On the Negative Pricing of WTI Crude Oil Futures

Adrian Fernandez-Perez*, Ana-Maria Fuertes** and Joëlle Miffre***

ABSTRACT

WTI crude oil futures markets experienced the unprecedented phenomenon of negative prices on April 2020. Energy market pundits have attributed the event to the large United States oil exchange traded fund ("USO") due to the rolling of positions out of the May 2020 contract (CLK20) before its maturity on April 21, 2020. We show empirically that USO flows do not cause the price of WTI futures in general, nor of CLK20 in particular. A blend of macroeconomic/geopolitical conditions, including the demand plunge associated with Covid19 pandemic-control measures and supply spikes due to Russia-Saudi Arabia tensions, contributed to a contangoed WTI futures curve that attracted cash-and-carry (C&C) arbitrage. C&C trades increased the inventory at Cushing, the physical settlement hub for WTI futures, which further steepened the curve and attracted more arbitrage. Long WTI futures holders panicked upon the possibility of a near tank-tops scenario, and sought hastily to unwind their positions.

Date: January 29, 2020

Keywords: WTI crude oil; Negative price; Theory of storage; Contango; Cash and carry

JEL classifications: G13, G14, Q4

Word count: 150

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*   Senior Research Fellow, Auckland University of Technology, Private Bag 92006, 1142 Auckland, New Zealand. Phone: +64 9 921 9999; Fax: +64 9 921 9940; Email: adrian.fernandez@aut.ac.nz

**   Professor of Finance and Econometrics, The Business School, City, University London, ECIY 8TZ, England; Tel: +44 (0)20 7040 0186 E-mail: a.fuertes@city.ac.uk.

***   Professor of Finance, Audencia Business School, 8 Route de la Jonelière, 44312 Nantes, France; Tel: +33 (0)2 40 37 34 34. Corresponding author.

Executive summary

On April 20, 2020, the price of the NYMEX WTI crude oil futures contract with maturity April 21, 2020 (known as the May 2020 delivery contract or CLK20) tumbled to a negative -$37.63. This is the first time a WTI futures contract has experienced a negative price since NYMEX WTI trading began on March 30, 1983. The purpose of this article is to investigate the reasons behind this unprecedented event.

Some energy market commentators have blamed the largest WTI crude oil exchange traded fund, United States Oil fund (USO), for having wacked the market. The implicit line of reasoning is that the massive USO long futures positions on WTI crude oil and the corresponding rolls nearer maturity are responsible for the collapse of WTI futures prices. Using Granger-causality tests fitted to daily data, we show that USO flows have little price impact on WTI futures and are unlikely to be responsible for the negative pricing observed in last April.

Further analysis suggests that speculative arbitrage is most likely to have led to the WTI crude oil price collapse. As from January 2020 the WTI futures market turned into contango which is likely to have attracted cash-and-carry (C&C) arbitrage. The latter together with disastrous blend of macroeconomic and geopolitical conditions, such as a demand shattered by the Covid-19 lockdowns and spikes in an already high supply triggered by Russia-Saudia Arabia tensions contributed to turn the contango into super-contango in March. The super-contango attracted rampant cash and carry (C&C) arbitrage, the long leg of which pushed the physical settlement hub (Cushing in Oklahoma) closer to a top tanks scenario. As the maturity of CLK20 became imminent, C&C traders panicked at the possibility of no feasible storage at Cushing and sought to get rid of their long positions at any price.

Thus, our findings suggest that, rather than long index trackers, the C&C arbitrageurs are responsible for the anomalous CLK20 negative pricing. Our investigation calls for C&C arbitrageurs to exert caution during super-contango stages as sudden jumps in storage costs effectively imply that the C&C strategy is not risk-free. Our findings may also call for regulators to monitor the long positions of C&C arbitrageurs close to contract maturity so that they do not dislocate the natural convergence at maturity of the futures and spot prices.

1. Introduction

The West Texas Intermediate (WTI) crude oil futures contract that is traded on the New York Mercantile Exchange (NYMEX) involves an obligation to buy or sell 1,000 barrels of light sweet crude oil at some pre-specified price and delivery date. Long (short) futures positions at contract maturity legally bind the holder to a physical settlement – taking delivery of (delivering) WTI crude oil at the Cushing hub in Oklahoma.[1] The price of WTI futures is often discussed in news reports on crude oil as benchmark. WTI crude oil is not any particular oil produced in any specific oil fields; oil produced in any world location can be considered WTI if it meets certain specifications as regards low density and low sulfur content.

The goal of this empirical investigation is to shed light on the recent anomalous pricing behavior of the May 2020 WTI futures contract with maturity date April 21, 2020 (formally known as CLK20).[2] The futures price of CLK20 swung dramatically from $18.27 (April 17, 2020) to a negative -$37.63 (April 20, 2020)[3] and climbed back to $10.01 at maturity (April 21, 2020). This is the first time that a WTI futures contract has experienced negative prices since NYMEX WTI trading began on March 30, 1983. The existence of the United States Oil fund (with ticker symbol USO), one of the main trackers of the WTI crude oil performance, has been controversial and a frequent target of criticism by energy market pundits. In particular, some oil market commentators have implicitly or explicitly stated that the massive USO long futures

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[1] Delivery should take place on any calendar day of the delivery month. For more details on WTI crude oil contract specifications see https://www.cmegroup.com/ trading/energy/crude-oil/light-sweet-crude_contract_specifications.html.

[2] CL is the NYMEX ticker symbol for WTI crude oil, K is the letter that states the delivery month (May) and the last two numbers refer to the delivery year.

[3] One long contract of WTI crude oil futures buys 1,000 barrels of oil. Thus, a negative price of -$37.63 per barrel (p/b) on April 20, 2020 meant that opening a long futures position then was highly beneficial to traders with storage facility as the contract holder would receive not only 1,000 barrels of oil at contract expiration, but also a $37,630 payment. See, for instance, https://www.bloomberg.com/news/articles/2020-05-13/one-trader-who-cashed-in-on-sub-zero-oil-prices-sees-rare-payout.

positions on WTI crude oil and the corresponding rolls as contract maturity approaches are to blame for the recent anomalous negative CLK20 pricing.[4]

This article contributes to the literature on the price behavior of WTI crude oil futures contracts, firstly, by empirically testing the conjecture that USO trading induced the negative price of CLK20 as of April 20, 2020. For this purpose, we conduct an eclectic set of Granger-causality tests to determine whether USO flows (changes in open interest) have any predictive power for subsequent price changes of CLK20. The results indicate that USO flows did not drive the returns of CLK20 which is not surprising upon the recognition that USO had already rolled all of its long positions on CLK20 to more distant contracts already as of April 13, 2020 (or seven days before the CLK20 crash). More generally, the finding that USO trading did not influence the price of CLK20 can be extended to any of the WTI futures contracts that USO has ever traded approximately since its inception from October 24, 2008 to June 29, 2020.

The second contribution of this article is to uncover the plausible causes of the negative pricing of CLK20. The empirical analysis suggests that the negative pricing of WTI futures in April 2020 was the outcome of an unfortunate blend of macroeconomic, geopolitical and storage conditions. In the early months of 2020, the worldwide demand for crude oil was shattered by 18.3% due to Covid-19 lockdowns; meanwhile, geopolitical tensions between Russia and Saudi Arabia in March 2020 increased by 3.5% an already overinflated world supply. Against this background, the WTI futures market steered into a super-contango state; namely, the spread or futures price difference between front- and second-nearest contracts, became very large and negative. Motivated by the theory of storage of Kaldor (1939), Working (1949) and Brennan (1958), we argue empirically that the Cushing storage blowout played a key role in the negative pricing. Specifically, we test the conjecture that the said super-

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[4] See, for instance, https://www.wsj.com/articles/the-fund-that-ate-the-oil-market-11587489 608 and https://www.forbes.com/sites/vineerbhansali/2020/04/21/negative-price-of-oil-is-telling-us-that-bigger-problems-are-afoot/#5536ed163a5a

contangoed WTI futures market acted as a strong catalyst for cash-and-carry (C&C) arbitrage which, in turn, depleted the Cushing storage facility. As Ederington et al. (2020) show, the C&C arbitrage on WTI crude oil – a market neutral strategy that combines the physical purchase of WTI crude oil through borrowing at a cheap spot or front-end futures price and the sale of the stored oil at a premium via distant-maturity futures contracts – is profitable as long as the WTI futures market is contangoed enough for the difference between the distant- and front-maturity prices to exceed the financing and storage costs of the long WTI crude oil position.

In the first two weeks of April 2020, numerous traders (e.g., hedge funds) saw the super contango as an opportunity for C&C arbitrage profits, and consequently, the long leg of their arbitrage pushed up the storage tanks at Cushing toward their limits. As days passed, and the maturity of CLK20 came closer, C&C traders realized that there was no spare storage facility at Cushing. As taking delivery at maturity appeared unfeasible, long CLK20 traders who had not secured storage resorted to closing their long positions at all costs, even if that meant selling at negative prices. As Nagy and Merton (2020) put it, WTI crude oil became like a toxic waste or a pile of garbage to long CLK20 traders on April 20, 2020; effectively, long traders cannot just dump crude in a lake or ocean to dispose of it; for that reason, they deemed *paying* up to $37.63 per WTI crude oil barrel *sold* as a lesser loss than taking physical delivery.

Our findings speak to the literature on the financialization of energy futures markets by showing that index traders, such as USO, did not drive the price of crude oil futures away from its fundamental value and thus, did not alter the price formation process (see e.g., Till, 2009; Tang and Xiong, 2012; Fattouh et al., 2013; Bessembinder et al., 2016; Byun, 2017). This suggests that calls for the regulation of index trackers might be, at this stage, premature. Further regulation could, in fact, be detrimental as it may discourage index trackers, important providers of risk-absorption and liquidity, from trading crude oil futures.

