. Also, to improve efficiency and impose some structure on spread coefficients we re-estimate our main regressions expressing the spread lags in a polynomial distributed lag (PDL) model where the lagged spreads follow a fourth degree polynomial. Table 8 presents the results using percentage changes in Model 1, controlling for PADD3 flows in Model 2, including the 2012 dummy in Model 3, and using the PDL structure in Model 4.

*****Insert Table 8 about here*****

Our results remain – inventories at Cushing are a function of current and past spreads. Model 1 results indicate that over a ten week period an increase in the spread of $1 results in about a 10% increase in storage levels at Cushing. Model 2 shows that both PADD3 imports and stocks have the expected sign but the change in imports is only significant at the 10% level and the change in stocks is insignificant.[27] Model 3 confirms the relationship between inventories and spreads

[27] Since the changes in PADD3 stocks and imports are correlated, we also estimated regressions with them individually. The results are unchanged. The change in PADD3 stocks is insignificant and the change in PADD3 imports is significant at the 10% level but not at the 5% level.

after controlling for Bakken related crude inventory inflows. Model 4 shows that imposing the structure with the PDL spread does not influence our main results.

Several other robustness checks are available upon request but our main results remain unchanged. Specifically, we estimate with winsorized variables to control for outliers, add lagged changes in operational variables to reduce the influence of asynchronous reporting, and estimate with monthly seasonal dummies in contrast to the weekly dummy variable measures.

## 6. Conclusions

Profit driven arbitrageurs move oil into and out of storage when spot-futures spreads create arbitrage opportunities. We study the relationship between changes in the futures-spot spread and changes in oil inventories and show that changes in futures-spot spreads impact the physical supply and demand for crude oil through changes in inventories as cash-and-carry arbitrage would predict. Specifically, crude inventories respond to changes in futures spreads. When futures spreads make it profitable to do so, arbitrageurs pull oil off the market and store, or conversely put more oil on the market by drawing down inventories. Our evidence indicates such arbitrage activity is concentrated at Cushing, Oklahoma, the delivery point for the WTI futures contract, but not in other U.S. crude oil storage locations (which are used predominantly for operational storage). We show that current inventory movements reflect *past* as well as contemporaneous changes in futures spreads indicative of arbitrageurs taking advantage of all arbitrage opportunities wrought by distortions in spreads. Our results provide two important directives for future research. First, not all storage locations are arbitrage hubs. This has important implications for tests of arbitrage activity and the finding may have implications for other commodity markets as well, although we leave that question for future research. Second, not only contemporaneous, but also past spreads must be considered in studies of inventory adjustments as changes in current inventories are partially due to spread changes several months in the past, implying the lack of an immediate change in crude oil inventories when crude oil prices change.

We find that cash-and-carry 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. We leave several questions for future research including the impact of physical or financial limits on arbitrage activity. We observe several periods when the futures-spot spread was very high (low) but inventories did not increase (fall) as the cash-and-carry arbitrage model predicts. While we point out one channel that explains the lack of immediate adjustment between futures spreads and inventories by highlighting the importance of past spreads for the inventory decision, future research should look to examine other factors, including shocks and possible frictions that may limit arbitrage activity.

