On the Negative Pricing of WTI Crude Oil Futures

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ABSTRACT

WTI crude oil futures markets experienced the unprecedented phenomenon of negative prices on April 20, 2020. Several energy market pundits 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 sudden demand plunge associated with Covid19 pandemic-control measures and various supply spikes due to Russia-Saudi Arabia tensions, contributed to a contangoed WTI futures curve that attracted cash-and-carry (C&C) arbitrage, sharply increased the inventories at Cushing, and fed into a super-contango. The very steep WTI futures curve kept attracting rampant arbitrage until eventually a panic selloff and liquidity freeze were sparked by fears of a near tank-tops scenario at Cushing.

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Executive summary

On April 20, 2020 the price of a barrel of oil for delivery the following month plummeted $40 in an hour, settling negatively at -$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 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 April 2020.

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 arbitrage trades, together with a disastrous blend of falling demand and rising supply conditions (triggered by the Covid-19 lockdowns and geopolitical Russia versus Saudi-Arabia tensions, respectively), turned the contango into a super-contango during March. The super-contango subsequently attracted rampant arbitrage which increased rapidly the inventories at Cushing (Oklahoma), the physical settlement hub for WTI futures. As the maturity of CLK20 became imminent, an unusually large number of traders with long positions sought to exit the market.

Our findings suggest that, rather than long index trackers, the C&C arbitrageurs created the conditions for the anomalous CLK20 negative pricing by filling up the Cushing tanks. It is likely that the massive sell-off and liquidity freeze were sparked by fears that Cushing had effectively reached tank-tops but we cannot rule out, in conjunction with this, that short position holders may have exercised “market power” on that day.

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) – meaning effectively that sellers paid buyers to take crude oil barrels off their hands[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

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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.

oil market commentators have implicitly or explicitly stated that the massive USO long futures 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 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 rampant cash-and-carry (C&C) arbitrage catalyzed by a dramatic oversupply of crude oil that effectively depleted the storage facility at Cushing. In the early months of 2020, the crude oil 'glut' inherited from the last decade was exacerbated by the shattered worldwide demand for crude oil due to Covid-19 lockdowns alongside geopolitical tensions between Russia and Saudi Arabia in March 2020 that resulted in various supply spikes. Against this background, the WTI futures market steered into a contango state; namely, the spread or futures price difference between front- and second-nearest contracts, became very large and negative. Numerous traders saw the contango as an opportunity for C&C arbitrage

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[4] See, for instance, https://www.wsj.com/articles/the-fund-that-ate-the-oil-market-11587489608 and https://www.forbes.com/sites/vineerbhansali/2020/04/21/negative-price-of-oil-is-telling-us-that-bigger-problems-are-afoot/#5536ed163a5a

profits, and consequently, the long leg of their arbitrage increased sharply the inventories at Cushing, and fed into a super-contango. As the maturity of CLK20 came closer, the large amount of long positions combined with fear of a tank tops scenario at Cushing created an unprecedented illiquidity problem. Long CLK20 traders who had not secured yet any storage facility 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 (Kaldor, 1939; Working, 1949; Brennan, 1958)[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. 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.

[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.

Likewise, traders not seeking to take physical delivery (e.g., swap dealers) need to exert caution in rolling their long positions sufficiently ahead of maturity to avoid being caught in such liquidity freeze outs in the future.

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 ($F_{t,T_1} - F_{t,T_2} < 0$ 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 *Refinitiv 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

[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.

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 *Refinitiv 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 as of June 29, 2020, it is the largest crude oil ETF. USO does not hold oil inventories, which would entail large storage costs, but instead holds long positions in front-end maturity contracts and rolls them to second-nearest contracts several days before the front-end contract expiry.[8]

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 futures market. A study of prices, liquidity and individual account trading activity around the large and predictable USO roll dates by Bessembinder et al. (2016) does not find evidence of systematic use of predatory strategies.[9] Specifically, the authors find the WTI crude oil

[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.

[8] 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.

[9] 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".

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.

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 *i*th contract ($N =$ 148 contracts and T_i varies across contracts with median value 23 business days). 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

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

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 robust standard errors (period clustered) that allow for contemporaneous correlation and heteroscedasticity across contracts.[10]

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 Adj-R^2 and Akaike Information Criterion (AIC) corresponds to the maximum 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.

[10] USO holds positions usually on one (at most two) contracts per day and therefore the White robust standard errors that are cross-section clustered are unfeasible in the present context.

[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,[11] 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.

[Insert Figure 1 around here]

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

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

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.

[11] We have anonymized USO's open interests (right-hand axis) for confidentiality reasons.

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 $(\gamma_{D,j} = 0)$ 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)[12]; 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 front-contract (May 2020 delivery) on March 30, 2020 was at \$22.76 and at \$22.74 on the maturity day March 31, 2020, the Brent futures contract for June delivery on April 20, 2020 was at \$25.57 and at \$19.33 on April 21, 2020.

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

[12] 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

over the preceding 50 trading days, basis-momentum[13], relative basis[14], 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. In addition, we consider an extension of Equations (1) and (2) that includes the effect of the futures 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 $Adj{-}R^2$, AIC and BIC has maximum lag order of either 2 or 3.

[Insert Tables 2 and 3 around here]

Hypotheses 1 and 2 are not rejected in Table 2 for any of the augmented models. In Table 3, some test rejections are observed but they are statistically quite mild at the 10% level and are driven by the first or second lag, $D_t \ x \ OI_{t-j}, j = 1$ or 2. This finding reassuringly suggests that any possible impact of changes in USO open interest on the futures price occurs at most with a one or two day delay. Given that USO did not have any position on CLK20 seven days before maturity and given also that it held only 25% of its CLK20 positions at the end of day eight before maturity, any impact of its flows on CLK20 could have only occurred with a six day delay which is unlikely according to these findings. Hence, it is highly unlikely that USO flows induced the April 20, 2020 price crash. In sum, both types of robustness tests confirm that USO's flows do not influence the price of WTI futures in general nor of CLK20 in particular.

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[13] 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.

[14] 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. 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.

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 it, a prominent one is the U.S. shale oil revolution that started in 2011 (Kilian, 2016) while 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).[15] Various international energy agencies began to issue warnings about the possibility of a massive oversupply in 2020.[16]

To make matters worse, 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

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

[16] "*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.

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 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 crisis exacerbating the inherited glut was not enough, Russia versus Saudi Arabia geopolitical tensions from March 2020 onwards resulted in various spikes of extra supply. 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 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 later 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 modest 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 ("super contango") with an all-time large and negative spread of -$58.06 on April 20, 2020. Brent also entered a super-contango state relative to its historical spread but not as much as WTI; the Brent futures price did not enter negative territory. These observations indirectly suggest that crude oil supply and demand imbalances and the associated (super)-contango of futures prices per se did not trigger the WTI futures price collapse on April 20, 2020 since otherwise, a negative price should have been observed also to some extent for Brent futures; something else linked to the Cushing storage hub must have played a key role.