Our findings also speak to the empirical literature on the theory of storage[5] by bringing indirect evidence that the law of one price implied by the cost-of-carry model does not hold in the presence of storage constraints. In so doing, it complements the analysis of Ederington et al. (2020) by focusing on the anomalous negative pricing of CLK20, and by showing that limits in the availability of storage facility (i.e., reaching the nightmare scenario of exhausted storage) can hinder the execution of C&C arbitrage to the extent that futures prices become negative. Our findings therefore call for C&C traders to exert caution during super-contangoed futures markets as sudden jumps in storage costs effectively imply that the C&C strategy can suddenly become physically impossible and thus, highly risky. Our findings may thus call for regulators to monitor the long positions of C&C arbitrageurs close to delivery so that they do not dislocate the natural convergence of the futures and spot prices at maturity.

The remaining of the article unfolds as follows. Section 2 describes the data. Section 3 provides empirical tests of the role of USO trading as regards the CLK20 price crash on April 20, 2020. Section 4 analyzes other potential drivers of the event related to the fundamentals of crude oil supply and demand, Cushing storage facility, and C&C arbitrage. Section 5 concludes.

2. Data

2.1 WTI crude oil futures market data

Our investigation relies on a wide sample of daily settlement prices and open interests (or total outstanding contracts) for all 446 WTI crude oil futures traded from March 30, 1983 to June 29, 2020. According to the theory of storage, a negative futures spread at time t $(F_{t,T_1} - F_{t,T_2} <$

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[5] Geman and Ohana (2009), Symeonidis et al. (2012), Geman and Smith (2013), Gorton et al. (2013), Alquist et al. (2020), and Ahmadi et al. (2020) confirm empirically for different commodity markets that low (high) inventory levels are associated with forward curves in backwardation (contango). Using intra-day data, Alquist et al. (2020) show that news of higher-than-expected (lower-than-expected) U.S. crude oil inventories lead to very quick, within minutes after the announcement, decreases (increases) in the front futures contract price.

0 with T_1 and T_2 denoting the front- and second-nearest maturities) or upward-sloping term structure signals contango or abundant inventories, while a positive futures spread (downward-sloping term structure) signals backwardation or scarce inventories. For comparison, we also obtain the settlement prices of front and second-nearest maturity futures contracts on Brent crude oil over the available period December 12, 1988 to June 29, 2020. [6] All prices are from *Thomson Reuters Datastream.* Our investigation employs also day-close long USO open interest data on WTI crude oil from October 24, 2008 to June 29, 2020 (source: USCF archives).

2.2 Crude oil storage capacity, supply and demand data

Our empirical analysis is also based on crude oil storage capacity, supply and demand data. Weekly working storage capacities for the U.S. and different Petroleum Administration for Defense Districts (PADDs) – PADD 1 (East Coast), PADD 2 (Midwest which includes Cushing), PADD 3 (Gulf Coast), PADD 4 (Rocky Mountains) and PADD 5 (West Coast) – are obtained from the *Energy Information Administration* (EIA) website. Also from the EIA website, we obtain monthly worldwide crude oil production, as measure of supply. Finally, we obtain monthly worldwide (and U.S.) crude oil and liquid fuels consumption data, as proxy for world (and U.S.) demand, from *Thomson Reuters Datastream.* The start date of the different datasets is dictated by data availability, and the end date is June 26, 2020 throughout.

3. USO trading and WTI crude oil futures price behavior

USO is a crude oil exchange traded fund (ETF) designed to provide returns that track those of WTI crude oil.[7] Launched on October 2006 and with around $4.78 billion under management

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[6] Unlike WTI crude oil futures contract that can only be physically settled, the Brent crude oil futures contract allows for either cash or physical delivery. For more details on Brent crude oil contract specifications see https://www.theice.com/products/219/Brent-Crude-Futures.

[7] For details on USO's investment objective and strategy, see the prospectus available at https://www.uscfinvestments.com/documents/united-states-oil-fund-pro-20190228.pdf.

as of June 29, 2020, it is the largest crude oil ETF. USO does not hold oil inventories, which would entail large storage costs. Instead, it holds long positions in front-maturity contracts and rolls them to second-nearest contracts several days before the expiration of the front contracts.

USO open interest on WTI crude oil represents 6.80% of total open interest on average over our sample period. USO has been often accused by the media of distorting the WTI crude oil market. A study of prices, liquidity and individual account trading activity around the large and predictable USO roll dates conducted by Bessembinder et al. (2016) does not find evidence of the systematic use of predatory strategies.[8] Specifically, the authors find the WTI crude oil market quality improves (narrower bid-ask spreads, greater order book depth, and improved resiliency) on the largely predictable USO roll dates. Our paper complements the latter by investigating empirically the more recent claim by energy market pundits that USO trading is responsible for the anomalous negative price of the CLK20 contract on April 20, 2020.

We begin by formulating and testing a general hypothesis that concerns the causal relationship between USO trades of WTI futures contracts and the pricing of these contracts:

Hypothesis 1: *USO flows do not influence the pricing of WTI futures.*

The second hypothesis is more specific as it pertains to the causal relationship between USO trades and the anomalous price behavior of CLK20 in April 2020, stated as:

Hypothesis 2: *USO flows do not drive the pricing of the May 2020 delivery contract (CLK20).*

The empirical models estimated as regards both hypotheses employ data for the entire cross-section of WTI futures contracts ever traded by USO from October 24, 2008 to June 29, 2020. The tests for Hypothesis 2 additionally rely on a discrete variable to capture the period from March 6, 2020 to April 13, 2020 during which USO held CLK20 positions.

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[8] As put by Bessembinder et al. (2016) "*a trader who learns that another investor will transact a substantial quantity of a security can potentially profit by trading in the same direction prior to or simultaneous with the investor, before subsequently reversing the trade*." Thus, USO with its highly predictable roll dates is the "prey" and the WTI investors are the "predators".

3.1 Granger-causality tests for all USO-traded WTI futures contracts

In order to test whether USO trading Granger-causes the price of WTI futures contracts, we begin by pooling the daily excess returns of the N futures contracts on WTI crude oil that USO traded over the period October 24, 2008 to June 29, 2020 ($N=148$); we do the same pooling for the daily changes in open interest. The pooled time-series have length $T = \sum_{i=1}^{N} T_i = 3,767$ where T_i is the number of days that USO held long positions on the ith contract. We estimate a panel regression of the pooled WTI excess returns on their lagged values as well as on lagged values of the changes in USO's open interest. Formally, we estimate the panel regression model

$$r_t = \alpha_i + \alpha_{tm} + \sum_{j=1}^{P} \beta_j r_{t-j} + \sum_{j=1}^{P} \gamma_j \Delta OI_{t-j} + \varepsilon_t, i = 1, \dots, 148, \ t = 1, \dots, T \qquad (1)$$

where r_t is the WTI excess return from the end of day $t - 1$ to the end of day t, ΔOI_t the change in USO's open interest from day $t - 1$ end to day t end, α_i are individual fixed effects to account for unobserved heterogeneity across futures contracts, α_{tm} are monthly time effects to account for seasonality in crude oil markets, β_j and $\gamma_j, j = 1, \dots, P$ denote the marginal effects of prior futures returns and USO's flows, respectively, on current returns, P is a maximum lag order to capture any serial dependence in daily returns, and ε_t is an error term. The model is estimated by OLS and inferences are based on the White cross-section covariance matrix clustered by contract that accommodates contemporaneous correlation and heteroscedasticity.

The first hypothesis can be formulated in the context of (1) as $H_0: \gamma_1 = \cdots = \gamma_P = 0$ (Hypothesis 1) which says that the addition of lagged USO's flows into the model does not improve its explanatory power for returns; in other words, past USO's flows into a given futures contract do not help predicting the upcoming price change (return) of that contract, namely, they do not Granger-cause the returns. Refuting H_0 implies that USO's flows impact the price behavior of WTI futures contracts, namely, USO is a price-maker as opposed to a price-taker.

Table 1, Panel I, presents the estimation results and diagnostics for four alternative specifications of Equation (1) using a maximum lag order $P = \{1,2,3,4\}$, alongside the

hypotheses tests. The selected model specification according to the $AdjR^2$, Akaike Information Criterion (AIC) corresponds to lag order $P = 3$.. The joint hypothesis H_0 cannot be rejected (for any of the specifications) by the Wald test, which is confirmed by individual ($\gamma_j = 0$) tests using *t*-statistics. This suggests that, nearly since USO's inception, from October 24, 2008 to June 29, 2020, its flows have not caused WTI futures price changes.

[Insert Table 1 around here]

3.2 Granger-causality tests for the CLK20 contract

We now tackle the controversial issue of whether USO has influenced the price of the controversial CLK20 contract. Figure 1, Panel A, plots for the CLK20 contract the daily USO open interest on the right-hand vertical axis,[9] and the daily settlement prices on the left-hand side. At day-close on April 13, 2020 (seven business days before the price crash of CLK20 on April 20, 2020) USO did already not hold any CLK20 contract which represents *prima facie* evidence to suggest that USO trading is unlikely to have caused the anomalous negative pricing of this contract. Relatedly, was USO a "smart" player that foresaw the price crash and pulled out of the market? Panel B of Figure 2 shows that it is usual practice of USO to roll all the long positions in a given contract typically (median value) five business days before maturity.[10]

[Insert Figure 1 around here]

We formally test whether USO trading over the period March 6, 2020 to April 13, 2020 (i.e., the short period during which USO held long positions on CLK20) influenced the subsequent price of CLK20. To do so, we re-specific the above Granger-causality models, Equations (1) and (2), by introducing a CLK20 dummy variable, D_t, as follows

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[9] We have anonymized USO's open interests (right-hand axis) for confidentiality reasons.
[10] Since May 2020, USO started rolling over a 10-day period whereas previously it rolled over a 4-day period. On each day during the 4-day roll period, USO rebalanced approximately 1/4th of the announced percentage of the notional value of its nearest month instrument. See https://www.uscfinvestments.com/resources-filings/commodities/uso.

$$r_t = \alpha_i + \alpha_{tm} + \left(\sum_{j=1}^{P} \beta_j + \sum_{j=1}^{P} \beta_{D,j} D_t\right) r_{t-j} + \left(\sum_{j=1}^{P} \gamma_j + \sum_{j=1}^{P} \gamma_{D,j} D_t\right) \Delta OI_{t-j} + \varepsilon_t \qquad (2)$$

where D_t is a dummy equal to 1 on days t from March 6, 2020 to April 13, 2020 (when USO held open interest on CLK20) and 0 otherwise; the additional parameters $\beta_{D,j}$ and $\gamma_{D,j}$ in these equations capture the specific effects of USO trading on CLK20 prices, over and above the effect of USO trading on all other WTI contracts (as captured by β_j and γ_j). The hypothesis $H_0: \gamma_{D,1} = \cdots = \gamma_{D,P} = 0$ in Equation (2) states that USO's flows on the CLK20 contract did not impact its price more than it impacted the price behavior of other WTI futures contracts.