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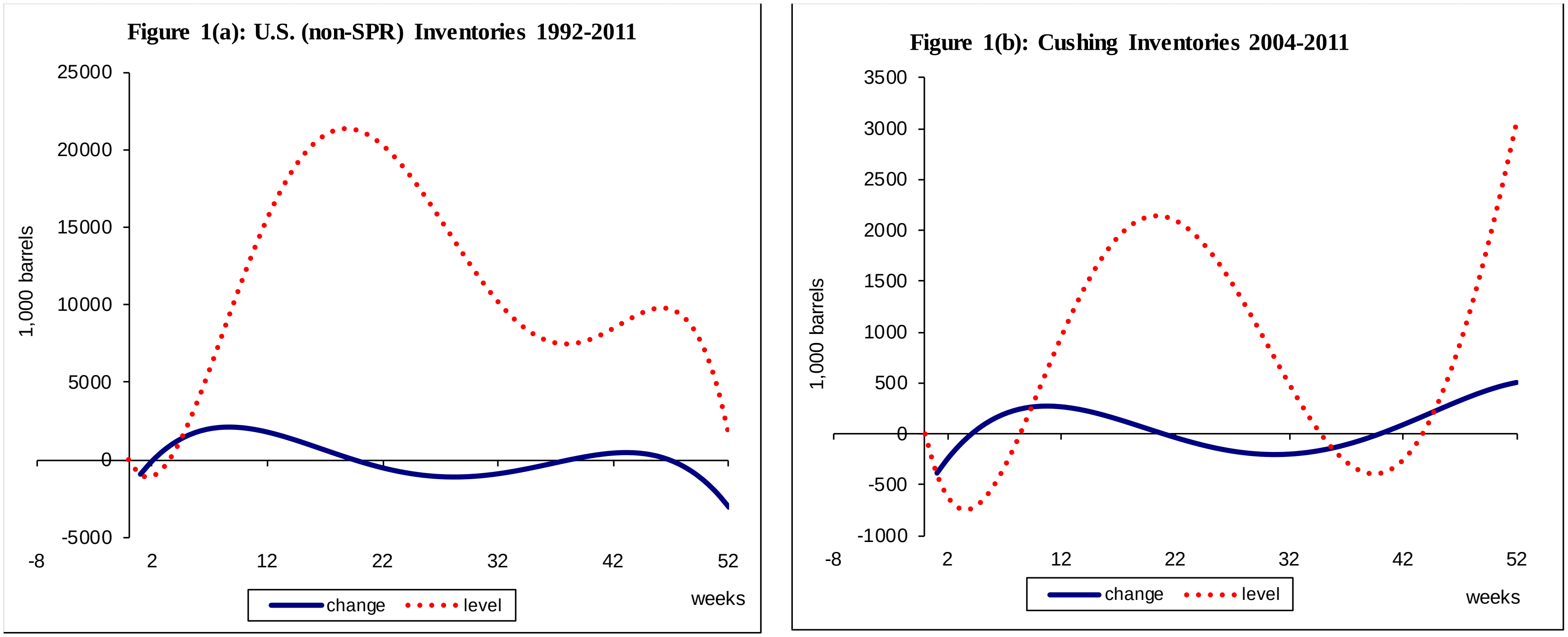


**Figure 1 – Crude Oil Inventory Levels and Changes as Predicted by the Seasonal Adjustment from the Z Variables**
This figure presents seasonal patterns in crude oil inventories as implied by the weekly seasonal Z variables. Both inventory levels and changes are presented. Figure 1(a) plots the U.S. (non-SPR) inventories over the 1992-2011 period; Figure 1(b) plots Cushing, Oklahoma inventories over the 2004-2011 period.