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

4.2.1 Sharp rise in storage utilization rate at Cushing

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 (broadly speaking, tank capacity filled up with crude oil over all tank capacity available), 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. There is an upward trend in the storage utilization rate in all hubs (even though the sharp rise at Cushing utilization rate belittles it) with implications for storage costs.[17]

[Insert Figure 3 around here]

The graph shows 54% of refineries and tank farms at Cushing were full in late March 2020, and a much higher 76% on April 17, 2020, and 59% in June 12, 2020. [18] 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. Although we cannot directly measure the changes in Cushing inventory due to C&C arbitrage, the contrast shown in Figure 3 between Cushing and the other hubs is quite revealing: the very sharp rise in the utilization rates at Cushing in April (and equally sharp fall in May), not seen in other U.S. storage hubs, clearly suggests that the Cushing inventory dynamics does reflect much more than operational factors; mostly, it reflects the fact that this is the WTI crude oil futures contract delivery point, unlike other U.S. storage hubs. Relatedly, using data over the 2004-2017 period Ederington et al. (2020) provide strong evidence that futures spreads affect crude-oil inventories, and thus the actual physical supply of crude oil, but that the relation is concentrated at the futures contract deliver point: Cushing. They further show that C&C arbitrage is constrained when there is little unused storage capacity. Building on the latter, we hypothesize that the rampant C&C arbitrage induced by super-contango (negative spreads) played a key role

[17] Another telltale of the storage buildup is that lease rates soared for very large crude carriers (VLCCs) as onshore space became increasingly scarce. VLCC rates jumped to $120,000 per day by March 29, 2020, up from about $40,000 at the start of March; see e.g. Oil Tanker Rates Double as Demand for Storage and Transport Resurface, *Reuters*, March 30, 2020.

[18] The storage utilization of 76% is very high because the working storage capacity of Cushing is not 100% of shell storage capacity which the EIA defines as the design capacity of a petroleum tank or cavern. Working storage capacity excludes tank bottoms (pump suction is ineffective below a certain level) and operational factors (some storage capacity must remain available for blending, tank-to-tank transfers and other routine operations).

in using up quickly the Cushing storage capacity. Then the mounting fear of a tank-tops scenario sparked a panic sell-off and liquidity came to a halt, which led to the negative price event on the 20th April, the day before contract maturity. This hypothesis is examined empirically next.

4.2.2 C&C arbitrage

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 would induce the sharp rise in storage utilization at Cushing during April. The main C&C traders are big financial institutions with ability to borrow capital (investment banks, hedge funds, proprietary trading houses) and also oil companies which lease storage capacity at Cushing; for further discussion see, e.g. Davis (2007) and Ederington et al. (2020). We revisit this point below.

In support of the claim that the WTI crude oil futures contango attracted C&C arbitrage which, in turn, quickly raised inventory levels at Cushing, raised storage costs and induced a super-contango, 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. This aligns with the evidence in Ederington et al. (2020) that Cushing levels are strongly linked to arbitrage activity; arbitrageurs contract storage capacity ahead to exploit distortions between futures prices at different maturities.

We provide next an illustrative example of how the C&C arbitrage might have induced the sharp inventory build-up at Cushing (as Figure 3 shows) during April 2020.[19] As of March 12, 2020, the then-contango market implied a negative futures spread 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.[20]

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

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[19] Various media outlets issued warnings of this storage buildup; see e.g. Oil Plunge Sets Off Search for Tanks, Revives Dormant Cushing Storage Trade, *Reuters*, March 17, 2020; Oil Market Shows Fear That U.S. Is Running Out of Storage Space, *Bloomberg*, March 25, 2020; Oil Ground Zero: Running Out of Storage, *Council on Foreign Relations*, April 6, 2020.

[20] Cushing storage rates rose sharply, reaching $0.50 p/b in March 2020 double its level the previous month, and five times its prior level at $0.10 p/b in 2019.

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 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.[21] Even though C&C traders may typically take futures positions and lease storage space simultaneously, it is likely that to take advantage of this anomalous super-contango situation, C&C traders did open futures positions without having secured storage space. Thus, C&C traders positioned long in the May 2020 contract and short in distant contracts could not at that late stage contract storage 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 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). More generally, the usual number of long CLK20 holders (over and above C&C arbitrageurs) on Monday 20th April found themselves in the dire position of not being able easily to close their contracts and could not lease storage space either, so they were willing to pay in order to get rid of their long contracts. Observing the open interest of the May

[21] Magellan Midstream Partners, Enterprise Products Partners, and Enbridge inc are examples of companies owning tanks at the hub, which they lease out for companies to store their oil. Some traders sublease that space. However "*All tanks were leased by mid-March, and we have not subleased any space since late March"* said Ernie Barsamian, chief executive officer of The Tank Tiger, a terminal storage clearinghouse in Princeton, New Jersey (April 20, 2020).

2020 contract in Figure 3, Panel B, it is noticeable that this is indeed what happened. The open interest fell from 108,593 at the end of Friday April 17, to 13,044 at the end of Monday April 20, or by 88%; such a huge drop had never been seen over one business trading day before.

In fact, all the WTI futures contracts then 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 (i.e., very deep contango). This made matters worse: the margin profits earned on the short (back-end) positions as the prices of far-maturity contracts fell mildly were not enough to hedge the margin calls received on the long (front-end) positions as the front futures contract, price fell brutally. Thus, we argue that even if most C&C traders had secured storage, the price drop observed on CLK20 as of April 20, 2020 can also be attributed to large numbers of C&C arbitrageurs choosing to close their long positions rather than paying exorbitant margin calls.[22] This key observation applies to all CLK20 traders, regardless of whether they had secured storage facility or were unsuccessfully seeking it.

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 (or stockouts), and the other for the downside squeeze at zero storage capacity. When both inventories and storage ability are available the spread converges 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, then 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

[22] Hecht (2015) describes the commodity C&C arbitrage, noting that these trades have in general "no risk other than margin flow via mark-to-market risk for the period" of the trade.

(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 at expiry of the front-end short contract because the inventory is zero.[23] In the second scenario (triggered in contango), the C&C trader fails to take delivery of physical barrels at expiry of the front-end long contract because storage facility is not available or relatively expensive. The model captures the fact that these actual default events do never happen because futures contracts are liquidated by the clearing broker, but the price of such liquidation is unbounded and therefore it can turn negative.

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 Which type of market participants drove the price crash?

