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King Abdullah Petroleum Studies and Research Center

Market Structure, Inventories and Oil Prices: An Empirical Analysis

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Key Points

According to conventional storage theory, the difference between spot and futures prices (known as the 'basis') can be explained by the total cost of storing a commodity for a specific period of time. This 'cost' is known as cost of carry and includes storage expenses, foregone interest on capital, and the marginal convenience yield, which measures the benefits of owning a physical asset. The theory predicts a positive relationship between inventory levels and the basis, and a negative correlation between inventories and marginal convenience yield.

This study investigates whether there is a defined and quantifiable relationship between inventory levels and market structure—defined for the purpose of this research as the basis or the corresponding degree of contango/backwardation—and what the exact nature of that relationship might be.

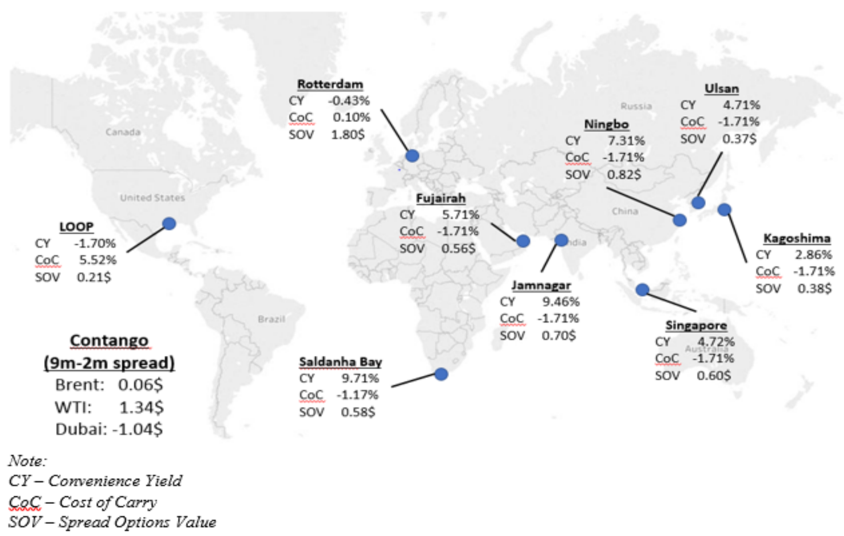
The analysis indicates that basic predictions of inventory theory are valid for daily and weekly frequencies but become less reliable for lower frequency data.

We propose an alternative: a spread option-based formulation that adds a locational dimension to the theory and is based on the prices of crude oil at two different locations, factoring in costs of storage and transportation, and the time required to transport oil between them.

This methodology offers a viable alternative to the traditional cost of carry approach; it can also estimate implied convenience yields and the shadow price of inventories, aiding commodity trading strategies.

The three key drivers of inventories—the cost of carry, convenience yield and spread option value—are estimated for eight primary international storage hubs located at major seaports using daily data from December 21, 2015 to January 25, 2019.

Snapshot of the major drivers of inventories on January 25, 2019.



Source: KAPSARC internal calculations.

Summary

Understanding the relationship between crude oil prices and inventory levels is critical for policymakers and economic actors. The size of the 'basis,' or spread between spot and futures prices, reflects the level of inventories and can trigger arbitrage trading. The basis also reflects broader underlying market conditions and can be useful to policymakers such as the International Energy Agency and OPEC attempting to monitor and stabilize world oil markets.

The basic economics of storage and the relationship between the basis and inventories have been addressed by two popular theories. The first, risk premium theory, explains the difference between spot and futures prices in terms of two values: a risk premium and a forecast of future spot prices. The former encapsulates all systematic 'risk' factors that affect futures prices, such as political instability and natural disasters; the latter reflects expectations of future spot prices.

The second, conventional storage theory, suggests that the basis can be explained by simply adding up the total costs of holding a physical commodity for a given time period. This includes foregone interest on capital, marginal storage cost and marginal convenience yield. The latter reflects the convenience of owning the physical commodity to meet contractual obligations or to mitigate the adverse effects of supply shocks; it is not directly observable.