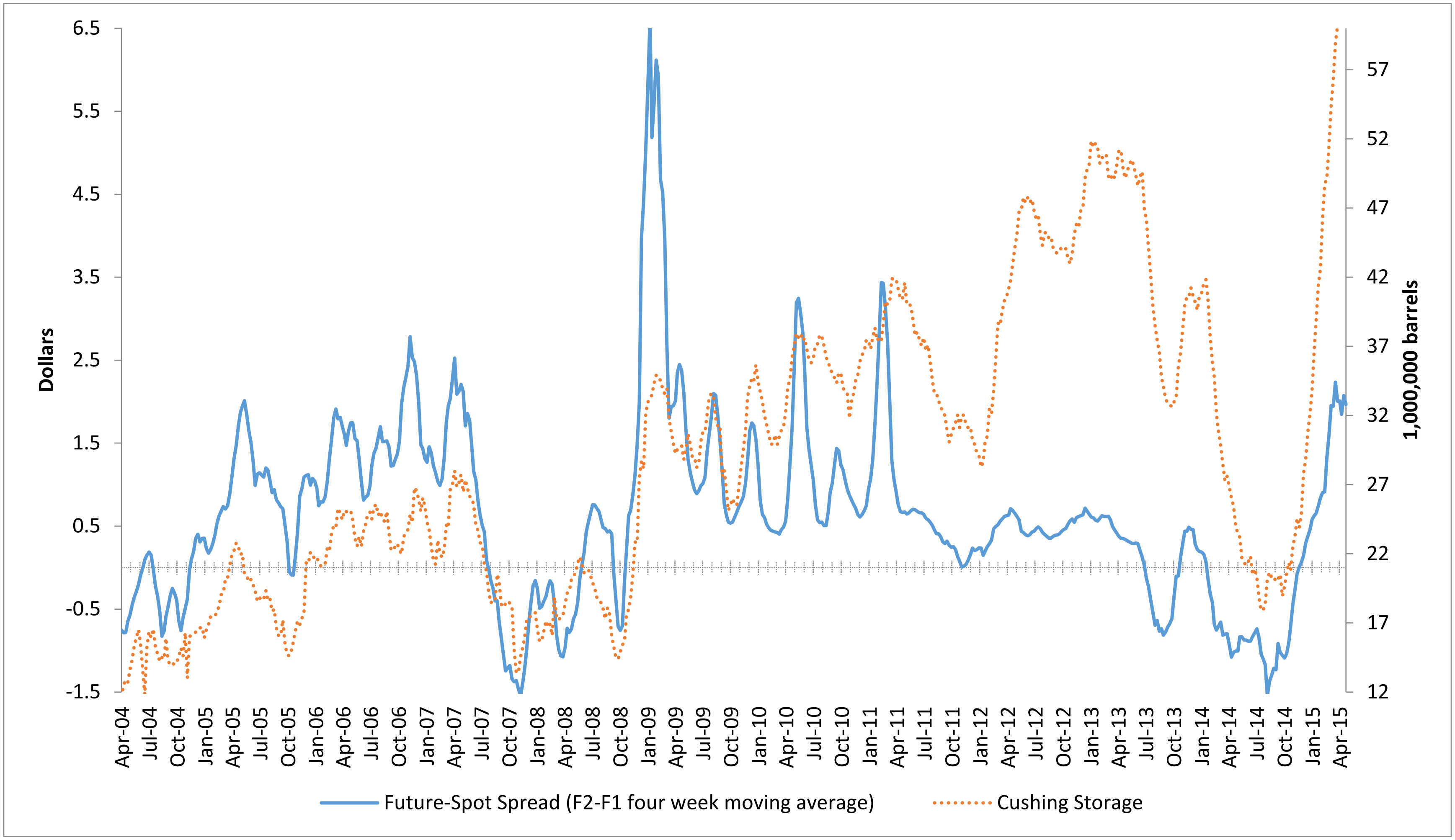


**Figure 2 – Cushing Crude Inventory and the Spread Between the Two- and One-Month NYMEX WTI Crude Futures.**
This figure plots crude oil inventories at Cushing, Oklahoma and the spread between the two- and one-month WTI crude futures, presented as a four week moving average, between 4/9/2004 and 5/1/2015.

**Table 1 - Descriptive statistics**

Weekly level and change statistics and Augumented Dickely-Fuller test p-values are presented for crude oil storage in thousand barrels in Panel A, prices in dollars in Panel B and other operational variables in thousand barrels in Panel C. All data are from the Energy Information Administration (EIA) website from 4/9/2004 to 5/1/2015 and includes 578 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.

| | Mean | Median | Std. Dev. | Maximum | Minimum | ADF p-val. |
|---|---|---|---|---|---|---|
| **Panel A -Storage in thousand barrels** | | | | | | |
| Cushing storage | 29256 | 27774 | 10897 | 62200 | 11677 | 0.351 |
| ΔCushing storage | 87 | 56 | 1038 | 4737 | -3678 | 0.000 |
| U.S. storage (no SPR, no Cushing) | 315438 | 312353 | 26123 | 429226 | 255566 | 0.617 |
| ΔU.S. storage (no SPR, no Cushing) | 246 | 434 | 3680 | 10784 | -11693 | 0.000 |
| PADD2 storage (no Cushing) | 55937 | 53541 | 10016 | 88106 | 42457 | 0.943 |
| ΔPADD2 storage (no Cushing) | 60 | 52 | 1133 | 4895 | -6625 | 0.000 |
| PADD1 storage | 13286 | 13371 | 2124 | 18647 | 9040 | 0.172 |
| ΔPADD1 storage | 1 | 6 | 1006 | 3122 | -4006 | 0.000 |
| PADD3 storage | 176514 | 176957 | 15924 | 243864 | 138168 | 0.176 |
| ΔPADD3 storage | 155 | 436 | 3166 | 10754 | -10297 | 0.000 |
| PADD4 storage | 15810 | 15571 | 2771 | 24669 | 10924 | 0.960 |
| ΔPADD4 storage | 21 | 32 | 324 | 1101 | -1151 | 0.000 |
| PADD5 storage | 53891 | 53931 | 2954 | 61751 | 43930 | 0.000 |
| ΔPADD5 storage | 10 | 82 | 1470 | 3959 | -4821 | 0.000 |
| **Panel B - Prices in dollars** | | | | | | |
| SP(fut-spot) | $0.53 | $0.45 | $1.01 | $8.49 | -$2.03 | 0.000 |
| ΔSP(fut-spot) | $0.00 | $0.02 | $0.57 | $5.65 | -$5.67 | 0.000 |
| SP(fut-fut) | $0.36 | $0.44 | $0.77 | $4.45 | -$1.75 | 0.005 |
| ΔSP(fut-fut) | $0.00 | $0.02 | $0.29 | $1.41 | -$2.90 | 0.000 |
| **Panel C - Other Operational Variables in thousand barrels** | | | | | | |
| Imports_PADD1 | 1204 | 1212 | 385 | 2376 | 369 | 0.421 |
| ΔImports_PADD1 | -3 | -4 | 289 | 849 | -884 | 0.000 |
| Imports_PADD2 | 1383 | 1251 | 368 | 2528 | 706 | 0.761 |
| ΔImports_PADD2 | 2 | 7 | 162 | 564 | -559 | 0.000 |
| Imports_PADD3 | 5136 | 5330 | 1097 | 7212 | 2602 | 0.695 |
| ΔImports_PADD3 | -5 | -25 | 537 | 2611 | -1751 | 0.000 |
| Imports_PADD4 | 278 | 276 | 48 | 451 | 88 | 0.000 |
| ΔImports_PADD4 | 0 | 0 | 56 | 268 | -232 | 0.000 |
| Imports_PADD5 | 1115 | 1114 | 208 | 1820 | 517 | 0.000 |
| ΔImports_PADD5 | 0 | -4 | 279 | 1144 | -844 | 0.000 |
| Imports _US non SPR | 9056 | 9235 | 1154 | 11314 | 6074 | 0.597 |
| ΔImports _US non SPR | -6 | -4 | 601 | 1846 | -2253 | 0.000 |
| Refinery inputs_PADD1 | 1266 | 1231 | 248 | 1790 | 621 | 0.009 |
| ΔRefinery inputs_PADD1 | -1 | 1 | 78 | 284 | -420 | 0.000 |
| Refinery inputs_PADD2 | 3324 | 3321 | 176 | 3818 | 2709 | 0.000 |
| ΔRefinery inputs_PADD2 | 2 | 7 | 99 | 322 | -348 | 0.000 |
| Refinery inputs_PADD3 | 7441 | 7428 | 602 | 8745 | 3468 | 0.000 |
| ΔRefinery inputs_PADD3 | 2 | 10 | 281 | 1600 | -2813 | 0.000 |
| Refinery inputs_PADD4 | 552 | 555 | 36 | 638 | 433 | 0.000 |
| ΔRefinery inputs_PADD4 | 0 | 0 | 24 | 92 | -73 | 0.000 |
| Refinery inputs_PADD5 | 2484 | 2470 | 174 | 2846 | 2016 | 0.000 |
| ΔRefinery inputs_PADD5 | -1 | 0 | 86 | 308 | -276 | 0.000 |
| Refinery inputs_US non SPR | 15066 | 15101 | 715 | 16627 | 11504 | 0.000 |
| Δ(Refinery inputs_US non SPR) | 3 | 18 | 325 | 1572 | -2905 | 0.000 |
| US production | 5973 | 5478 | 1270 | 9422 | 3813 | 0.997 |
| ΔUS production | 6 | 6 | 130 | 751 | -1067 | 0.000 |