Market participants can be classified according either to their trading (e.g., hedging versus pure speculative) motive or by the nature of their business as the CFTC in its Commitment of Traders (COT, hereafter) report carries out (e.g., swap dealers vs money managers). We ask two questions. First, who were the main type of market participants that drove the WTI price demise? Second, who was predominantly holding long positions in CLK20 on April 20, 2020, when the panic selloff (illiquidity squeeze) and negative price occurred? Effectively, these two questions boil down who "sparked off the fire" versus who was "caught in the fire".

[23] The reverse C&C arbitrage is attracted by a downward-sloping term structure; selling the physically-owned oil (at a high front-end futures price), re-investing the proceeds at the risk-free rate and buying it forward to replenish the stocks at a discount (i.e., long back-end futures).

As regards the first question, our prior analysis suggests that C&C arbitrageurs induced the rapid increase of the capacity utilization rates at Cushing which, as days passed and the maturity of the May delivery contract approached, sparked panic about the likelihood of a tank-tops scenario.[24] This fear created a liquidity squeeze as long holders of CLK20 sought to close their positions on April 20, 2020. Thus, the C&C arbitrage was the spark towards the fire. But it is not easy to say who was behind these C&C trades; a precise answer to this question is complicated by unavailability of direct data. In principle, any type of business can engage in C&C arbitrage as long as there is the possibility of contracting storage space for the crude oil. Generally-speaking, the main C&C arbitrageurs are typically financial institutions (investment banks, hedge funds and proprietary trading houses), alongside oil companies.

We seek to answer the second question as to who was caught holding long positions in CLK20 on April 20, 2020 with reference to the CFTC/COT Interim Report (November 2020).

4.3.1. CFTC/COT Interim Report (November 2020)

The CFTC in its Legacy COT report and its Disaggregated COT report classifies futures market participants as "reportable" and "non-reportable"; a non-reportable position is broadly-speaking a small position. The Legacy COT report classifies reportable traders merely into "commercial" and "non-commercial" categories. For the sake of increasing transparency, the Disaggregated COT report classifies the reportable traders into four categories: (i) Producer/Merchant/Processor/User, (ii) Swap dealers, (iii) Managed money, and (iv) Other reportable. These COT reports are based on position data as supplied by reporting traders, and

[24] The capacity remaining at Cushing on Friday April 17, 2020 was 18,305 million barrels (mb) while the CLK20's open interest at the end of that day was 108,593 contracts, representing 108,593mb to be delivered during May 2020. In other words, the contracts still open before the CLK20 maturity (on Tuesday April 21, 2020) exceeded the available storage capacity at Cushing by a factor of six. The sheer magnitude of this imbalance, with just two days remaining to expiry, is quite unusual. For example, for the WTI February 2020, March 2020, April 2020, June 2020 and July 2020 contracts, two days before maturity, the open interest exceeded the available storage at Cushing only by a factor of 1.5, on average.

the actual trading category is based on the predominant nature of their business, also as self-reported by traders on the CFTC Form 40 which is reviewed by CFTF staff. For instance, all the WTI futures position data of a crude oil processor (refinery) on any given week will appear under the "producer/merchant/processor/user" category of the CFTC/COT report regardless of whether the motive of these positions was hedging, speculation or arbitrage.

The CFTC's Interim Staff report (November 2020) emphasizes that the proportion of total long positions on April 20, 2021 held by "non-reportable" traders was then higher than the trailing 12-month average of their long positions for this category on the penultimate trading day before delivery, but similar in magnitude to the WTI March 2020 contract. Remarkably, the proportion of total long positions on that critical day held by "other reportable" was also higher than the trailing 12-month average of their long positions. Since C&C arbitrageurs did not only spark the fire (by rapidly filling the Cushing tanks) but were also caught in the fire by holding long CLK20 positions on the day before maturity (since the first leg of the C&C arbitrage requires taking physical delivery), we deduce that many "other reportable" traders could have then engaged in C&C trading. But nobody outside of the NYMEX operators and CFTC regulators can say exactly who "other reportable" traders are. In principle, this category contains larger pools of non-institutional capital like family office money and wealthy foundations, and proprietary trading houses who constantly watch for arbitrage opportunities. These traders could have also sought benefit from the super-contango through C&C arbitrage.

4.3.2 Index-trackers and long-only asset managers

These traders pertain to the broad CFTC category known as "swap dealers" since they sell to their clients slices of a bundled futures product, and simultaneously hedge their exposure by taking long futures positions. The empirical tests in Section 3 suggest that USO's (an ETF that can be referred to as a long-only asset manager) flows did not cause the CLK20 prices and there is also the fact that USO did not hold CLK20 since 7 days before its price crash.

Likewise, it is unlikely that most other long-only or long-short index managers would have held CLK20 on April 20, 2020. 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.

There may be, of course, exceptions. A prominent one is the Bank of China's Crude Oil Treasure which surprisingly had still not rolled its long positions on CLK20 on the day before maturity – a possible reason for this is that the fund managers hoped for the deeply contango curve to mean revert to a less contango curve to save rolling costs. The price crash implied large losses and the bank has been penalized by the China regulator for irregular product management, imprudent risk management and non-compliant sales management.[25]

By delaying the rolling of their long positions, Bank of China's Crude Oil Treasure could have been subject to the "strategic behavior" of commercials holding short futures positions (against physical holdings). As short CLK20 holders anticipated the barrage of long open interest coming into the futures contract's maturity, they might have delayed reversing their short hedges, an activity which would normally provide a bid for exiting non-commercial long

[25] Regulator fines Bank of China over loss-making product linked to crude oil, *Reuters*, December 5, 2020; China's 'Crude Oil Treasure' Promised Riches. Now Investors Owe the Bank, *New York Times*, May 21, 2020. In Depth: A bitter $1.4bn lesson on commodity price speculation, *Nikkei Asia*, April 28, 2020.

futures contract holders. As the events of April 20, 2020 arguably showed, this liquidity provision is not automatic during the day *before* the futures contract expires if such participants elect to exert "market power" (Pirrong, 2020a; Pirrong, 2020b; Pirrong, 2020c).[26]

4.3.2 Hedge funds

Hedge funds are "money managers" according to the CFTC classification. Hedge funds in futures markets typically engage either in C&C arbitrage[27] or in pure speculation. Our previous analysis suggests that hedge funds engaging in C&C arbitrage created the conditions (tank-tops) for the negative prices. Since the C&C arbitrage by definition requires taking physical delivery of crude oil at the first leg of the strategy, it is likely that many of the long futures positions held on April 20, 2020 (the day before maturity) were associated to C&C arbitrageurs who saw themselves subject to very large margin calls due to the deepening of the contango.