Table 1, Panel II, presents the results. Again the model for maximum lag *P*=3 is the best specification according to the $Adj - R^2$, Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC). The joint restrictions implied by the above H_0 are not rejected by the Wald statistic, which is confirmed by the individual significance $\left(\gamma_{D,j} = 0\right)$ *t*-tests. These findings in conjunction with those from the prior tests based on Equation (1), and the fact that USO did not hold any CLK20 contract already 7 business days before its maturity, suggest that overall USO's flows (changes in open interest on CLK20) did not drive the anomalous price changes of this contract, in line with Hypothesis 2. Overall, the evidence suggests that USO is unlikely to have "whacked" the market, that is, it did not induce the negative pricing of CLK20 on April 20, 2020, one day before contract expiry. Another fact worth noting in support of the contention that USO did not induce the price crash of CLK20 is that USCF launched on 2010 an ETF on Brent crude oil (United States Brent Oil Fund; ticker: BNO)[11]; if indeed USO "wacked" the WTI crude oil market we should have observed also negative prices for Brent crude oil but this is not the case – e.g., the Brent's front-end (June 2020) settlement price on April 20, 2020 was $25.57 and $19.33 on April 21, 2020.

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[11] For details on BNO's investment objective and strategy, see the prospectus available at https://www.uscfinvestments.com/documents/united-states-brent-oil-fund-pro-20200420.pdf

We test the robustness of the previous results to the inclusion of widely-accepted predictive signals within the WTI futures market as well as macroeconomic and financial predictors of WTI futures returns. Specifically, we augment Equations (1) and (2) with the one-day lagged values of the WTI crude oil futures spread, momentum or the average of CLK20 daily returns over the preceding 50 trading days, basis-momentum[12], relative basis[13], the Baker et al. (2016) Economic Policy Uncertainty index, the Aruoba et al. (2009) index designed to track real business conditions at high observation frequency, and CBOE volatility index. Table 2 reports the Wald test statistic and associated p-value for hypothesis 1 and 2. We consider an extension of Equations (1) and (2) that includes the effect of the spread in lag-distributed form, namely, the equations are augmented with $spread_{t-j}, j = 1, .., P$. Table 3 reports the estimation results, model diagnostics and Wald tests. The selected model specification according to all three criteria $AdjR^2$, AIC and BIC corresponds to maximum lag order of either 2 or 3.

[Insert Table 2 and Table 3 around here]

Both types of robustness tests suggest that the main finding remains unchallenged; USO's flows do not influence the price of WTI futures contracts in general nor of CLK20 in particular,

4. Other explanations for the anomalous pricing of CLK20

Having ruled out the USO's flows as influential on the unprecedented negative price of the CLK20 contract, this section tries to uncover the plausible causes of the event.

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[12] The basis momentum signal is designed by Boons and Prado (2019) to capture imbalances in supply and demand of futures contracts that materialize when the market-clearing ability of speculators and financial intermediaries is impaired (e.g., during episodes of high volatility and illiquidity). It is defined as the difference between the 50-day averaged returns of the front- and second-nearest contracts. Lower values predict lower excess returns in the near future.

[13] The relative basis signal is designed by Gu et al. (2020) as a measure of the convexity or concavity of the price curve. A concave futures curve (or negative relative-basis) indicates a low convenience yield, an abundant commodity and thus, a contango market. The relative basis signal is defined as $F_{t,T_1} - 2F_{t,T_2} + F_{t,T_3}$ where T_1, T_2 and T_3 are the maturities of the front, second-nearest and third-nearest contracts and F_{t,T_k} is the time t settlement price.

4.1 The super contango of March-April 2020

The world oil market experienced an ongoing oversupply (or "glut") in the last decade. Amongst the various factors contributing to the massive oversupply, a prominent one is the U.S. shale oil revolution that started in 2011 (Kilian, 2016). Other factors include *i*) a steadily falling worldwide demand for crude oil due to, e.g. the slowdown of the Chinese economy and also due to *ii*) the end of U.S. quantitative easing, and *iii*) environmental policies that promote an increasing share of energy consumption away from fossil fuels (e.g., the *Paris Agreement* of 2015). In 2019 concerns about oil demand centered on the US-China trade dispute, thorny Brexit negotiations and slower-than-expected India's economic growth. In order to prop up crude oil prices, against this background, the Organization of Petroleum Exporting Countries (OPEC) and Russia cut production during 2019 by about 1.2 million barrels a day (mb/d) or by 1.4% (compared to the world production on December 2018). As meanwhile the oil supply was being boosted by the shale oil revolution,[14] various international energy agencies began to issue warnings as regards the risk of a massive oversupply in 2020.[15]

In the early months of 2020, the Covid-19 outbreak turned the 2010s oil "glut" into a tsunami of oversupply. As of January 30, 2020, the World Health Organization (WHO) officially declared the Covid-19 outbreak as a public health emergency of international concern; on March 11, 2020, it was declared a pandemic. Attempts to curb the rapid contagion lead to worldwide economic lockdowns with thousands of restaurants and other businesses closed, factories reducing or ceasing production, fewer public transport services, residents staying out of cars, and air travel sharply reduced. As a result, the crude oil and liquid fuels consumption

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[14] See for instance https://www.reuters.com/article/us-oil-opec-report/opec-cuts-oil-supply-steeply-but-sees-growing-2019-headwinds-idUSKCN1Q11GA

[15] "*Overall, we will continue to see a well-supplied market in 2020.* […] *we will see a surplus probably, unless there is very strong demand growth recovery.*" Keisuke Sadamore, Director of Energy Markets and Security, Singapore International Energy Week, October 29, 2019.

dropped suddenly by 18.28% worldwide (19.63% in the U.S.) from March 2020 to April 2020; the corresponding figures over the period from April 2019 to April 2020 are equally shocking (-25.48% and -27.74% worldwide and for the U.S., respectively).

As if the Covid-19 pandemic was not enough, the substantial crude oil surplus was exacerbated by Russia versus Saudi Arabia geopolitical tensions from March 2020 onwards. In response to the Covid-19 led dramatic drop in demand, the OPEC members agreed on March 5, 2020 to cut production further by 1.5 mb/d prompting Russia and other non-OPEC members to follow suit (such a cut would represent a decrease by about 2% of the crude oil supply worldwide with regard to the world production on February 2020). However, on March 6, 2020 Russia rejected the call which triggered a $10 fall in crude oil prices on March 9, 2020 (or a drop by 28.22% in one day). In retaliation, Saudi Arabia announced on March 10, 2020, that it would increase its production by 2.6 mb/d (from 9.7 mb/d to 12.3 mb/d), Russia declared a similar plan to rise its supply by 0.3 mb/d. These announcements, which represented an increase in global crude oil supply by 3.5% of the world production on February 2020, only served to worsen the crude oil price fall. Following political pressure by the U.S., Saudi Arabia and other (non)-OPEC countries such as Russia and Mexico agreed on April 9, 2020 to cut production by 9.7 mb/d (or by 11.8% of the world production on March 2020). These production cuts were "too little too late" in the light of the Covid-19 demand shock and as a result, prices kept on dropping. Figure 2, Panel A, shows the timeline of these events alongside the CLK20 price.

[Insert Figure 2 around here]

The theory of storage predicts that, in this setting of a staggering high supply and low demand, the crude oil futures curve turns into contango. To confirm the latter, we plot in Figure 2, Panel B the daily futures spreads for WTI and Brent crude oil from December 2, 2019 to June 29, 2020. The switch from a positive spread (backwardation) to a persistently negative spread (contango) occurs on January 14, 2020 for WTI and on March 4, 2020 for Brent.

The sudden slowdown of crude oil demand (driven by Covid-19) alongside the Russia versus Saudi Arabia tensions are likely to have played a key role in turning the early 2020 contango in the WTI futures market into a super-contango in late March 2020; then, the WTI spread fell below the 5th percentile of its distribution over the entire available period from March 30, 1983 to June 29, 2020. Eventually, the WTI futures market reached unprecedented levels of contango with an all-time large and negative spread of -$58.06 on April 20, 2020. Brent also remained in contango but not as much as WTI and its price did not turn negative. These observations indirectly suggest that crude oil supply and demand imbalances and the associated futures contango per se did not trigger the WTI crude oi futures price collapse of April 20, 2020 since otherwise, a negative price should have been observed also to some extent for Brent futures; something else linked to the storage facility at Cushing played a key role.

4.2 C&C arbitrages "squeeze" as driver of the negative CLK20 pricing

4.2.1 Storage utilization

Given the geopolitical and economic conditions described above and the super contango observed as of late March 2020, one might naturally be concerned about the possibility of crude oil storage tanks reaching maximum storage capacity – the so called tank tops scenario. As noted, there are five PADDs in the U.S. where crude oil is stored. All hubs act as providers of storage facility for operational (e.g. refinery) purposes while, in addition, Cushing, included as part of PADD 2, is the delivery point of NYMEX WTI crude oil futures contracts.

Figure 3 plots the weekly rate of utilization of storage capacity at Cushing, at all five PADDs (excluding Cushing from PADD 2), and at the entire U.S. (excluding Cushing) in the time window from January 17, 2020 to June 26, 2020 around the negative CLK20 price event. The graph shows that 54% of refineries and tank farms at Cushing were used in late March 2020, and a much higher 76% on April 17, 2020, and 59% in June 12, 2020.