**Table 2 - Impact of crude oil futures spread on inventory changes at Cushing, Oklahoma, U.S., and PADD2**

Weekly changes in crude oil storage for: (1) Cushing,(2) the U.S. excluding the Strategic Petroleum Reserve and excluding Cushing, and (3) the PADD2 excluding Cushing, are regressed on the current and five lagged values of the futures-spot spread and the futures-futures spread lagged from six to nine 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 one week lead values of these variables 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. Z2-Z5 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 4/9/2004 to 5/1/2015.

| | (1) Cushing | | (2) U.S. (no SPR, no Cushing) | | (3) PADD2 (no Cushing) | |
|---|---|---|---|---|---|---|
| | Coefficient | p-value | Coefficient | p-value | Coefficient | p-value |
| ΔSP(fut-spot) | 362.04 | 0.000 | -55.35 | 0.797 | -16.25 | 0.865 |
| ΔSP(fut-spot)(-1) | 186.68 | 0.028 | 320.62 | 0.149 | 25.60 | 0.795 |
| ΔSP(fut-spot)(-2) | 474.33 | 0.000 | -25.93 | 0.905 | -80.24 | 0.411 |
| ΔSP(fut-spot)(-3) | 443.43 | 0.000 | -189.20 | 0.385 | -75.09 | 0.439 |
| ΔSP(fut-spot)(-4) | 298.92 | 0.000 | -145.28 | 0.502 | 76.68 | 0.427 |
| ΔSP(fut-spot)(-5) | 292.89 | 0.000 | 42.80 | 0.836 | -60.05 | 0.515 |
| ΔSP(fut-fut)(-6) | 498.65 | 0.001 | 392.98 | 0.305 | 126.33 | 0.461 |
| ΔSP(fut-fut)(-7) | 207.67 | 0.157 | 307.28 | 0.423 | 0.55 | 0.998 |
| ΔSP(fut-fut)(-8) | 477.75 | 0.001 | -259.59 | 0.499 | -30.91 | 0.856 |
| ΔSP(fut-fut)(-9) | 308.61 | 0.034 | -182.47 | 0.631 | -33.46 | 0.843 |
| ΔRefinery input | -0.35 | 0.400 | -1.77 | 0.000 | -2.12 | 0.000 |
| ΔRefinery input(+1) | 0.42 | 0.322 | 2.79 | 0.000 | 0.07 | 0.889 |
| ΔImports | 0.34 | 0.227 | 2.23 | 0.000 | 1.10 | 0.001 |
| ΔImports(+1) | 0.11 | 0.694 | -1.92 | 0.000 | -0.45 | 0.179 |
| ΔUS production | 0.44 | 0.159 | 3.83 | 0.000 | 0.70 | 0.056 |
| ΔUS production(+1) | -0.40 | 0.203 | -0.14 | 0.880 | 0.50 | 0.176 |
| ΔSpot Price | 11.11 | 0.349 | -75.43 | 0.015 | -17.25 | 0.212 |
| Z2 | 177.85 | 0.002 | 1180.22 | 0.000 | 132.95 | 0.046 |
| Z3 | -14.53 | 0.001 | -109.03 | 0.000 | -11.43 | 0.024 |
| Z4 | 0.39 | 0.002 | 3.25 | 0.000 | 0.33 | 0.022 |
| Z5(x.01) | -0.32 | 0.006 | -3.11 | 0.000 | -0.30 | 0.026 |
| Intercept | -323.99 | 0.145 | -1039.55 | 0.086 | -239.06 | 0.357 |
| | | | | | | |
| Cumulative - 10 spreads | 3550.97 | 0.000 | 205.85 | 0.864 | -66.83 | 0.900 |
| Cumulative - 6 futures-spot | 2058.28 | 0.000 | -52.35 | 0.941 | -129.35 | 0.681 |
| Cumulative - 4 futures-futures | 1492.68 | 0.000 | 258.20 | 0.776 | 62.51 | 0.877 |
| Adjusted r-square | 0.1798 | | 0.553 | | 0.0606 | |