Are the hedge funds that engage in pure speculation (e.g., CTAs) likely also to have been caught in the fire (i.e., holding long CLK20 on April 20, 2020)? We see this as unlikely for two reasons. First, speculators do not want to take physical delivery; they roll their contracts a few weeks prior to maturity to avoid exposure to illiquidity-driven price fluctuations. Second, various trading signals in March predicted a poor performance of CLK20 and thus, rational speculators ought to have then taken short (as opposed to long) positions in that contract.

As of March 31, 2020 (or 15 days before maturity of CLK20; hereafter, *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, the *futures spread* was very negative at -$4.03 (compared to a 5th percentile

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[26] Pirrong discusses additional hypotheses on the events of April 20, 2020 such as the kinds of market manipulation that can potentially occur during times of limited storage.

[27] Commodity C&C can be seen a mix of "arbitrage" and "speculation" and can therefore be referred to as speculative arbitrage. Commodity C&C arbitrage is not as risky as speculation since long and short positions on near and far futures contracts are taken to exploit the contango. But commodity C&C arbitrage is not fully risk free not only because storage costs can rise, but mainly because the contango may deepen with adverse implications for margin calls.

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).

Likewise, the average of CLK20 daily returns over the preceding 50 trading days was on day *T*-15 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).

Moreover, the *basis-momentum* signal took at *T*-15 the very negative value of -0.0036 (the 5th percentile from March 30, 1983 to June 29, 2020 is -0.0006) also predicting 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., a few weeks before CLK20 maturity or even at *T*-2), these short speculators offered the barrage of long CLK20 traders who were seeking to reverse their positions (to exit the market) 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.[28] However, in line with commercial short traders, it is possible that "strategic behavior" on the part of short speculators (delaying the closing of their positions) might have also contributed to the liquidity freeze.

4.3.3 What about the long hedgers?

These pertain to the "producer/merchant/processor/user" category of the CFTC/COT report. Could one explanation for the negative pricing of CLK20 on April 20, 2020 be that many long CLK20 hedgers (i.e., processors or users 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, long hedgers typically close their positions weeks before maturity to avoid illiquidity issues since they are not interested in taking delivery from Cushing, as this would imply transportation costs to their operation base. Second, 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).[29] Some processors and consumers of WTI crude oil 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. The CFTC's Interim Staff report (November 2020) confirms this; traders in the "Product/Merchant" group held below average long positions on CLK20, namely, only 14.7% of the open interest on April 20, 2020 which is considerably lower than the trailing average of 52.5% on the penultimate day

[28] A London prop-trading house has been in the spotlight of the CFTC by taking many long positions in CLK20 in the TAS market on April 20, 2020 (buying at whatever the trade-at-settlement price would be on the day) thus hoovering many of the long contracts that traders sought to get rid of on that day. Then as the settlement period approached they aggressively shorted outright WTI contracts. See London Traders Hit $500 Million Jackpot When Oil Went Negative, *Bloomberg*, August 5, 2020 https://www.bloomberg.com/news/articles/2020-08-04/oil-s-plunge-below-zero-was-500-million-jackpot-for-a-few-london-traders

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

of trading of contracts active in the previous 12-months.[30] In sum, relatively few long hedgers ended up in the dire predicament of holding long positions on CLK20 as of April 20, 2020.

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, moved the WTI futures market into a "super-contango" price structure in early April 2020. 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 long leg of the C&C arbitrage increased rapidly the inventories at Cushing. On April 20, 2020 an abnormal illiquidity situation was created in the WTI futures market when a historically high number of long CLK20 positions could not be easily closed as there was no sufficient buying interest. However, a thorough understanding of the price crash phenomenon of April 20, 2020 requires an investigation of market microstructure on that day which we leave for further research.

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[30] This group held then a number of short positions similar to the 12-month trailing average.

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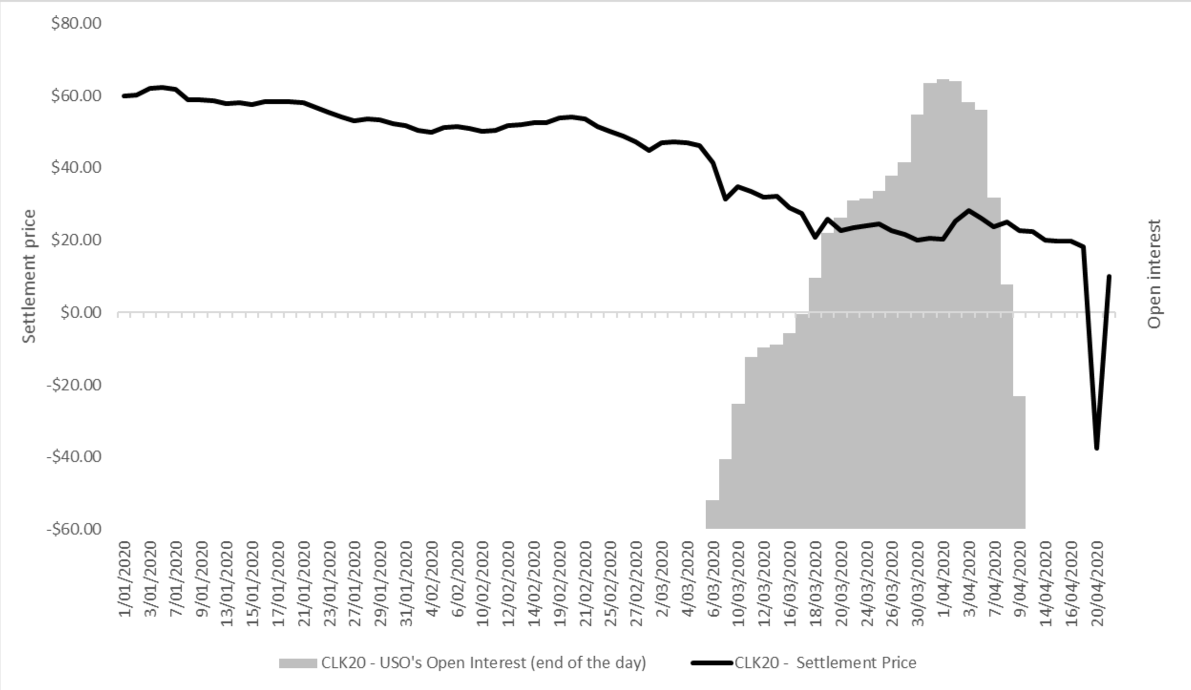
Figure 1. WTI crude oil futures prices and USO trading