[Insert Figure 3 around here]

The storage utilization rate outside Cushing is far less volatile, with the U.S. total (excluding Cushing) utilization rate steadily rising but never exceeding 63% over the period considered. The sharp sudden rise in the utilization rates at Cushing in April (and subsequent fall in May), not seen in other U.S. storage hubs, is a reflection of the fact that the Cushing inventory dynamics does not just reflect operational factors, that is, is not exclusively a macroeconomic/geopolitical phenomenon (i.e., by-product of a large crude oil supply and shuttered demand). As shown by Ederington et al. (2020), the inventory dynamics at Cushing reflect largely the fact that this is the WTI crude oil futures contract delivery point, unlike other U.S. storage hubs. Thus, we hypothesize that the rampant C&C arbitrage induced by super-contango played a key role in pushing up the tank levels at Cushing and, in turn, expectations of a tanks top in May 2020 led to the negative price event of CLK20 on the 20th April, the day before contract maturity. This hypothesis is examined empirically next.

4.2.2 C&C arbitrage trade

In contangoed markets, C&C arbitrageurs have an incentive to take long positions in the spot asset (or in front-maturity contracts) and short positions in distant-maturity contracts. As long as the difference between the distant- and front-maturity prices is large enough relative to the cost of funding and carrying the physical commodity, the arbitrage trade will be profitable. We argue that the super-contango that prevailed as of early 2020 in the WTI futures market incentivized C&C traders to open long positions on front-end WTI contracts in March 2020, as well as short positions in more distant contracts. The long leg of the C&C trades induced the aforesaid sharp rise in storage utilization at Cushing.[16] Although they could also be hedgers, the main C&C traders are financial institutions such as hedge funds which lease storage capacity at Cushing (for further discussion see, e.g. Davis, 2007; Ederington et al., 2020).

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[16] The sample period for these correlations starts on January 17, 2020 (Friday) as opposed to January 14, 2020 (Tuesday) when the WTI futures market turned into contango) because the inventory data is only available at the weekly frequency.

In support of the claim that the WTI crude oil futures contango attracted C&C arbitrage which, in turn, subsequently raised inventory levels at Cushing, we obtain the weekly crude oil inventory levels (excluding strategic petroleum reserve) at Cushing from the EIA website and measure the correlation between the futures spread at week t (measured as the difference between the front and second-nearest futures prices) and the inventory at week $t + 2$. From January 17, 2020 to June 19, 2020, the correlation is a highly negative and significant -0.86; the more negative the futures spread at time t (deeper contango), the more C&C arbitrage trades, and, consequently, the Cushing inventories rise 2 weeks ahead when the delivery of the expired long position takes place. Similarly, the correlations between spread at t and inventory at $t + j$, $j = \{1,3,4\}$ weeks are significant and negative at -0.77, -0.82 and -0.70, respectively.

We provide next an illustrative example of how the C&C arbitrage can explain the build-up of storage tanks at Cushing in April 2020 and, in turn, the panic selling of CLK20 and negative prices that ensued driven by expectations of a tank tops scenario. As of March 12, 2020, the futures spread was at -$0.48 p/b, with the (front) April 2020 contract (CLJ20) trading at $31.50 and the (second nearest) May 2020 contract (CLK20) trading at $31.98 p/b. On that day, a C&C arbitrageur could buy (long) WTI crude oil for delivery on April 2020 (CLJ20) at $31.50 through borrowing, and sell (short) crude oil for delivery on May 2020 (CLK20) at $31.98; this strategy requires storage facility for the oil from the buy delivery date on April 2020 until the sell delivery date on May 2020. As more C&C trades engaged in this arbitrage, the Cushing hub utilization sharply increased in April and dropped in May, which is consistent with the pattern observed in Figure 3. Insofar as the costs of carrying and financing the spot

(front futures) position in April 2020, net of any convenience yield, did not exceed $0.48 p/b, the C&C arbitrage was still deemed profitable.[17]

If our conjecture regarding the role of C&C trading on the negative pricing of CLK20 is correct, the open interest of the April 2020 (CLJ20) and May 2020 (CLK20) contracts should have been particularly high on March 2020 versus historical levels. To assess this, we plot over the 150 trading days preceding the expiration day: *i*) the open interest of CLJ20 and CLK20, and *ii*) the 95th percentile of open interest of all the contracts with maturity April and May in prior years (e.g., CLJ19, CLK19 and so on). Figure 4, Panels A and B, present the results and confirm our intuition: contango attracted on March 2020 an unusually large number of positions in CLJ20 and CLK20; for example, the open interest of CLJ20 on March 12, 2020 (that is, 6 trading days before its maturity on March 18, 2020) was at 221,602 and thus very close to the 95th percentile for all April contracts at 230,953. Likewise, the open interest on the May 2020 contract kept rising in March 2020 and reached on April 2, 2020 a level of 634,727; that level of open interest 13 days before maturity had never been attained by any other futures contract before. These unusually large levels of open interest suggest that many traders, seeking to seize risk-free arbitrage profits, acted upon the contango by carrying out C&C arbitrage strategies.

[Insert Figure 4 around here]

We further hypothesize that the deepening of the contango lead to more and more C&C traders seeking to profit from buying cheap crude oil "spot" prices (i.e., long front futures contract) and selling (short positions on) more distant futures contracts. The futures spread as of April 17, 2020 (or 2 business days before the maturity of CLK20) was at -$6.76 suggesting that C&C arbitrageurs taking a long position in the controversial May 2020 (CLK20) contract

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[17] Typical monthly storage costs at Cushing are between 10 and 50 cents a barrel. https://www.wsj.com/articles/why-oil-is-11-a-barrel-now-but-three-times-that-in-autumn-11587392745 and https://br.reuters.com/article/global-oil-storage/oil-plunge-sets-off-search-for-tanks-revives-dormant-cushing-storage-trade-idUKL4N2B95KD.

at $18.27 combined with a short position in the June 2020 contract at $25.03, could theoretically make a high profit. In support of the hypothesis that many C&C trades were initiated as of April 17, 2020, Figure 4, Panel B shows that the open interest of the May 2020 contract (at 108,593) was unusually high at that very late stage exceeding by a large margin the 95th percentile of open interest on all previous May contracts (66,375). Figure 4, Panel C, likewise confirms our conjecture for the short leg of the C&C trade, the June 2020 contract: its open interest was historically high on April 17, 2020, at 538,038 above the 95th percentile at 524,410.

In the same spirit as for the other panels, Figure 4, Panel D compares the open interest of the July 2020 contract to the 95th percentile of open interests on previously traded July contracts over the 150 days preceding their maturity. The figure suggests an unusually high level of open interest of the July 2020 contract as of April 17, 2020, suggesting that C&C traders could also have used that contract for the short leg of their strategy. This is likely since on April 17, 2020, the spread between the price of the May 2020 contract and that of the July 2020 contract was at a staggering low level of -$11.15.

The inventories held at Cushing represented 76% of storage capacity on April 17, 2020 and rose to a high of 83% on May 1, 2020 (as shown in Figure 3) with the remaining storage capacity likely already leased by then.[18] C&C traders positioned long in the May 2020 contract and short in distant contracts could not at that late stage contract store space for crude oil at Cushing, which suddenly turned the expected amazing C&C profits into expected large losses. They were thus left with either one of the following stark choices: (a) paying exorbitant storage costs at maturity (if oil tank leasing was at all feasible) or (b) entering a reversing trade at all costs before maturity, just to avoid taking delivery, even if that implied selling at the negative price

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[18] *"The terminals have already contracted their storage 100%"* said Ernie Barsamian, chief executive officer of The Tank Tiger, a terminal storage clearinghouse in Princeton, New Jersey (April 20, 2020). Although the companies having leased the remaining storage could sublease, the storage costs of these sublease contracts when there is hardly spare capacity at Cushing would have been then prohibitively high.

of $-37.63 p/b. In effect, the second alternative amounts to closing the long CLK20 leg of the C&C trade by paying $37.63 a barrel to a counterparty with storage facility (the counterparty thus receives both the barrels of oil and the payment); namely, the C&C traders (and possibly, other long CLK20 holders) on Monday 20th April were willing to pay in order to get rid of their long contracts so as to avoid the obligation of having to take physical delivery. Observing the open interest of the May 2020 contract on April 20, 2020 (one day before maturity) in Figure 3, Panel B, it is noticeable that this is indeed what happened. The open interest fell from 108,593 on Friday April 17, to 13,044 on Monday April 20, or by 88%; such a huge drop had never been seen over one business trading day before.[19]

This empirical evidence is consistent with the model of the "squeeze" put forward by Bouchouev (2021) where the value of the futures spread is determined by the difference between two probability density functions, one for the upside squeeze at zero inventories, and the other for the downside squeeze at zero storage capacity. When both inventories and storage ability are available the spread coverges to the negative of the storage cost as maturity approaches. However, if inventories are within reach of the two danger zones, zero inventories or zero storage capacity, them the spread is driven by the likelihood (probability) of approaching the extremes which represent two extreme scenarios of default by the C&C trader who seeks to profit from the carry arbitrage but fails to make or take delivery (e.g., default of C&C arbitrageurs). In the first scenario (triggered in backwardation), the "reverse C&C" trader fails to deliver the crude oil because the inventory is zero. In the second scenario, (triggered in

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[19] On April 20, 2020, all the WTI futures contracts available experienced a negative return from April 17, 2020 to April 20, 2020 ranging from a brutal -305.97% (CLK20) to -1% (December 2023; CLZ23). The term structure of WTI futures prices was thus subject not only to a parallel shift down but also to a severe steepening of its slope (contango). This made matters worse: the margin profits earned on the short (back-end) positions were not enough to hedge the margin calls received on the long (front-end) positions. Thus, we argue that the price drop observed on CLK20 as of April 20, 2020 is in part due to C&C traders choosing to close their long positions rather than paying ever-increasing margin calls. This observation applies to all CLK20 traders, not just to those who were unable to secure storage facilities.

contango) the C&C trader fails to deliver physical barrels at expiry as barrels are not available. The model captures the fact that the actual default event does never happen because futures contracts are liquidated by the clearing broker, but the price of such liquidation is unbounded.

What happened next? Figure 4, Panels B and C suggests that on April 20, 2020 the C&C traders closed the long May 2020 leg, and gradually the short June 2020 leg of their arbitrage strategy. This is evidenced by open interests on the June 2020 contract dropping by 21% on April 21, 2020 and by 44% over 4 trading days (from April 20, 2020 to April 24, 2020). The open interest of the July 2020 contract dropped by 7.66% in one trading day (from April 20 to April 21, 2020), confirming that the July 2020 contract could have been part of the C&C trade.