**Table 3 - Subperiod results**

The regressions in Table 2 are repeated for several sub-periods: (1) the 4/9/2004-5/1/2015 sub-period for which Cushing data is available and over which the Cushing inventories can be separated out, (2) the full period for which EIA data is available from 9/11/1992 to 5/1/2015, and (3) the prior 9/11/1992-4/8/2004 sub-period. Reported are estimated cumulative impacts of the lagged spread variables, their p-values, and the adjusted r-squares. All regressions include controls as in Table 2. The p-values are for Wald tests based on the variance-covariance matrix estimated using the Newey-West procedure.

| | Ten future-spot spreads | | Six futures-spot spreads | | Four futures-futures spreads | | Adj. r-square |
|---|---|---|---|---|---|---|---|
| | Estimated Cumulative Impact | p-value | Estimated Cumulative Impact | p-value | Estimated Cumulative Impact | p-value | |
| **(1) 4/9/2004 to 5/1/2015** | | | | | | | |
| Cushing | 3550.97 | 0.000 | 2058.28 | 0.000 | 1492.68 | 0.000 | 0.180 |
| U.S. (no Cushing) | 205.85 | 0.864 | -52.35 | 0.941 | 258.20 | 0.776 | 0.553 |
| PADD 2 (no Cushing) | -66.83 | 0.900 | -129.35 | 0.681 | 62.51 | 0.877 | 0.061 |
| U.S. (with Cushing) | 3747.71 | 0.002 | 2007.35 | 0.004 | 1740.36 | 0.052 | 0.587 |
| PADD2 (with Cushing) | 3487.86 | 0.000 | 1935.16 | 0.000 | 1552.70 | 0.002 | 0.162 |
| **(2) 9/11/1992 to 5/1/2015** | | | | | | | |
| U.S. (with Cushing) | 4927.44 | 0.000 | 2534.05 | 0.002 | 2393.40 | 0.021 | 0.322 |
| PADD2 (with Cushing) | 4240.00 | 0.000 | 2284.80 | 0.000 | 1955.21 | 0.000 | 0.141 |
| **(3) 9/11/1992 to 4/9/2004** | | | | | | | |
| U.S. (with Cushing) | 8265.41 | 0.014 | 4613.89 | 0.026 | 3651.53 | 0.140 | 0.189 |
| PADD2 (with Cushing) | 5418.33 | 0.000 | 2986.25 | 0.000 | 2432.08 | 0.002 | 0.109 |
| **Difference (3) vs (1)** | | | | | | | |
| U.S. (with Cushing) | 4517.70 | 0.161 | 2606.53 | 0.193 | 1911.17 | 0.416 | |
| PADD2 (with Cushing) | 1930.47 | 0.128 | 1051.09 | 0.199 | 879.38 | 0.324 | |
| **Other PADDs:** | | | | | | | |
| **9/11/1992 to 5/1/2015** | | | | | | | |
| PADD 1 | 105.53 | 0.802 | -81.49 | 0.747 | 187.02 | 0.558 | 0.123 |
| PADD 3 | -270.64 | 0.815 | 48.25 | 0.945 | -318.89 | 0.717 | 0.255 |
| PADD 4 | -3.43 | 0.979 | 87.40 | 0.252 | -90.82 | 0.347 | 0.066 |
| PADD 5 | 854.60 | 0.269 | 345.66 | 0.457 | 508.94 | 0.387 | 0.069 |