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

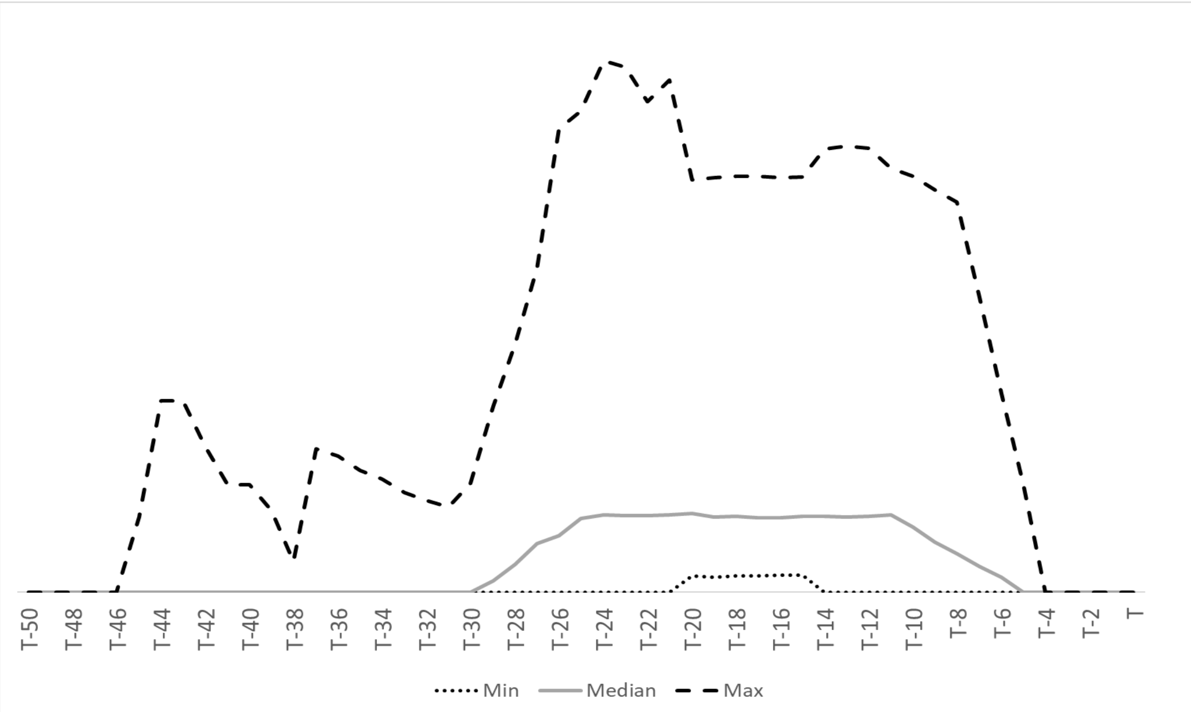
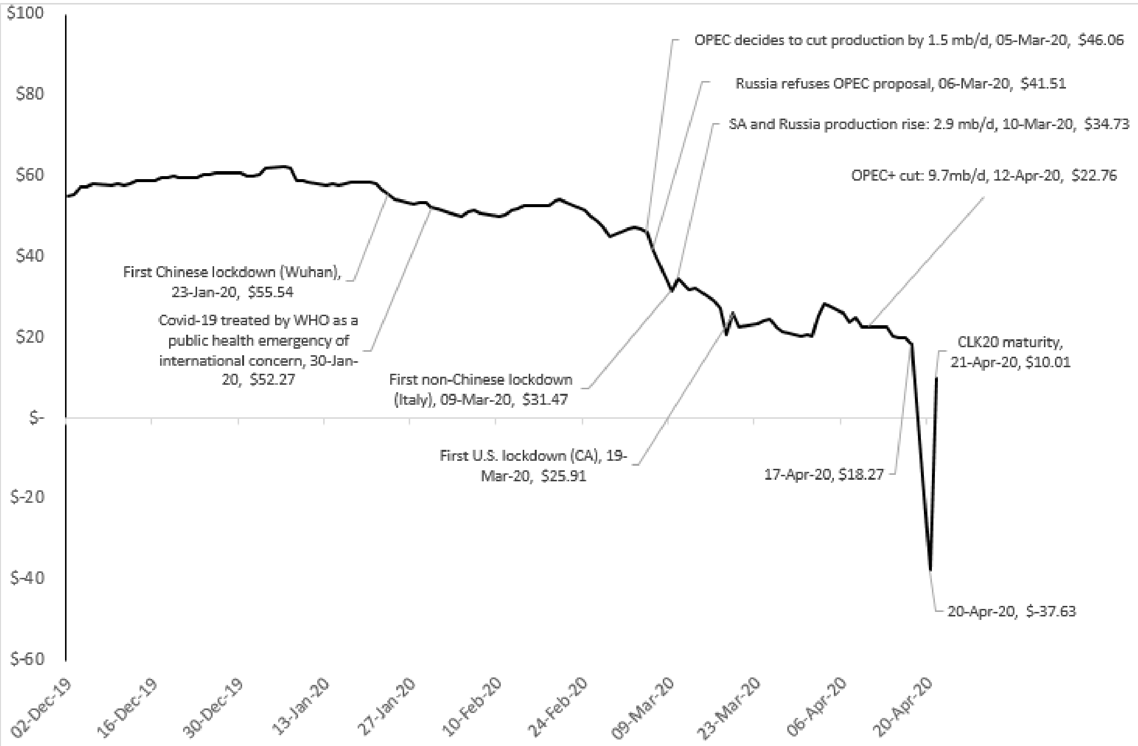