4.3 Who else could be responsible for the negative CLK20 pricing?

Aside from C&C traders, who else could have taken long positions in CLK20 and precipitously closed these positions as of April 20, 2020, bringing the price of CLK20 into negative territory?

4.3.1 Index-trackers and long-only asset managers

The empirical tests in Section 3 ruled out USO as responsible for the negative pricing which ties well with the fact that it did not hold the CLK20 contract since 7 days before its price crash. For the same reason, it is unlikely that long-only or long-short index managers are responsible for the event since they did not held CLK20 a few days before its maturity. Commodity index providers have no interest in taking or making delivery of the physical asset at maturity and thus, they typically roll their positions to more distant contracts a few weeks before front-end contracts mature. For instance, the S&P-GSCI (the first investable commodity index and a recognizable benchmark of commodity futures performance) rolls its positions from the 5th to 9th business day of the maturity month. Consistent with this observation, Figure 4, Panel B indicates a sharp fall in CLK20 open interest from 11 to 8 days before maturity (or from April 6, 2020 to April 9, 2020), and more generally sharp falls in the open interest of all contracts over the same dates. Hence, like USO, index trackers are very unlikely to have held positions

on CLK20 on the days preceding its negative pricing, and therefore their trades cannot have induced the event. Anecdotal evidence from the *Financial Times* (April 28, 2020) or the *New York Times* (May 21, 2020) reveals, however, that some long-only fund managers (e.g., Crude Oil Treasure managed by Bank of China) still had not rolled their positions on CLK20 two days before maturity and thus, to avoid delivery, they closed their positions on April 20, 2020 at negative prices. These ill-informed investment managers bore the same losses as those incurred by the C&C traders who had not secured storage facility.

4.3.2 Hedge funds other than those engaging in C&C trades

Could long-short speculators (e.g., CTA managers) other than the ones who engaged in C&C trades be blamed for the negative pricing of CLK20? We see this as unlikely, first, because speculators also roll their contracts at least two weeks prior to maturity to avoid illiquidity-driven price distortions. Second, because as of March 31, 2020 (or 15 days before maturity; *T*-15) various trading signals hinted towards a poor forthcoming performance of CLK20 and thus, rational speculators ought to have then taken short, rather than long, positions in that contract.

First, at *T*-15 and as detailed in the sections above, the crude oil supply was at a staggering high level while demand was very low, and inventories at Cushing were rising, hinting towards a price fall (Gorton et al., 2013). Relatedly, second, the *futures spread* was very negative at -$4.03 (compared to a 5th percentile of -$1.41 from March 30, 1983 to June 29, 2020). Thus, the term structure of crude oil futures prices was upward-sloping and very steep at *T*-15 which predicts a drop in CLK20 prices (Erb and Harvey, 2006; Gorton and Rouwenhorst, 2006).

Third, at *T*-15 the average of CLK20 daily returns over the preceding 50 trading days was very low at -2.11% (compared to the 5th percentile of the distribution of all contracts from March 30, 1983 to June 29, 2020 at -0.56%). According to the *momentum* literature, this highly negative momentum signal predicted poor performance of CLK20 in the run-up to maturity (Miffre and Rallis, 2007; Moskowitz et al., 2012).

Fourth, the *basis-momentum* signal took at *T*-15 the very negative value of -0.0036 (compared to a 5th percentile of -0.0006 from March 30, 1983 to June 29, 2020) which is also a warning signal of a price drop.

Finally, the *relative basis* signal at *T*-15 takes a negative value of -$0.85 (compared to a 5th percentile of -$0.52 from March 30, 1983 to June 29, 2020). Thus, the term structure of WTI futures prices was unusually concave, suggesting that the-then front-maturity contract (CLK20) might be overpriced. Table 4 summarizes all predictive signals over the entire sample period.

[Insert Table 4 around here]

Since CTAs and managed futures funds rely on some (or a mix) of the above signals as predictors of futures prices (e.g. Asness et al., 2015; Fernandez-Perez et al., 2019), it is reasonable to assume that they took short (instead of long) positions in CLK20 on March 31, 2020, in the hope of closing them nearer maturity at much lower prices, and thus, earning a premium. By entering a reversing (long) trade closer to maturity (e.g., at *T*-2), these short speculators offered the C&C traders that were seeking to reverse their positions part of the liquidity that they craved for and thus, if anything, they prevented the negative price event suffered by the May 2020 delivery contract from being even more dramatic than it was.

4.3.3 What about the long hedgers?

Could one explanation for the negative pricing of CLK20 on April 20, 2020 be that many long CLK20 hedgers (i.e., processors or consumers of crude oil) desperately sought to enter a reversing trade one day before maturity and precipitated the negative pricing of the contract? We see this as unlikely for two reasons. First, as the WTI market entered a phase of deep contango, long hedgers had an incentive to decrease their long hedge, rather than increase it (see Stulz, 1996 on selective hedging).[20] Some processors and consumers of WTI crude oil

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[20] Selective hedging is a common practice of hedgers (consumers and producers) who simultaneously seek to reduce the risk of their spot position (risk minimization) and earn a

might even have considered the possibility of not hedging at all, hoping to buy crude oil in the spot market at a very low price when needed in the near future. Second, hedgers typically close their positions before maturity and therefore, do not take (or make) delivery; thus, very few hedgers shall have ended up in the dire predicament of C&C traders; namely, as of April 20, 2020 very few hedgers shall have been long CLK20 and short storage facility.

5. Conclusions

On April 20, 2020 the NYMEX WTI crude oil futures market crashed and the prices of the May 2020 delivery contract (CLK20) fell into very negative territory. Energy market pundits hinted that United States Oil fund (USO), the largest WTI crude oil exchange traded fund, had induced the negative pricing. Using a comprehensive data set of WTI crude oil futures prices and USO open interest we conduct formal empirical tests of this contention. The results reveal that USO is not responsible for the negative pricing of CLK20. More generally, we show that USO flows do not Granger-cause the prices of WTI futures contracts in general, nor of CLK20 in particular.

Further analysis suggests that a disastrous blend of macroeconomic and geopolitical conditions, such as a rising surplus triggered by geopolitical tensions and a demand obliterated by the Covid-19 lockdowns, prompted a super-contangoed WTI futures market. The steep upward-sloping term structure of WTI futures prices, in turn, attracted a splurge of cash-and-carry (C&C) arbitrages with a perverse feedback effect. The increase in long front-maturity C&C positions contributed to boost the storage utilization at Cushing, the storage hub where the NYMEX WTI futures contract is settled. The sharp build-up of inventory induced by the long leg of C&C arbitrage strategies ended up depleting the available storage capacity at Cushing. In the second and third weeks of April 2020, long WTI futures holders (mostly C&C arbitrageurs) panicked upon the realization that there was effectively no storage facility left at

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premium by forecasting price changes (speculation). Through selective hedging they under- or over-hedge their risk exposures.

Cushing, and sought to get rid of their contracts at unprecedented negative prices to avoid taking

delivery. Rather than the long index trackers like USO, the C&C arbitrageurs played a key role.

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Figure 1. WTI crude oil futures prices and USO trading

Panel A plots the daily CLK20 settlement price (left axis) and USO open interest (right axis) from January 1, 2020 to April 21, 2020. Panel B plots for the pool of 148 WTI contracts ever held by USO over the sample period, the maximum, median and minimum of USO open interest.