The risk premium theory of storage is the subject of considerable controversy. There is no consensus on the ability of futures prices to forecast future spot prices, or whether the risk premium exists in any meaningful way. The principles of conventional storage theory, on the other hand, are widely accepted. The model reliably predicts a positive relationship between inventories and the basis, and a negative one between inventories and marginal convenience yield, as are often exhibited in commodity markets.

This study investigates whether there is a defined and quantifiable relationship between inventory levels and market structure—defined for the purpose of this research as the basis and corresponding degree of contango/backwardation—and what the exact nature of that relationship might be.

The paper makes two contributions to existing literature. The first is the analysis of daily data on crude oil inventory levels collected from real-time satellite imagery, facilitating a detailed examination of world oil markets. The second is the application of a spread option-based approach to model the behavior of commodity price responses to changes in inventory levels.

The results show that the basic theories of inventory hold for daily and weekly frequencies but become less reliable for lower frequency data.

We show that a locational spread option-based approach offers a viable alternative to the prevailing methodology; it can also be used to estimate implied convenience yields and shadow prices of storage. This is because the spread option-based approach incorporates all information found in the futures curves for all major competing crudes, thereby accounting for the implied volatility of prices across the spectrum of relevant futures curves.

Finally, we calculate three variables that are the primary drivers of global crude inventories—the cost of carry, convenience yield and spread option value—for key storage locations, providing a snapshot of global oil inventories at any point in

time from December 21, 2015 to January 25, 2019. Specifically, we estimate the three variables for eight primary international storage hubs located at major seaports: Fujairah (United Arab Emirates), Jamnagar (India), Kagoshima (Japan), Louisiana (United States), Ningbo (China), Rotterdam (Netherlands), Saldanha Bay (South Africa), Singapore and Ulsan (South Korea). The result will be available on the KAPSARC website, and the underlying dataset will be provided on request.

Introduction

An understanding of the complex relationships between crude oil prices, market structure—defined for the purpose of this research as the basis or the corresponding degree of contango/backwardation—and inventories is critical to understanding world energy markets. At any time, the global market, as well as any given regional market, may be relatively well-balanced or experiencing either surplus or shortage. Sufficiently large movements in crude oil supplies and inventory levels trigger price reactions that move oil markets back toward equilibrium. Meanwhile, the potential consequences of political, economic or other shocks depend on market conditions, including inventory levels and the degree of contango/backwardation at the time of forecast.

'Contango' describes normal, or stable, market conditions when forward contracts trade above the spot price. The crude oil market is generally in this state due to the positive costs of storage, including warehousing, foregone interest, and convenience yield (Fama and French 1987). 'Backwardation' refers to the inverse scenario, when forward contracts trade below the spot price. This encourages firms to hold minimal (or 'just-in-time') inventories and increase production to meet demand.

This study conducts an empirical analysis of the relationship between futures market structure and inventories. Is there a well-defined correlation between the term structure of crude oil prices and inventories? How steep does contango in crude oil markets have to be for storage to be 'in the money,' thereby guaranteeing rising inventory levels?

The paper makes two contributions to existing literature. The first is the analysis of granular data on crude oil inventory levels collected from real-time satellite imagery, facilitating a detailed examination of world oil markets. The results show that the two prevailing models—conventional storage theory and risk premium theory—tend to hold for daily and weekly frequencies but become less reliable for monthly and quarterly time series, although the relationship between market structure and inventories varies significantly across these time frames. This study suggests that, while the market can be very responsive in the short term, reactions may be masked when prices are averaged over longer time periods.

The second is the application of a spread option-based approach to model the behavior of commodity prices in response to changes in inventory levels. Our results show that this offers a viable alternative to conventional storage theory (i.e., the cost of carry approach); it can also estimate implied convenience yields, helping to inform market participants such as policymakers and commodity trading houses.

The main body of this paper is organized as follows. The first section, "The Two Established Theories of Storage," examines two popular storage models: risk premium theory and conventional storage theory. A number of alternative approaches are also discussed, giving a general overview of contemporary thinking on the relationships between market structure, oil prices and inventories.