Figure 2. WTI crude oil supply and demand fundamentals and CLK20 prices

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

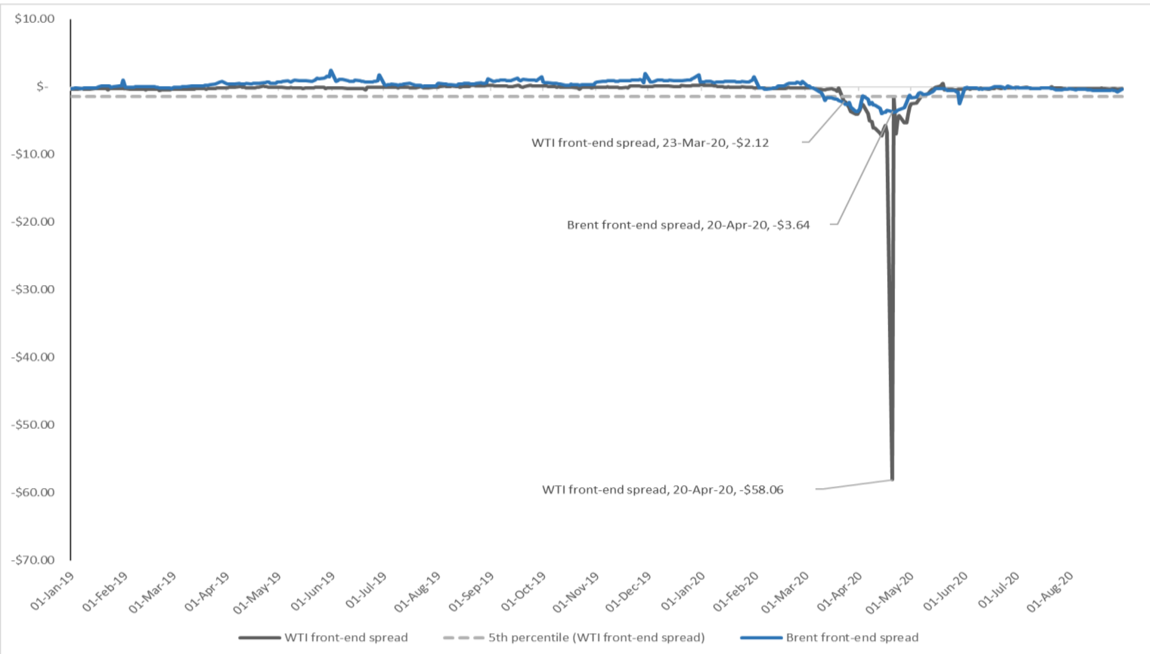


Figure 3. Crude oil storage capacity utilization in different PADDs

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.

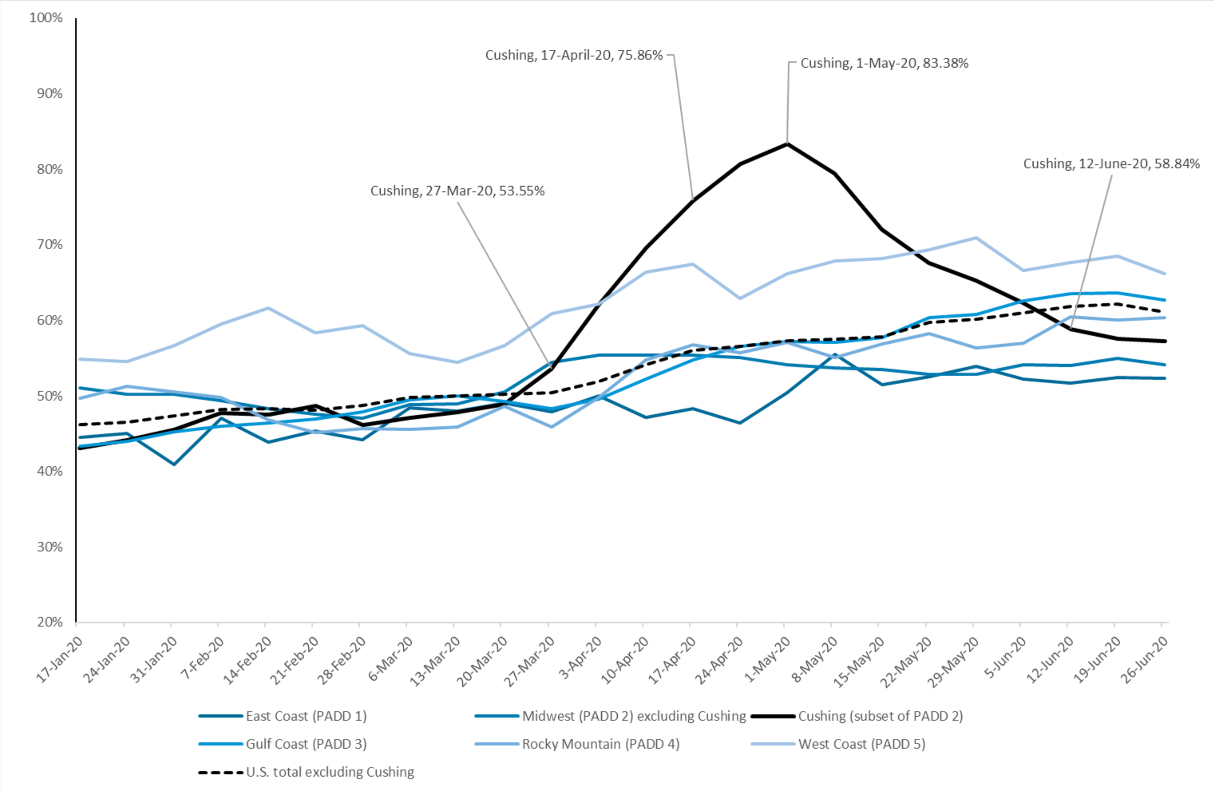
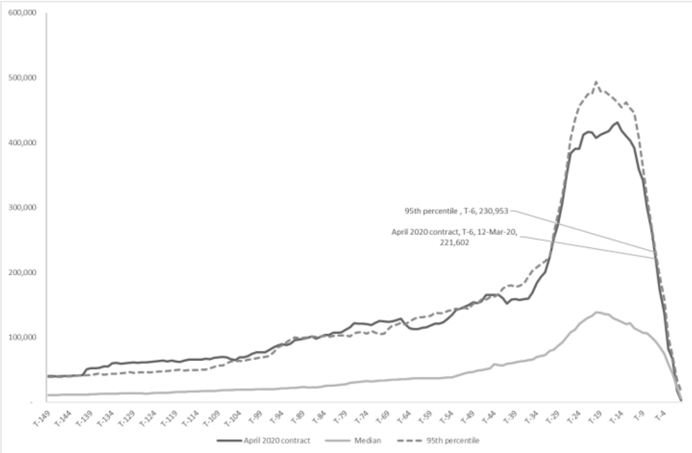


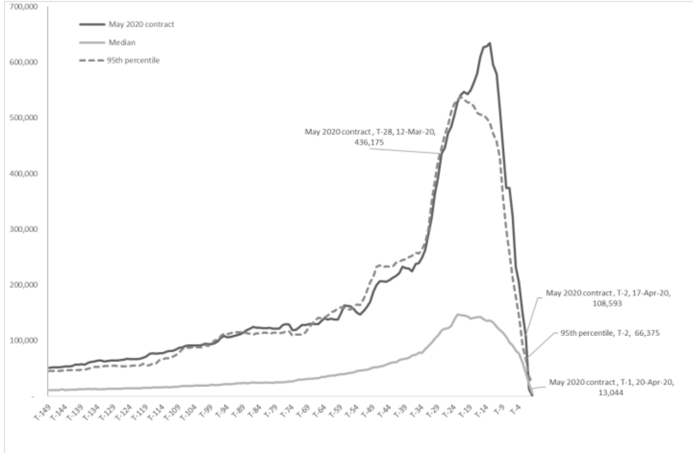
Figure 4. Open interest of various WTI contracts up to 150 days before maturity

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.