Panel A: price of May 2020 delivery contract and USO's open interest
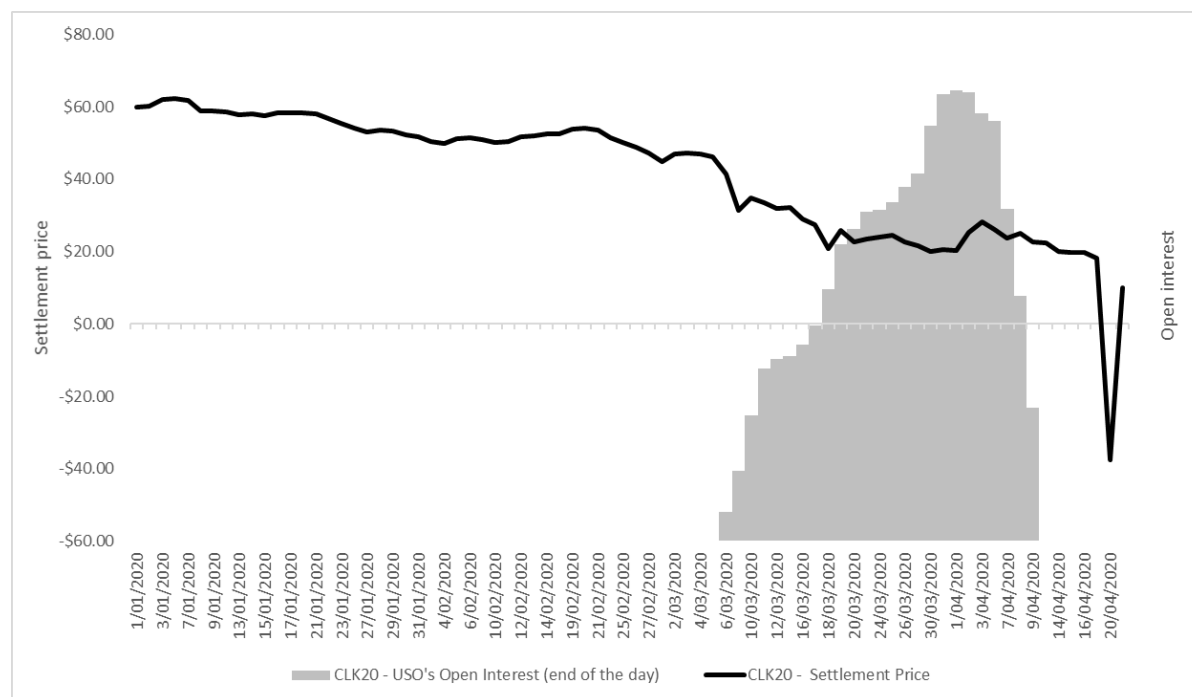
Panel B: distribution of open interest across the 148 WTI contracts ever held by USO
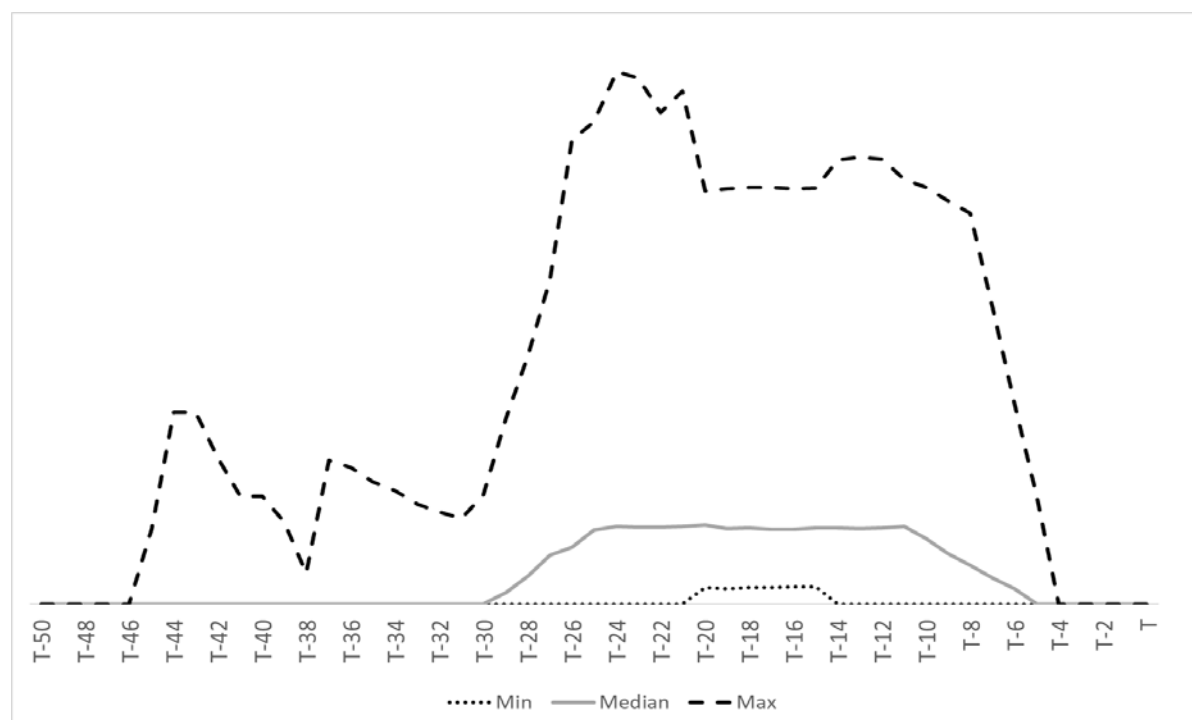
Figure 2. WTI crude oil supply and demand fundamentals and CLK20 prices

Panel A plots the evolution of CLK20 prices alongside various economic and geopolitical events. Panel B plots the futures spreads of WTI and Brent crude oil with the horizontal line denoting the 5th percentile of the distribution of WTI spreads from March 30, 1983 to June 29, 2020.

Panel A: Timeline of economic and geopolitical events and the price of CLK20
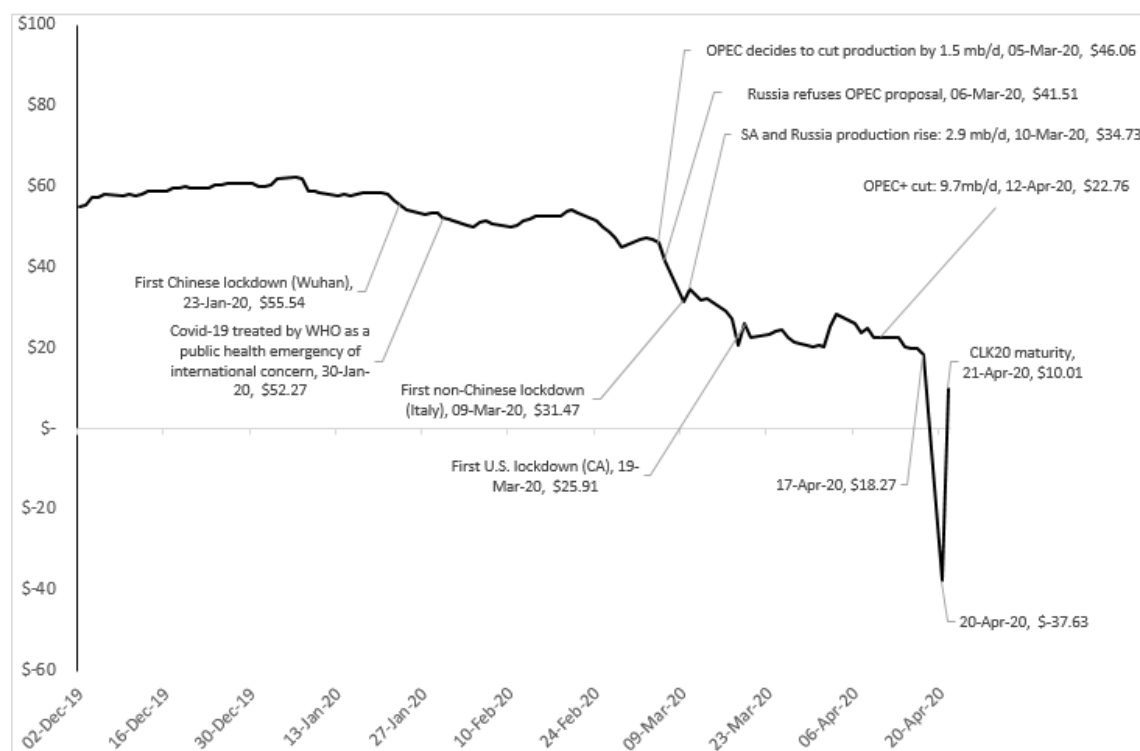
Panel B: Evolution of futures spreads
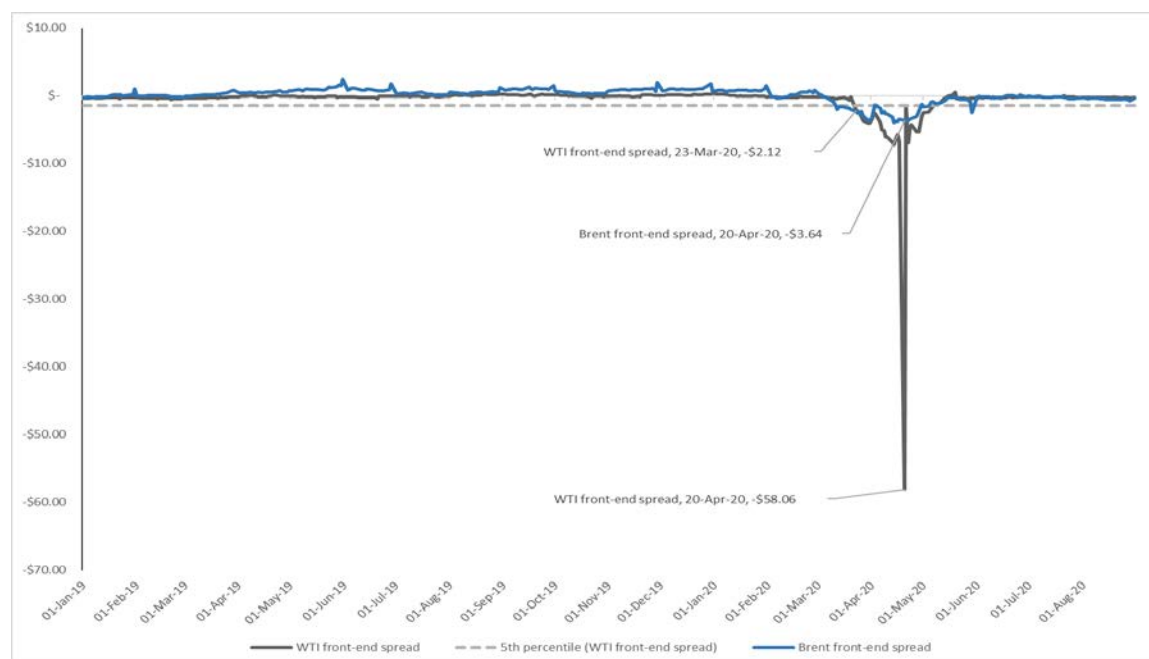
Figure 3. Crude oil storage capacity utilization in different PADDs