Section two, "Data and Key Variables," describes the data used in the analysis, and the construction of the key variables of convenience yield, cost of carry, and spread option value.

The third section, "Empirical Evidence," presents the results of the statistical analysis and robustness tests. Finally, the "Conclusion" gives a summary of findings and outlines areas for future research.

The Two Established Theories of Storage

Risk premium theory

Two popular theories address the relationship between the basis and inventory levels. The first, known as risk premium theory, explains the difference between spot and futures prices in terms of two values: a 'risk premium' and a forecast of future spot prices (Cootner 1960; Dusak 1973; Hazuka 1984; Bailey and Chan 1993). The former is essentially compensation for the uncertainties associated with holding a risky asset.

Market players must pay close attention to both spot and futures prices. If the difference between a given futures price and the underlying spot price is sufficiently large, then an arbitrage profit will be possible—in other words, it will pay to buy the asset on the spot market and sell it forward, or vice versa. The arbitrage opportunity acts as an invisible hand, pushing the prices of the undervalued assets up, and the prices of the overvalued assets down, until the market is in balance.

Let F(t,T) be the futures price at time t for delivery of crude oil at later time T, and S(t) be the spot price at time t. According to the risk premium theory, the return from purchasing the commodity at time t and selling it forward for delivery at time T (i.e., the basis), denoted here as F(t,T) – S(t), will equal the expected future price—measured as the difference between the spot price at maturity and the current spot price, E_t (S(T) and S(t))—plus a risk premium E_t (π(t,T)).

1) $$F(t,T) - S(t) = E_t(S(T) - S(t)) + E_t(\pi(t,T))$$

Where S(T) is the spot price at maturity (T), E is the expectation operator, and π(t,T) is the expected value at time t of the risk premium that will be realized at maturity time T.

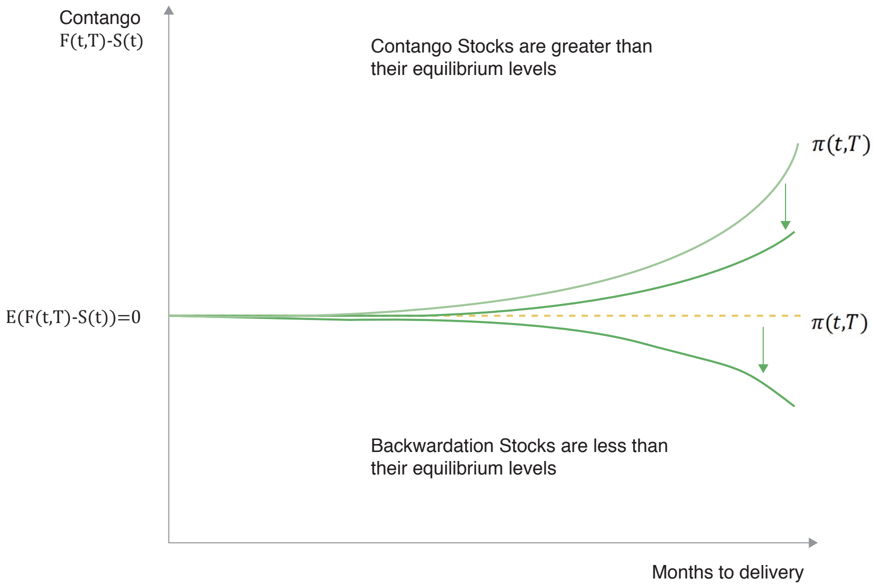
Fama and French (1987) defined the expected risk premium as the bias of the futures price as a forecast of the future spot price. It can be positive or negative according to an economic actor's beliefs, endowments or preferences (Bailey and Chan 1993).

2) $$E_t(\pi(t,T)) = F(t,T) - E_t(S(T))$$

The risk premium reflects the basic systematic risks that affect any market, such as demand shocks and political risk (Hicks 1939), as well as those unique to a particular commodity—oil spills, for example. In fact, a number of equilibrium models have been developed in which risk premiums for systematic and commodity-specific risks can exist at the same time. The more inefficient that markets are at allocating risk, the more likely this is to occur, due to limited market participation and the existence of non-marketable risks.