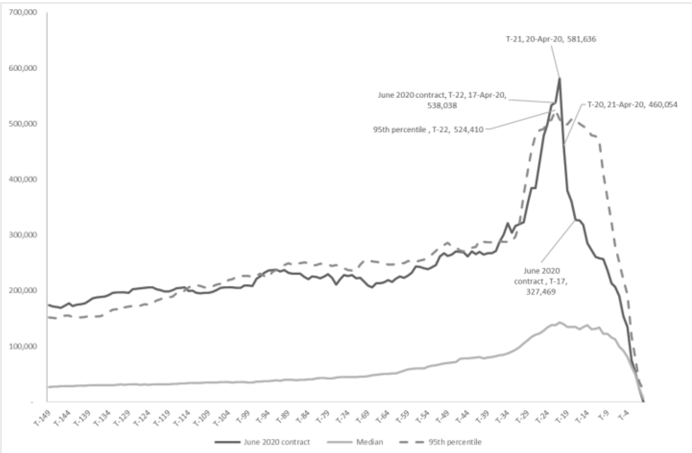
Panel A: April contracts



Panel B: May contracts



Panel C: June contracts



Panel D: July contracts

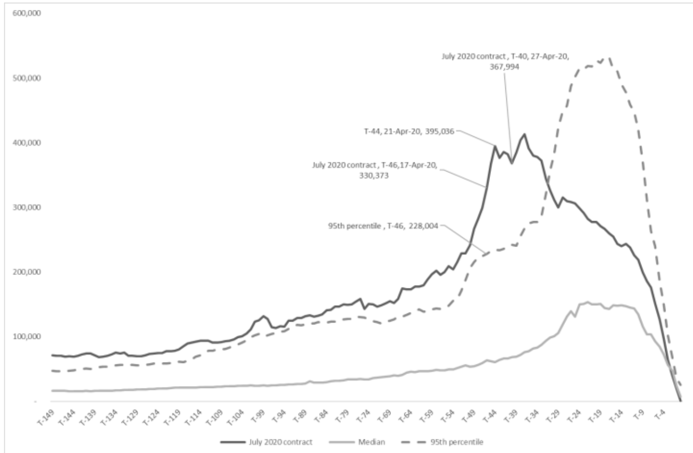


Table 1. Granger causality tests for daily WTI futures returns

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. Shaded grey is used to indicated the selected model specification according to the Adj-R^2, AIC and BIC criteria.

Panel I: USO flows and WTI futures prices				
Panel A: Coefficients on lagged returns				
β_1	-0.1023	**-0.1222**	**-0.1389**	**-0.1324**
	(-1.59)	(-1.98)	(-2.61)	(-2.38)
β_2		**-0.1246**	**-0.1277**	**-0.1299**
		(-2.56)	(-2.81)	(-2.95)
β_3			-0.0893	-0.0861
			(-1.86)	(-1.87)
β_4				0.0044
				(0.07)
Panel B: Coefficients on USO lagged position change				
γ_1	-0.2820	-0.0948	-0.0533	-0.0734
	(-1.37)	(-0.19)	(-0.11)	(-0.14)
γ_2		-0.1280	-0.3440	-0.4420
		(-0.29)	(-0.60)	(-0.75)
γ_3			0.3100	0.3510
			(1.01)	(0.79)
γ_4				0.0882
				(0.27)
$H_0: \gamma_1 = \cdots = \gamma_P = 0$	1.87	1.11	1.23	1.64
	{0.172}	{0.575}	{0.746}	{0.802}
Individual FE	Yes	Yes	Yes	Yes
Month FE	Yes	Yes	Yes	Yes
Adj-R²	1.22%	2.48%	3.72%	3.56%
AIC	-4.204	-4.222	-4.251	-3.913
BIC	-3.930	-3.935	-3.949	-4.116
#Num. Obs.	3620	3473	3326	3179

Panel II: USO flows and CLK20 price				
Panel A: Coefficient on USO lagged position change				
γ_1	-0.3000	-0.0669	0.0223	-0.0105
	(-1.42)	(-0.13)	(0.04)	(-0.02)
γ_2		-0.1920	-0.4150	-0.5210
		(-0.43)	(-0.73)	(-0.89)
γ_3			0.2570	0.2630
			(0.89)	(0.62)
γ_4				0.1280
				(0.39)
Panel B: Coefficient on USO lagged position change x D				
$\gamma_{1,D}$	0.5150	-3.5300	-4.6900	-4.8200
	(0.45)	(-1.43)	(-1.71)	(-1.62)
$\gamma_{2,D}$		**6.2200**	4.0300	4.3000
		(2.08)	(1.35)	(1.36)
$\gamma_{3,D}$			4.6600	5.1000
			(1.17)	(1.19)
$\gamma_{4,D}$				-1.6400
				(-0.35)
$H_0: \gamma_{D,1} = \cdots = \gamma_{D,P} = 0$	0.20	**7.52**	5.03	5.24
	{0.651}	{0.023}	{0.170}	{0.264}
Individual FE	Yes	Yes	Yes	Yes
Month FE	Yes	Yes	Yes	Yes
Adj-R²	1.33%	3.83%	5.31%	5.14%
AIC	-4.205	-4.234	-4.266	-4.244
BIC	-3.927	-3.940	-3.953	-3.912
#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. Shaded grey is used to indicated the selected model specification according to the Adj-R^2.

Panel I: USO flows and WTI futures prices				
P =	1	2	3	4
Panel A: Augmented by lagged futures spread				
$H_0: \gamma_1 = \cdots = \gamma_P = 0$	0.74	0.81	3.70	4.39
	{0.390}	{0.666}	{0.295}	{0.356}
Adj-R^2	10.04%	12.35%	10.94%	11.06%
Panel B: Augmented by lagged momentum				
$H_0: \gamma_1 = \cdots = \gamma_P = 0$	2.13	1.34	1.15	1.56
	{0.144}	{0.512}	{0.764}	{0.817}
Adj-R^2	2.85%	3.82%	4.97%	4.93%
Panel C: Augmented by lagged basis-momentum				
$H_0: \gamma_1 = \cdots = \gamma_P = 0$	1.80	1.08	0.99	1.38
	{0.180}	{0.583}	{0.805}	{0.848}
Adj-R^2	2.07%	3.14%	4.61%	4.56%
Panel D: Augmented by lagged relative basis				
$H_0: \gamma_1 = \cdots = \gamma_P = 0$	0.58	1.94	4.97	5.17
	{0.446}	{0.378}	{0.174}	{0.270}
Adj-R^2	11.53%	13.61%	12.28%	12.28%
Panel E: Augmented by lagged EPU				
$H_0: \gamma_1 = \cdots = \gamma_P = 0$	1.88	1.11	1.22	1.64
	{0.171}	{0.574}	{0.747}	{0.801}
Adj-R^2	1.20%	2.46%	3.69%	3.55%
Panel F: Augmented by lagged ADS				
$H_0: \gamma_1 = \cdots = \gamma_P = 0$	1.88	1.10	1.18	1.58
	{0.170}	{0.576}	{0.758}	{0.813}
Adj-R^2	1.19%	2.46%	3.70%	3.53%
Panel G: Augmented by lagged VIX				
$H_0: \gamma_1 = \cdots = \gamma_P = 0$	2.03	1.13	1.23	1.63
	{0.155}	{0.568}	{0.747}	{0.803}
Adj-R^2	1.33%	2.45%	3.69%	3.53%