**Table 4 - Inventories and operational factors for PADD1-5 and Cushing, Oklahoma**

Weekly changes in crude oil storage for PADD1-5 and Cushing, OK are regressed on the current and five lagged values of the futures-spot spread and the futures-futures spread lagged from six to nine weeks as in Table 2 but are suppressed and shown cumulatively. PADD2 (no Cushing) and Cushing results are replicated from Table 2 for convenience. 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 one week lead values of these variables to proxy for inventory changes to meet expected future changes in supply and demand. The refinery input and import figures are PADD specific. Z2-Z5 are polynomial terms to measure normal calendar inventory patterns. The p-values shown in parentheses are based on Newey-West standard errors. ***, **, * designate coefficients significantly different from zero at the 0.10, 0.50 and 0.01 levels, respectively, in two-tailed test. The regressions are estimated using weekly data from 4/9/2004 to 5/01/2015.

| | PADD 1 | PADD2 (no Cushing) | Cushing | PADD3 | PADD4 | PADD5 |
|---|---|---|---|---|---|---|
| *10 spreads Cumulative* | 193.48 | -66.83 | 3550.97*** | -816.48 | -11.44 | 918.20 |
| | (0.391) | (0.900) | (0.000) | (0.497) | (0.939) | (0.166) |
| ΔRefinery input | -0.91* | -2.12*** | -0.35 | -1.32** | -2.34*** | -1.84** |
| | (0.062) | (0.000) | (0.400) | (0.003) | (0.000) | (0.008) |
| ΔRefinery input(+1) | 0.99** | 0.07 | 0.42 | 2.49*** | 1.9*** | 0.81 |
| | (0.047) | (0.889) | (0.322) | (0.000) | (0.001) | (0.243) |
| ΔImports | 1.01*** | 1.1*** | 0.34 | 1.81*** | 0.42 | 1.31*** |
| | (0.000) | (0.001) | (0.227) | (0.000) | (0.123) | (0.000) |
| ΔImports(+1) | -0.65*** | -0.45 | 0.11 | -1.85*** | 0.18 | -0.42* |
| | (0.000) | (0.179) | (0.694) | (0.000) | (0.504) | (0.096) |
| ΔUS production | 0.52* | 0.70* | 0.44 | 0.96 | 0.10 | 0.73 |
| | (0.069) | (0.056) | (0.159) | (0.295) | (0.32) | (0.105) |
| ΔUS production(+1) | 0.12 | 0.50 | -0.40 | -0.22 | 0.2** | -0.29 |
| | (0.617) | (0.176) | (0.203) | (0.809) | (0.049) | (0.516) |
| ΔSpot Price | 2.42 | -17.25 | 11.11 | -37.86 | -1.43 | -12.09 |
| | (0.796) | (0.212) | (0.349) | (0.221) | (0.714) | (0.481) |
| Z Cumulative | 22.73*** | 2.24* | 7.61*** | 30.81*** | 4.03** | 9.53*** |
| | (0.000) | (0.082) | (0.000) | (0.000) | (0.003) | (0.000) |
| Intercept | 18.23 | -239.06 | -323.99 | 280.72 | -69.96 | -1125.56 |
| | (0.864) | (0.357) | (0.145) | (0.636) | (0.337) | (0.001) |
| Adjusted r-square | 0.159 | 0.061 | 0.180 | 0.401 | 0.089 | 0.143 |

**Table 5 - Future changes in spot price and futures market predictions basis**

This table shows the percentage of times the direction of the change in the spot price from month t to month t+i matches the sign of the predicted change based on the futures-spot spread observed at time t is reported for i=1 and 2. The predicted change based on the future-spot spread is estimated using St+i-St = α + β(Ft+i,t-St), where St is the spot price measured as the nearby futures over the five days just before expiration and Ft+i,t is the futures price of the futures contract expiring at month t+i observed at time t. Data is monthly over the 1985-2015 period. Results are separately reported for cases when the absolute value of the basis exceeds $0.50, $1.00 and $1.50 as well as the entire sample. *, **, and *** denote percentage significantly different from 50% at the 0.1, 0.05 and 0.01 levels respectively.