Figure 1 illustrates the risk premium theory of storage. When the difference between the futures price and the spot price is higher than the best industry forecasts of the futures price, plus the risk premium, then it will pay to buy crude (whether on physical or futures markets) and sell it forward. In this case inventories will be above their equilibrium level, which is represented in Figure 1 as the light blue line. The purchase of spot oil and sale of futures will reduce the level of contango, and inventories, until the market returns to equilibrium.

Figure 1. Risk premium theory.



Source: KAPSARC 2019.

The risk premium theory explains backwardation by the fact that a buyer of futures contracts will earn a positive risk premium when futures prices are trading below the spot price. Market players can reduce exposure to storage costs by taking long positions in futures, effectively hedging against storage costs, rather than selling inventories short (Hirshleifer 1989).

This does not necessarily imply costless storage, as has often been falsely attributed to Maynard Keynes (Keynes 1978).

Indeed, in his words:

"The existence of surplus stocks must cause the forward price to rise above the spot price […]; and this contango must be equal to the cost of the warehouse, depreciation and interest charges of carrying the stocks. But the existence of a contango does not mean that the producer can hedge himself without paying the usual insurance against price changes. On the contrary, the additional element of uncertainty introduced by the existence of stocks and the additional supply of risk bearing which they require mean that he must pay more than usual. In other words, the quoted forward price, though above the present spot price, must fall below the anticipated future spot price by at least the amount of the normal backwardation; and the present spot price, since it is lower than the quoted forward price, must be much lower than the anticipated future spot price." (Keynes 1978b, 129)

While widely accepted, the risk premium theory is not without controversy. There is no consensus on whether futures prices contain risk premiums or have the ability to forecast spot prices. To cite just one example, Jin (2017) proposes a futures-based unobserved components model to forecast crude oil and commodity prices, and finds that it outperforms futures price forecasts in multiple dimensions.

Conventional storage theory

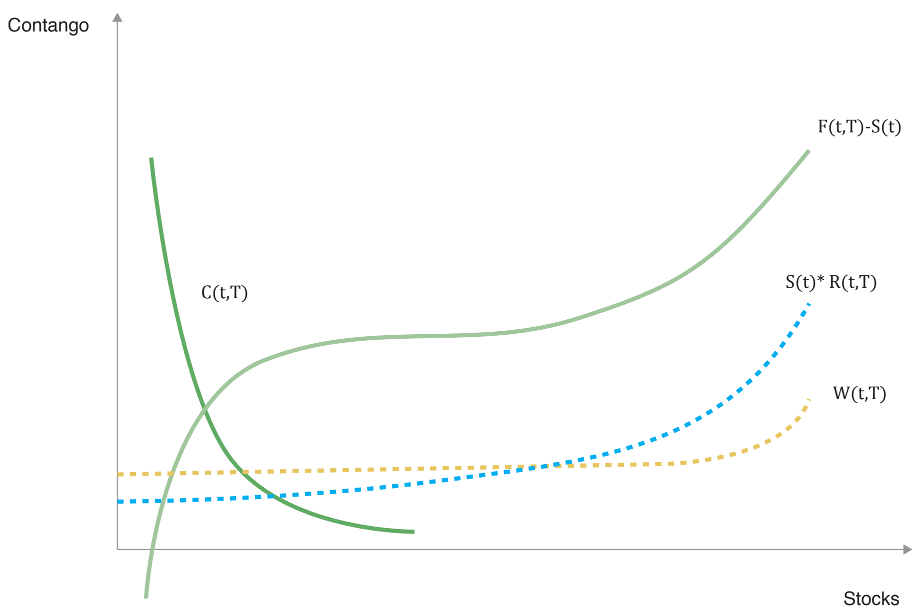
The second popular theory of storage, known as the conventional storage theory, explains the difference between spot and futures prices as the total costs of storing a commodity for a given time period. The return from purchasing the asset at time t and selling it forward for delivery at time T (i.e., the basis), again expressed at F(t,T) – S(t), will be equal to forgone interest S(t)*R(t,T) plus marginal storage costs W(t,T), minus the marginal convenience yield C(t,T) (Fama and French 1987, 1989; Pindyck 2001).

$$F(t,T) - S(t) = S(t) * R(t,T) + W(t,T) - C(t,T) \quad \text{3)}$$

The marginal convenience yield C(t,T) reflects the value of holding a physical commodity rather than a derivative contract. The advantages of owning the physical asset could stem from industrial needs, contractual obligations, hedging against disruptions from supply shocks, or for a variety of other purposes (Fattouh 2009).