The figure plots the weekly crude oil storage capacity utilization in Cushing, in the U.S. (excluding Cushing) and in different Petroleum Administration for Defense Districts (PADDs); PADD 1 (East Coast), PADD 2 (Midwest which excludes Cushing), PADD 3 (Gulf Coast), PADD 4 (Rocky Mountains) and PADD 5 (West Coast). The sample is from January 17, 2020 to June 26, 2020.
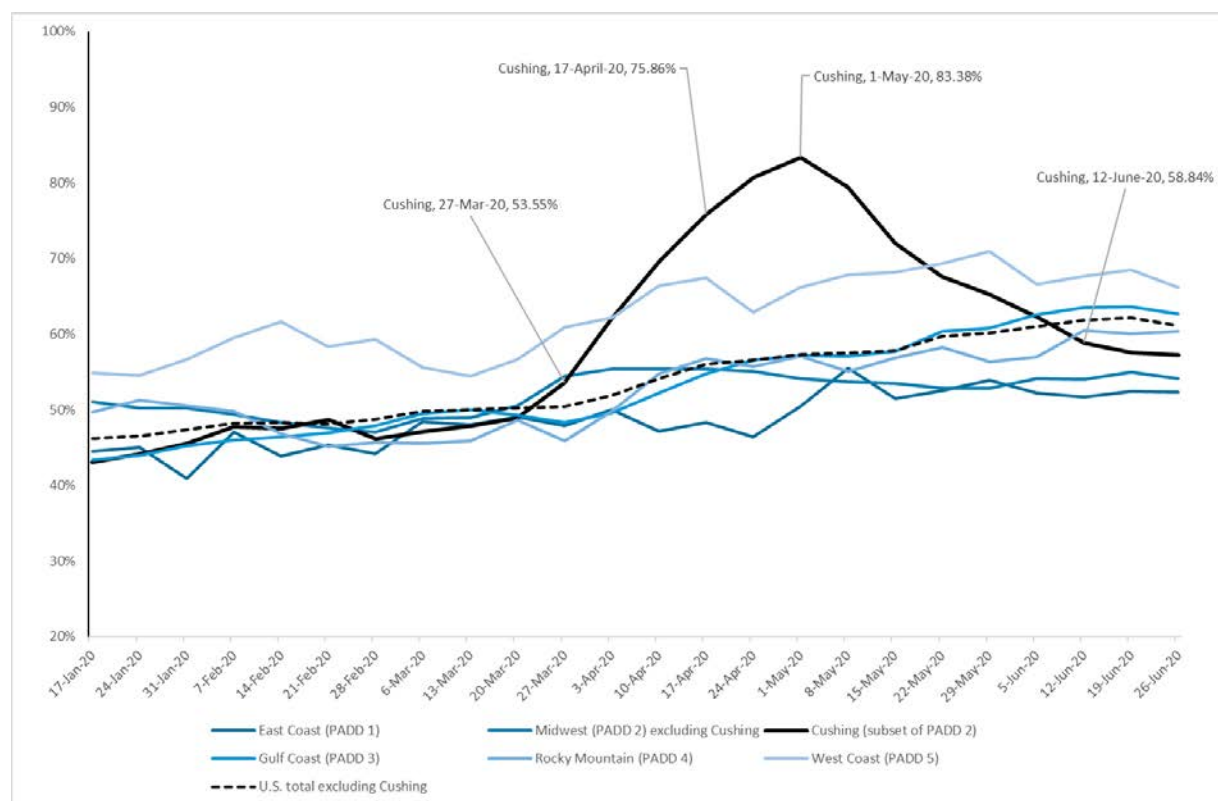
Figure 4. Open interest of various WTI contracts up to 150 days before maturity

The figure plots the open interests of the WTI April (May, June and July) 2020 contracts 150 days before their maturity against the 95th percentile and median of open interest of all WTI April (May, June and July, respectively) contracts traded before 2020 since inception.

Panel A: April contracts
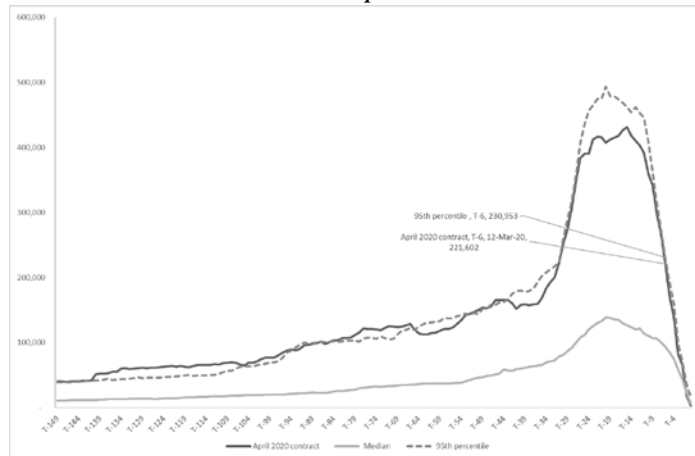
Panel B: May contracts
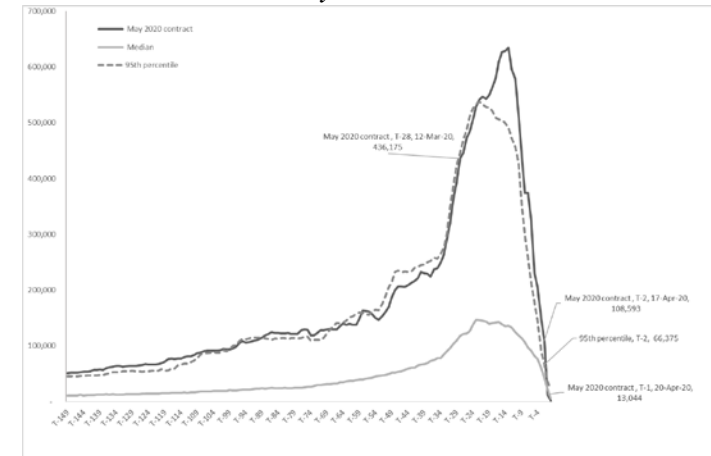
Panel C: June contracts
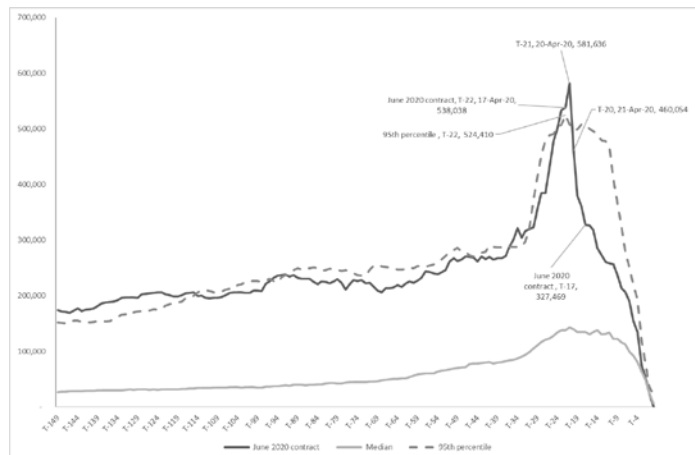
Panel D: July contracts
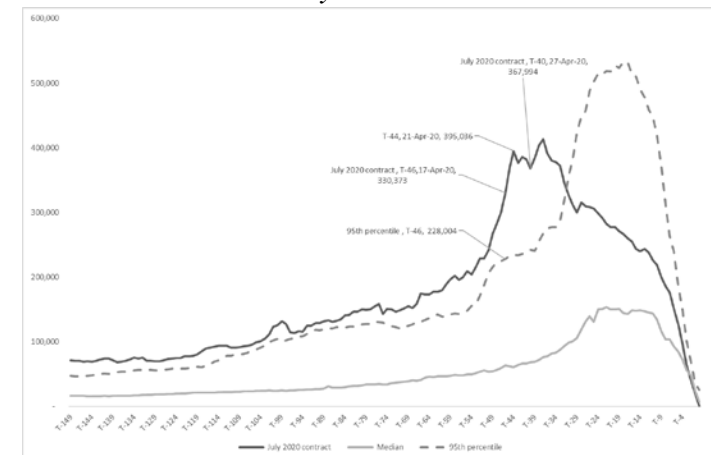
Table 1. Granger causality tests for daily WTI futures returns

The table reports parameter estimates and robust *t*-statistics in parentheses for the panel Equations (1) and (2) based on daily returns and daily USO flows (changes in open interest) using as maximum lag order $P=\{1,2,3,4\}$. The null hypothesis for the Wald test in Panel I is $H_0: \gamma_1 = \cdots = \gamma_P = 0$ in Equation (1) which states that USO's flows do not Granger-cause WTI futures returns, and in Panel II is $H_0: \gamma_{D,1} = \cdots = \gamma_{D,P} = 0$ implying that USO's flows do not cause the returns of CLK20 more than they caused the returns of other contracts. Inferences are based on the White period covariance - errors clustered by contract - that accommodates heteroscedasticity and serial dependence (within cluster) of arbitrary form. Bold denotes 5% level significant. The estimation sample are the pooled daily returns and daily USO open interest changes for all contracts traded by USO from October 23, 2008 to June 29, 2020. For ease of presentation, the γ_p and $\gamma_{p,D}$ estimates are multiplied by 10^6.

| Panel I: USO flows and WTI futures prices					Panel II: USO flows and CLK20 price				
Panel A: Coefficients on lagged returns					**Panel A: Coefficient on USO lagged position change**				
β_1	-0.1023	**-0.1222**	**-0.1389**	**-0.1324**	γ_1	-0.3000	-0.0669	0.0223	-0.0105
	(-1.59)	(-1.98)	(-2.61)	(-2.38)		(-1.42)	(-0.13)	(0.04)	(-0.02)
β_2		**-0.1246**	**-0.1277**	**-0.1299**	γ_2		-0.1920	-0.4150	-0.5210
		(-2.56)	(-2.81)	(-2.95)			(-0.43)	(-0.73)	(-0.89)
β_3			-0.0893	-0.0861	γ_3			0.2570	0.2630
			(-1.86)	(-1.87)				(0.89)	(0.62)
β_4				0.0044	γ_4				0.1280
				(0.07)					(0.39)
Panel B: Coefficients on USO lagged position change					**Panel B: Coefficient on USO lagged position change x D**				
γ_1	-0.2820	-0.0948	-0.0533	-0.0734	$\gamma_{1,D}$	0.5150	-3.5300	-4.6900	-4.8200
	(-1.37)	(-0.19)	(-0.11)	(-0.14)		(0.45)	(-1.43)	(-1.71)	(-1.62)
γ_2		-0.1280	-0.3440	-0.4420	$\gamma_{2,D}$		**6.2200**	4.0300	4.3000
		(-0.29)	(-0.60)	(-0.75)			(2.08)	(1.35)	(1.36)
γ_3			0.3100	0.3510	$\gamma_{3,D}$			4.6600	5.1000
			(1.01)	(0.79)				(1.17)	(1.19)
γ_4				0.0882	$\gamma_{4,D}$				-1.6400
				(0.27)					(-0.35)
$H_0: \gamma_1 = \cdots = \gamma_P = 0$	1.87	1.11	1.23	1.64	$H_0: \gamma_{D,1} = \cdots = \gamma_{D,P} = 0$	0.20	**7.52**	5.03	5.24
	{0.172}	{0.575}	{0.746}	{0.802}		{0.651}	{0.023}	{0.170}	{0.264}
Individual FE	Yes	Yes	Yes	Yes	**Individual FE**	Yes	Yes	Yes	Yes
Month FE	Yes	Yes	Yes	Yes	**Month FE**	Yes	Yes	Yes	Yes
Adj-R²	1.22%	2.48%	3.72%	3.56%	**Adj-R²**	1.33%	3.83%	5.31%	5.14%
AIC	-4.204	-4.222	-4.251	-3.913	**AIC**	-4.205	-4.234	-4.266	-4.244
BIC	-3.930	-3.935	-3.949	-4.116	**BIC**	-3.927	-3.940	-3.953	-3.912
#Num. Obs.	3620	3473	3326	3179	**#Num. Obs.**	3620	3473	3326	3179

Table 2. Granger causality tests for daily WTI futures returns with various controls.