Panel II: USO flows and CLK20 price				
P =	1	2	3	4
Panel A: Augmented by lagged futures spread				
$H_0: \gamma_{D,1} = \cdots = \gamma_{D,P} = 0$	0.08	4.07	3.93	4.09
	{0.782}	{0.131}	{0.269}	{0.395}
Adj-R^2	10.06%	13.52%	12.35%	12.48%
Panel B: Augmented by lagged momentum				
$H_0: \gamma_{D,1} = \cdots = \gamma_{D,P} = 0$	0.19	**7.73**	5.28	5.48
	{0.664}	{0.021}	{0.152}	{0.242}
Adj-R^2	2.99%	5.16%	6.57%	6.56%
Panel C: Augmented by lagged basis-momentum				
$H_0: \gamma_{D,1} = \cdots = \gamma_{D,P} = 0$	0.36	**8.47**	5.65	5.92
	{0.549}	{0.015}	{0.130}	{0.205}
Adj-R^2	2.23%	4.52%	6.27%	6.23%
Panel D: Augmented by lagged relative basis				
$H_0: \gamma_{D,1} = \cdots = \gamma_{D,P} = 0$	0.02	4.87	4.55	4.60
	{0.895}	{0.088}	{0.208}	{0.331}
Adj-R^2	11.56%	14.79%	13.75%	13.75%
Panel E: Augmented by lagged EPU				
$H_0: \gamma_{D,1} = \cdots = \gamma_{D,P} = 0$	0.19	**7.43**	5.09	5.36
	{0.667}	{0.024}	{0.166}	{0.252}
Adj-R^2	1.31%	3.80%	5.29%	5.16%
Panel F: Augmented by lagged ADS				
$H_0: \gamma_{D,1} = \cdots = \gamma_{D,P} = 0$	0.21	**7.16**	5.11	5.31
	{0.649}	{0.028}	{0.164}	{0.257}
Adj-R^2	1.30%	3.80%	5.31%	5.14%
Panel G: Augmented by lagged VIX				
$H_0: \gamma_{D,1} = \cdots = \gamma_{D,P} = 0$	0.11	**7.31**	5.07	5.28
	{0.738}	{0.026}	{0.167}	{0.259}
Adj-R^2	1.43%	3.80%	5.29%	5.12%

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. Shaded grey is used to indicated the selected model specification according to the Adj-R^2, AIC and BIC criteria.

Panel I: USO flows and WTI futures prices					Panel II: USO flows and CLK20 price				
Panel A: Coefficients on lagged futures spread					**Panel A: Coefficients on lagged futures spread**				
θ_1	**0.0063**	**0.0068**	**0.0081**	**0.0084**	θ_1	**0.0063**	**0.0068**	**0.0080**	**0.0083**
	(8.92)	(14.25)	(11.92)	(15.81)		(9.12)	(14.66)	(11.63)	(16.63)
θ_2		**-0.0022**	**-0.0020**	**-0.0033**	θ_2		**-0.0024**	**-0.0023**	**-0.0036**
		(-2.88)	(-2.81)	(-3.28)			(-3.18)	(-3.15)	(-3.80)
θ_3			**-0.0015**	**-0.0014**	θ_3			-0.0014	**-0.0014**
			(-2.15)	(-2.30)				(-1.91)	(-2.20)
θ_4				(-0.00)	θ_4				-0.0007
Panel B: Coefficients on lagged returns					**Panel B: Coefficient on USO lagged position change**				
β_1	**-0.1321**	**-0.1354**	**-0.1481**	**-0.1486**	γ_1	-0.1150	**0.5960**	**0.6220**	**0.7470**
	(-2.54)	(-3.03)	(-3.32)	(-3.24)		(-0.79)	(2.37)	(2.19)	(2.61)
β_2		**-0.1316**	**-0.1076**	**-0.1165**	γ_2		**-0.6440**	**-0.9400**	**-1.0600**
		(-2.57)	(-2.14)	(-2.44)			(-2.25)	(-3.02)	(-3.14)
β_3			**-0.0764**	-0.0555	γ_3			0.3070	0.2470
			(-1.46)	(-1.14)				(1.21)	(0.77)
β_4				0.0151	γ_4				0.2500
				(0.25)					(0.97)
Panel C: Coefficients on USO lagged position change					**Panel C: Coefficient on USO lagged position change x D**				
γ_1	-0.1220	**0.5060**	0.4890	**0.6120**	$\gamma_{1,D}$	-0.3180	-4.4700	**-5.5200**	-5.6700
	(-0.86)	(1.96)	(1.66)	(2.05)		(-0.28)	(-1.83)	(-1.97)	(-1.91)
γ_2		-0.5500	**-0.8230**	**-0.9290**	$\gamma_{2,D}$		**6.4200**	4.5500	4.8900
		(-1.83)	(-2.54)	(-2.64)			(2.12)	(1.53)	(1.55)
γ_3			0.3410	0.3010	$\gamma_{3,D}$			4.1400	4.9400
			(1.29)	(0.88)				(1.01)	(1.14)
γ_4				0.2210	$\gamma_{4,D}$				-2.2900
				(0.82)					(-0.49)
$H_0: \gamma_1 = \cdots = \gamma_P = 0$	0.74	3.98	6.53	8.44	$H_0: \gamma_{D,1} = \cdots = \gamma_{D,P} = 0$	0.08	4.91	4.67	5.09
	{0.390}	{0.136}	{0.089}	{0.077}		{0.782}	{0.086}	{0.197}	{0.278}
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%	13.22%	12.19%	12.70%	**Adj-R²**	10.06%	14.55%	13.71%	14.29%
AIC	-4.297	-4.338	-4.342	-4.328	**AIC**	-4.297	-4.352	-4.358	-4.344
BIC	-4.022	-4.047	-4.035	-4.003	**BIC**	-4.018	-4.054	-4.040	-4.004
#Num. Obs.	3620	3473	3326	3179	**#Num. Obs.**	3620	3473	3326	3179

Table 4. Predictive signals for WTI 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 price), 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