| **Panel A – One month ahead** | 2004-2015 | 1985-2015 | 1985-2004 |
|---|---|---|---|
| **Full sample** | | | |
| Percent | 53.38% | 51.10% | 49.57% |
| Observations | 133 | 364 | 230 |
| **│Basis│ > $0.50** | | | |
| Percent | 56.34% | 53.06% | 50.00% |
| Observations | 71 | 147 | 76 |
| **│Basis│> $1.00** | | | |
| Percent | 68.75%** | 71.93%*** | 76.00%** |
| Observations | 32 | 57 | 25 |
| **Panel B – Two months ahead** | | | |
| **Full sample** | | | |
| Percent | 54.07% | 51.79% | 50.22% |
| Observations | 135 | 363 | 229 |
| **│Basis│ > $1.00** | | | |
| Percent | 58.75% | 58.78%** | 57.97% |
| Observations | 80 | 148 | 74 |
| **│Basis│> $1.50** | | | |
| Percent | 70.45%** | 70.00%*** | 69.44%** |
| Observations | 44 | 80 | 36 |

**Table 6. Relative prices around C&C arbitrage related storage changes for Cushing, Oklahoma and U.S. (excluding Strategic Petroleum Reserve and Cushing)**

Two-way tables present increasing (decreasing) prices and increasing (decreasing) forecast change in crude oil storage due to C&C arbitrage. The relative price level during the week of the storage change as compared to j (j=2,4) weeks surrounding it (before and after). 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. Panel A utilizes Cushing storage data; Panel B uses total U.S. storage data excluding the Strategic Petroleum Reserve and Cushing storage. Data is weekly from 4/9/2004 to 5/1/2015

**Panel A. Cushing**

| | | **Forecast Storage Positive** | **Forecast Storage Negative** | **Total** |
|---|---|---|---|---|
| | **Relative Price (j=2) >1** | 134 | 168 | **302** |
| | **Relative Price (j=2) < 1** | 141 | 132 | **273** |
| | | **275** | **300** | **575** |
| Chi-Square | 3.043 | | | |
| p-value | **0.081** | | | |
| | **Relative Price (j=4) >1** | 123 | 161 | **284** |
| | **Relative Price (j=4) < 1** | 150 | 139 | **289** |
| | | **273** | **300** | **573** |
| Chi-Square | 4.240 | | | |
| p-value | **0.039** | | | |

**Panel B. U.S. (no SPR, no Cushing)**

| | | **Forecast Storage Positive** | **Forecast Storage Negative** | **Total** |
|---|---|---|---|---|
| | **Relative Price (j=2) >1** | 162 | 140 | **302** |
| | **Relative Price (j=2) < 1** | 135 | 138 | **273** |
| | | **297** | **278** | **575** |
| Chi-Square | 1.009 | | | |
| p-value | **0.315** | | | |
| | **Relative Price (j=4) >1** | 147 | 137 | **284** |
| | **Relative Price (j=4) < 1** | 148 | 141 | **289** |
| | | **295** | **278** | **573** |
| Chi-Square | 0.017 | | | |
| p-value | **0.895** | | | |

**Table 7: C&C arbitrage-related inventory changes when not price stabilizing**

The table presents a sum of the number of weeks each year and month when C&C arbitrage-related forecasted inventory changes at Cushing, Oklahoma changes were not price stabilizing. Panel A presents weeks when oil was forecast to go into storage during the period of high prices. Panel B presents weeks when oil was forecast to come out of storage during the period of low prices. The data is weekly from 4/9/2004-5/1/2015.

**Panel A: Weeks with high relative prices and forecasted storage additions**

| | |
|---|---|
| 2004 | 12 |
| 2005 | 14 |
| 2006 | 18 |
| 2007 | 5 |
| 2008 | 16 |
| 2009 | 10 |
| 2010 | 10 |
| 2011 | 9 |
| 2012 | 15 |
| 2013 | 7 |
| 2014 | 11 |
| 2015 | 7 |
| **Total** | **134** |

**Panel B: Weeks with low relative prices and forecasted storage withdrawals**

| | |
|---|---|
| 2004 | 5 |
| 2005 | 9 |
| 2006 | 7 |
| 2007 | 14 |
| 2008 | 9 |
| 2009 | 16 |
| 2010 | 17 |
| 2011 | 18 |
| 2012 | 11 |
| 2013 | 15 |
| 2014 | 11 |
| 2015 | 0 |
| **Total** | **132** |

**Table 8 - Robustness checks**

We present results for variations of Table 2 regressions. In model 1 the dependent variable is the percentage change in Cushing stocks; the refinery inputs, imports, and production variables are also changed to percentage change terms. In model 2, the lagged change in PADD3 stocks and inputs is added. In model 3, a dummy variable to denote observations in 2012 is added to the Cushing regression. In model 4, spread changes are presented in a polynomial distributed lag (PDL) format. Regressions are estimated with weekly data from 4/9/2004 to 5/1/2015.