There are a number of minor variations to conventional storage theory, including the cost of carry model. The cost of carry refers to the total costs incurred as a result of holding crude oil in storage, or equivalently the net yield of holding the underlying asset. This can be estimated by the basis, or in percentage terms as (F(t,T) – S(T))/S(T)) and includes the expenses of storing the commodity, any necessary insurance, interest costs (such as on relevant bonds, margin accounts, or loans used to secure the good) and other opportunity costs associated with taking the position. It is essentially an arbitrage model that links spot and forward markets for assets that can be held in storage. For example, one can buy a barrel of crude oil now, on the spot market, and hold it in storage, or buy a futures contract. Economic arbitrage will ensure that current asset price minus the futures contract is equal to the cost of carrying the asset, so that this relationship holds when markets are in equilibrium (Bruzda 2009; Chen 2018; Vineet 2015).

Figure 2. Conventional storage theory.



Source: KAPSARC 2019.

As illustrated by Figure 2, conventional storage theory predicts a positive relationship between inventory levels and cost of carry, or equivalently a negative relationship between inventories and marginal convenience yield. For example, in the case of refinery operations where crude oil is needed for the production of gasoline, there is a negative relationship between the level of inventories and the marginal convenience yield of holding a physical barrel of oil, as crude oil supplies will be readily available for the production process. This reflects the inconvenience of holding physical barrels when storage tanks are nearing full capacity.

The level of contango must equal the market-determined cost of carry for the commodity between those two dates. Competition in the oil market, and arbitrage, will ensure that the return from purchasing the commodity, represented as $F(t,T) – S(t)$, will equal forgone interest $S(t)*R(t,T)$ plus marginal storage costs, $W(t,T)$ minus the marginal convenience yield from holding a unit of inventory, $C(t,T)$. When oil is in tight supply, and stocks are low, the market price of storage and therefore the level of contango will be lower than the actual costs of storage, and might even be negative, due to an increase in the convenience yield (Brennan 1958).

The relationship between market structure and inventories

The exact relationship between crude inventories and the structure of oil markets as defined by the shape of the futures curve is extremely hard to quantify. Reliable data on the elusive variables of convenience yield, marginal storage cost, and the shadow price of inventories is virtually non-existent. The convenience yield and shadow price of inventories are simply not observable and must be estimated. While marginal storage cost data does exist, industry transactions are generally carried out according to bilateral agreements and contracts, the terms of which are difficult if not impossible to obtain. One notable exception is the first physically delivered crude oil storage futures contract, for the Louisiana Offshore Oil Port (LOOP), which began trading on the New York Mercantile Exchange (NYMEX) on March 30, 2015.

While the conventional theory of storage implies that the marginal convenience yield (i.e., the rate of change of the yield curve) falls at a decreasing rate as inventory levels rise (Fama and French 1987), the analysis of the data suggests a slightly different story. Pyndyck (1994) shows that, while for some commodities the relationship is considerably more complex, the marginal value of storage can still be estimated as a convex function of inventory levels. When stocks are kept low, the marginal convenience yield exceeds the cost of carry, and the basis is negative. As stocks rise, the convenience yield falls, and the basis becomes positive, rising toward the cost of carry (see Figure 2).