The table reports the Wald test statistics and p-values for panel Equations (1) and (2) based on daily returns and daily USO flows (changes in open interest) using maximum lag $P=\{1,2,3,4\}$, augmented by several controls. The main variables are the pooled daily returns and USO open interest changes for all contracts traded by USO from October 23, 2008 to June 29, 2020. The controls are the one-day lagged values of the futures spread (Panel A), momentum (Panel B), basis-momentum (Panel C), relative basis (Panel D), economic policy uncertainty (EPU; Panel E), Aruoba-Diebold-Scotti Business Conditions Index (ADS; Panel F), and CBOE volatility index (VIX; Panel G). The null hypothesis in Panel I is H_0: $\gamma_1 = \cdots = \gamma_P = 0$ for Equation (1) which states that USO's flows do not Granger-cause WTI futures returns, and in Panel II is H_0: $\gamma_{D,1} = \cdots = \gamma_{D,P} = 0$ for Equation (2) implying that USO's flows do not cause the returns of CLK20 more than they caused the returns of other contracts. Inferences are based on the White period covariance - errors clustered by contract - that accommodates heteroscedasticity and serial dependence (within cluster) of arbitrary form. Bold denotes 5% level significant.

Panel I: USO flows and WTI futures prices					Panel II: USO flows and CLK20 price				
$P=$	*1*	*2*	*3*	*4*	$P=$	*1*	*2*	*3*	*4*
Panel A: Augmented by lagged futures spread					**Panel A: Augmented by lagged futures spread**				
$H_0: \gamma_1 = \cdots = \gamma_P = 0$	0.74	0.81	3.70	4.39	$H_0: \gamma_{D,1} = \cdots = \gamma_{D,P} = 0$	0.08	4.07	3.93	4.09
	{0.390}	{0.666}	{0.295}	{0.356}		{0.782}	{0.131}	{0.269}	{0.395}
Panel B: Augmented by lagged momentum					**Panel B: Augmented by lagged momentum**				
$H_0: \gamma_1 = \cdots = \gamma_P = 0$	2.13	1.34	1.15	1.56	$H_0: \gamma_{D,1} = \cdots = \gamma_{D,P} = 0$	0.19	**7.73**	5.28	5.48
	{0.144}	{0.512}	{0.764}	{0.817}		{0.664}	{0.021}	{0.152}	{0.242}
Panel C: Augmented by lagged basis-momentum					**Panel C: Augmented by lagged basis-momentum**				
$H_0: \gamma_1 = \cdots = \gamma_P = 0$	1.80	1.08	0.99	1.38	$H_0: \gamma_{D,1} = \cdots = \gamma_{D,P} = 0$	0.36	**8.47**	5.65	5.92
	{0.180}	{0.583}	{0.805}	{0.848}		{0.549}	{0.015}	{0.130}	{0.205}
Panel D: Augmented by lagged relative basis					**Panel D: Augmented by lagged relative basis**				
$H_0: \gamma_1 = \cdots = \gamma_P = 0$	0.58	1.94	4.97	5.17	$H_0: \gamma_{D,1} = \cdots = \gamma_{D,P} = 0$	0.02	4.87	4.55	4.60
	{0.446}	{0.378}	{0.174}	{0.270}		{0.895}	{0.088}	{0.208}	{0.331}
Panel E: Augmented by lagged EPU					**Panel E: Augmented by lagged EPU**				
$H_0: \gamma_1 = \cdots = \gamma_P = 0$	1.88	1.11	1.22	1.64	$H_0: \gamma_{D,1} = \cdots = \gamma_{D,P} = 0$	0.19	**7.43**	5.09	5.36
	{0.171}	{0.574}	{0.747}	{0.801}		{0.667}	{0.024}	{0.166}	{0.252}
Panel F: Augmented by lagged ADS					**Panel F: Augmented by lagged ADS**				
$H_0: \gamma_1 = \cdots = \gamma_P = 0$	1.88	1.10	1.18	1.58	$H_0: \gamma_{D,1} = \cdots = \gamma_{D,P} = 0$	0.21	**7.16**	5.11	5.31
	{0.170}	{0.576}	{0.758}	{0.813}		{0.649}	{0.028}	{0.164}	{0.257}
Panel G: Augmented by lagged VIX					**Panel G: Augmented by lagged VIX**				
$H_0: \gamma_1 = \cdots = \gamma_P = 0$	2.03	1.13	1.23	1.63	$H_0: \gamma_{D,1} = \cdots = \gamma_{D,P} = 0$	0.11	**7.31**	5.07	5.28
	{0.155}	{0.568}	{0.747}	{0.803}		{0.738}	{0.026}	{0.167}	{0.259}

Table 3. Granger causality tests for daily WTI futures returns on lag-distributed spreads.

The table reports parameter estimates and robust *t*-statistics in parentheses for panel Equations (1) and (2) where the main variables are the pooled daily returns and daily USO open interest changes for all contracts traded by USO from October 23, 2008 to June 29, 2020, now augmented by the distributed-lag daily futures spread up to a maximum lag $P=\{1,2,3,4\}$. The null hypothesis for the Wald test in Panel I is $H_0: \gamma_1 = \cdots = \gamma_P = 0$ for Equation (1) which states that USO's flows do not Granger-cause WTI futures returns, and in Panel II is $H_0: \gamma_{D,1} = \cdots = \gamma_{D,P} = 0$ for Equation (II) implying that USO's flows do not cause the returns of CLK20 more than they caused the returns of other contracts. Inferences are based on the White period covariance - errors clustered by contract - that accommodates heteroscedasticity and serial dependence (within cluster) of arbitrary form. Bold denotes 5% level significant. To ease presentation, the γ_p and $\gamma_{p,D}$ estimates are multiplied by 10^6.

Panel I: USO flows and WTI futures prices					Panel II: USO flows and CLK20 price				
Panel B: Coefficients on lagged returns					**Panel B: Coefficient on USO lagged position change**				
β_1	**-0.1321**	**-0.1602**	**-0.1663**	**-0.1631**	γ_1		-0.1150	0.2790	0.2820	0.2690
	(-2.54)	(-3.66)	(-3.83)	(-3.66)			(-0.79)	(0.90)	(0.83)	(0.77)
β_2		**-0.1425**	**-0.1375**	**-0.1428**	γ_2			-0.3620	-0.7610	**-0.8360**
		(-2.86)	(-3.04)	(-3.24)				(-1.14)	(-1.88)	(-1.96)
β_3			**-0.0966**	-0.0874	γ_3				0.4210	0.2320
			(-1.96)	(-1.90)					(1.65)	(0.70)
β_4				-0.0054	γ_4					0.3730
				(-0.09)						(1.25)
Panel C: Coefficients on USO lagged position change					**Panel C: Coefficient on USO lagged position change x D**				
γ_1	-0.1220	0.2110	0.1730	0.1690	$\gamma_{1,D}$		-0.3180	-4.2900	-5.3000	-5.3800
	(-0.86)	(0.69)	(0.51)	(0.49)			(-0.28)	(-1.72)	(-1.84)	(-1.75)
γ_2		-0.2910	-0.6960	-0.7600	$\gamma_{2,D}$			6.0300	4.3000	4.6500
		(-0.89)	(-1.68)	(-1.74)				(1.95)	(1.43)	(1.43)
γ_3			0.4760	0.3060	$\gamma_{3,D}$				3.8300	4.7600
			(1.73)	(0.86)					(0.92)	(1.05)
γ_4				0.3390	$\gamma_{4,D}$					-3.0000
				(1.12)						(-0.62)
$H_0: \gamma_1 = \cdots = \gamma_P = 0$	0.74	0.81	3.70	4.39	$H_0: \gamma_{D,1} = \cdots = \gamma_{D,P} = 0$		0.08	4.07	3.93	4.09
	{0.390}	{0.666}	{0.295}	{0.356}			{0.782}	{0.131}	{0.269}	{0.395}
Individual FE	Yes	Yes	Yes	Yes	**Individual FE**		Yes	Yes	Yes	Yes
Month FE	Yes	Yes	Yes	Yes	**Month FE**		Yes	Yes	Yes	Yes
Adj-R²	10.04%	12.35%	10.94%	11.06%	**Adj-R²**		10.06%	13.52%	12.35%	12.48%
AIC	-4.297	-4.328	-4.328	-4.310	**AIC**		-4.297	-4.340	-4.343	-4.324
BIC	-4.022	-4.039	-4.025	-3.991	**BIC**		-4.018	-4.044	-4.028	-3.990
#Num. Obs.	3620	3473	3326	3179	**#Num. Obs.**		3620	3473	3326	3179

Table 4. Predictive signals of futures prices

This table reports the descriptive statistics of various signals used in the literature as predictors of futures prices: spread (difference between the front-maturity minus the second-maturity futures prices), momentum (50-day moving average returns of the front-maturity futures contracts), basis-momentum (the difference between the 50-day moving average returns of the front-maturity futures contracts and the second-maturity futures contracts) and relative basis (the difference between the front-maturity and second-maturity spreads). The sample period is from March 30, 1983 to June 29, 2020.

	Futures spread	Momentum	Basis-momentum	Relative basis
Signal as of March 31, 2020	-4.03	-0.0211	-0.0036	-0.8500
Percentile 5%	-1.41	-0.0056	-0.0006	-0.5200
Median	-0.07	0.0004	0.0000	-0.0300
Percentile 95%	0.98	0.0044	0.0006	0.4260
Mean	-0.10	0.0000	-0.0001	-0.0540
Standard deviation	1.01	0.0035	0.0005	0.6485
Skewness	-20.59	-1.72	-3.81	-53.60
Excess kurtosis	1142.76	8.98	52.11	4340.54