| | Cushing percentage change | | Cushing with PADD3 changes | | Cushing with 2012 dummy | | Cushing with PDL | |
|---|---|---|---|---|---|---|---|---|
| | Coeff. | p-value | Coeff. | p-value | Coeff. | p-value | Coeff. | p-value |
| ΔSP(fut-spot) | 0.015 | 0.000 | 355.93 | 0.000 | 363.56 | 0.000 | 304.42 | 0.000 |
| ΔSP(fut-spot)(-1) | 0.007 | 0.071 | 125.69 | 0.193 | 119.75 | 0.224 | 348.93 | 0.000 |
| ΔSP(fut-spot)(-2) | 0.017 | 0.000 | 415.97 | 0.000 | 400.48 | 0.000 | 371.65 | 0.000 |
| ΔSP(fut-spot)(-3) | 0.015 | 0.000 | 390.05 | 0.000 | 386.43 | 0.000 | 374.81 | 0.000 |
| ΔSP(fut-spot)(-4) | 0.010 | 0.009 | 269.98 | 0.000 | 259.9 | 0.000 | 360.64 | 0.000 |
| ΔSP(fut-spot)(-5) | 0.010 | 0.008 | 270.97 | 0.000 | 272.99 | 0.000 | 331.37 | 0.000 |
| ΔSP(fut-fut)(-6) | 0.011 | 0.085 | 399.45 | 0.003 | 403.05 | 0.003 | 289.25 | 0.000 |
| ΔSP(fut-fut)(-7) | 0.002 | 0.728 | 45.77 | 0.727 | 38.89 | 0.773 | 236.51 | 0.000 |
| ΔSP(fut-fut)(-8) | 0.011 | 0.085 | 392.67 | 0.005 | 375.81 | 0.007 | 175.38 | 0.002 |
| ΔSP(fut-fut)(-9) | 0.006 | 0.369 | 168.44 | 0.178 | 156.38 | 0.205 | 108.09 | 0.148 |
| $\Delta PDL_1$ | | | | | | | 336.55 | 0.000 |
| $\Delta PDL_2$ | | | | | | | -32.21 | 0.166 |
| $\Delta PDL_3$ | | | | | | | -8.39 | 0.007 |
| $\Delta PDL_4$ | | | | | | | -0.14 | 0.894 |
| ΔRefinery input | -0.062 | 0.340 | -0.4071 | 0.379 | -0.3981 | 0.389 | -0.32 | 0.450 |
| ΔRefinery input(+1) | -0.004 | 0.956 | 0.1504 | 0.757 | 0.1767 | 0.719 | 0.14 | 0.735 |
| ΔImports | 0.027 | 0.100 | 0.4162 | 0.154 | 0.451 | 0.12 | 0.30 | 0.302 |
| ΔImports(+1) | -0.002 | 0.884 | -0.0091 | 0.975 | -0.0332 | 0.91 | 0.07 | 0.818 |
| ΔUS production | 0.151 | 0.036 | 0.4189 | 0.052 | 0.4281 | 0.055 | 0.30 | 0.335 |
| ΔUS production(+1) | -0.083 | 0.250 | -0.3908 | 0.057 | -0.4249 | 0.041 | -0.27 | 0.386 |
| ΔPADD3 stocks(-1) | | | 0.0005 | 0.976 | | | | |
| ΔPADD3 imports(-1) | | | 0.1222 | 0.080 | | | | |
| 2012 dummy | | | | | 292.73 | 0.039 | | |
| Z2 | 0.010 | 0.000 | 235.384 | 0.000 | 235.757 | 0.000 | 171.33 | 0.003 |
| Z3 | -0.001 | 0.001 | -17.784 | 0.000 | -17.805 | 0.000 | -14.27 | 0.001 |
| Z4 | 0.000 | 0.002 | 0.455 | 0.001 | 0.455 | 0.001 | 0.38 | 0.002 |
| Z5 (x.01) | 0.000 | 0.007 | -0.371 | 0.006 | -0.37 | 0.005 | -0.32 | 0.007 |
| ΔSpot price | -0.026 | 0.075 | 17.797 | 0.200 | 17.044 | 0.21 | 12.32 | 0.301 |
| Intercept | -0.026 | 0.011 | -622.97 | 0.004 | -652.34 | 0.003 | -276.11 | 0.222 |
| Cumulative -all spreads | 0.104 | 0.000 | 2835 | 0.000 | 2777 | 0.000 | | 0.000 |
| Cum. - 6 futures -spot | 0.073 | 0.000 | 1829 | 0.000 | 1803 | 0.000 | | |
| Cum. - 4 futures - futures | 0.031 | 0.0048 | 1006 | 0.0035 | 974 | 0.0043 | | |
| Adjusted r-square | 0.129 | | 0.185 | | 0.191 | | 0.1571 | |