Larson (1991) offers a similar alternative non-linear formulation and suggests that the shadow price of refined copper inventories is convex. “Just as the price of a call option contains a premium based on price variability, so the shadow price of inventories contains a dispersion premium associated with the unplanned component of inventories. When inventory levels are low, the value of the premium increases to the point where inventories will be held even in the face of a fully anticipated fall in price.” (Larson 1991)

The conventional theory of storage has been criticized for being primarily a work of econometric theory, rather than economics and competitive optimization models (Pindyck 1992). Indeed, the original ‘working curve,’ the first curve relating the basis of inventories, originated from a curve drawn by hand by Holbrook Working in 1933, and was not derived from a competitive optimization model. It has often been referred to as a stylized fact for the industry, and remains highly controversial to this day (Carter and Revoredo Giha 2007; Working 1933).

An alternative formulation of conventional storage theory uses a competitive rational expectation framework, and non-negative inventory constraints, to derive the relationship between inventory levels and the basis (Deaton and Laroque 1990). In this model, the convenience yield is viewed as an embedded timing option, because at any time the holder of a physical commodity has the choice to sell or consume the asset. For example, the owner of physical crude oil can sell it on the spot market or deploy it for industrial purposes. In such cases, the forward price will reflect a convenience yield. Or, the holder can continue to store the commodity, in which case the forward price will reflect the total cost of storage. Under these conditions the conventional linkage between spot prices, storage costs and future prices will be broken (Routledge, Seppi, and Spatt 2000).

The term ‘rational expectations’ generally refers to situations in which the outcome depends to a large extent on what economic agents believe will happen in the future, given the information set currently available to them. For example, the prices of crude oil futures are heavily influenced by the predictions of market participants (Lucas and Sargent 1988). If prospective buyers and sellers expect prices to increase, they will buy crude now, causing spot prices to rise. Thus, if the majority of economic actors have the same or similar beliefs, they can create a self-fulfilling prophesy In the words attributed to Abraham Lincoln, “One can fool some men, or fool all men in some places and times, but one cannot fool all men in all places and ages.” (Abbadie and ThéoTeX 2017).

An excellent summary of prevailing storage theory is provided by Emmons and Yeager (2002) of the St. Louis Federal Reserve Bank. In their view, the ability of futures prices to accurately forecast spot prices is weak for certain commodities, including crude oil under some circumstances. They argue that storable commodities such as crude oil can sometimes behave as if they are non-storable, including when inventory levels are low relative to consumption requirements and futures markets are liquid; however, at other times they act as storable assets, such as during illiquid market conditions with large inventory overhangs.

When crude oil markets are in backwardation, supply is expected to increase in the future. While traders could profit by selling oil in the spot market, they may be prevented from doing so by a shortage of inventory. Under these circumstances crude oil tends to trade as a non-storable commodity, and futures prices provide a relatively accurate forecast of the corresponding future spot prices (Emmons and Yeager 2002).

In periods of contango, a given futures price will normally not exceed the current underlying spot price plus the costs of storage. If storage space is available, traders will be able to buy oil on the spot market with borrowed money and store the oil for future delivery. These actions will tend to raise the spot price and lower the futures price, restoring markets to balance. In this situation the conventional theory of storage applies, so that the difference between spot and futures prices reflects foregone interest, warehousing costs, and a convenience yield (Emmons and Yeager 2002).

Another variation of established storage theory views the convenience yield as a financial call option, implying that value increases with market volatility. Several studies illustrate that convenience yields are negatively related to inventory levels, and can be valued by variations of the Black-Scholes options pricing model (Heinkel, Howe, and Hughes 1990; Milonas and Thomadakis 1997). Considine and Larson (2001) suggest another model in which inventory levels depend on convenience yield, and an options value related to price volatility. When tested on crude oil and natural gas prices, this approach suggests that both risk premiums and convenience yields are relevant to determining inventory equilibrium levels: “The risk premiums rose sharply with greater price volatility, and help to explain why prices for immediate sales often exceed prices for future delivery” (Considine and Larson 2001).

A number of studies have shown that a options-based approach to storage valuation models is superior to traditional methods that rely on simple calculations or estimates of the cost of carry, basis and convenience yield (Omura and West 2015). It is important to note that these studies focus exclusively on calendar-spread options, which are positions established by selling a call (i.e., the right to buy in the future) on a specific volume of an asset, at a given price, and buying a call on the same amount further in the future, at the same price.

Note: The value of a calendar spread option arises from the fact that prices tend to fall on out of the money options as they reach their expiration dates. A trader can generally buy back the shorter-term call, assuming it is out of the money, just before it expires for next to nothing. Ideally the trader can then sell the longer-term call option at a higher price to profitably close out their position (Chen 2019).

Building on the spread option model described above, this study employs a location-based spread option approach, which has the potential to improve the accuracy and precision of methods that rely on convenience yields, contango and cost of carry in relation to stored inventories. This is a result of the fact that this model uses all of the information in the forward curves for all major competing crudes, including time to delivery, interest rates, and transportation costs. It thereby incorporates the most informative data about market expectations and accounts for the implied volatility of commodity prices across the entire spectrum of relevant forward curves.

To summarize, there are two popular theories for understanding the relationship between inventory levels and market structure: the risk premium theory and the conventional storage theory. While each has controversial elements, it is generally accepted that there is a well-defined quantitative relationship between market structure and oil inventories that changes according to market conditions and inventory levels.

Data and Key Variables

In this section we describe the data used in the analysis and the construction of key variables, including a simple measure of contango, convenience yield, cost of carry, and real options value. We estimate these variables, the main drivers for crude oil inventory levels, for eight primary international storage hubs located at major seaports. These include: Fujairah (United Arab Emirates [UAE]), Jamnagar (India), Kagoshima (Japan), Louisiana (United States [U.S.]), Ningbo (China), Rotterdam (Netherlands), Saldanha Bay (South Africa), Singapore and Ulsan (South Korea). The formulas used are given in Appendix A.

To calculate the convenience yield, we used the daily futures values (2-month and 9-month futures) of the major crude oil benchmarks geographically closest to the specified locations: West Texas Intermediate (WTI) for Louisiana, Brent crude for Rotterdam, and Dubai crude for the remaining six locations. The daily future 2-month and 9-month values for the WTI and Brent benchmarks were also used as inputs for the contango variable. Data was sourced from Bloomberg (2019).

As a proxy for the cost of capital, we applied the relevant national central bank rates effective on each day of the estimation period of December 21, 2015 to January 25, 2019. These rates were taken from the websites of the respective central banks and from Triami Media (2019). In the case of the Netherlands, we used a one-year zero coupon bond rate derived from sector curve and for Japan the Japanese yen LIBOR rate; both data sets were taken from Bloomberg (2019).

To determine the cost of carry, we adjusted each location's daily spot crude oil prices based on shipping costs between each pair of ports. The shipping costs were calculated using the weekly spot freight rates taken from Clarksons Research (2019) for crude oil tankers on similar routes. The resulting weekly shipping costs in U.S. dollars per barrel ($/b) were interpolated to obtain daily values using a cubic spline multiplicative procedure from Eviews. For the cost of carry, we again used central bank rates as proxies of the cost of capital.

The spread option value was also calculated on a daily basis for all of the chosen locations. For each location, we selected the geographically nearest crude oil benchmark and compared its delivered cost (equal to the spot price plus shipping costs) to the prices of a number of alternative competing crudes of similar average gravity. In the case of LOOP, where the daily storage rates are available, we added the monthly storage rate on a particular day to the delivery costs. The spot prices for crudes and the LOOP storage costs were taken from Bloomberg (2019) and the shipping costs from Clarksons Research (2019). Central bank rates once more serve as proxies for the cost of capital. The expiry date chosen for the spread option value was one month from the date of valuation.

For the dependent variable—crude oil storage volumes—we picked the daily floating tank top storage volumes in Rotterdam, Louisiana and Fujairah. This data was provided by Orbital Insight (2019).

For the detailed description of sources of data and equations used in the specific estimations of this study, please refer to Appendix A.

Empirical Evidence

The theory of storage suggests that the relationship between market structure—namely the degree of contango/backwardation—and inventories is well-defined and quantifiable, and that the exact nature of that relationship changes with market conditions. The data required to validate these theories is difficult to obtain: risk premium and convenience yield cannot be directly observed, and data for marginal storage costs is scare. However, these values should be reflected in changes in the spot and futures prices for crude oil.

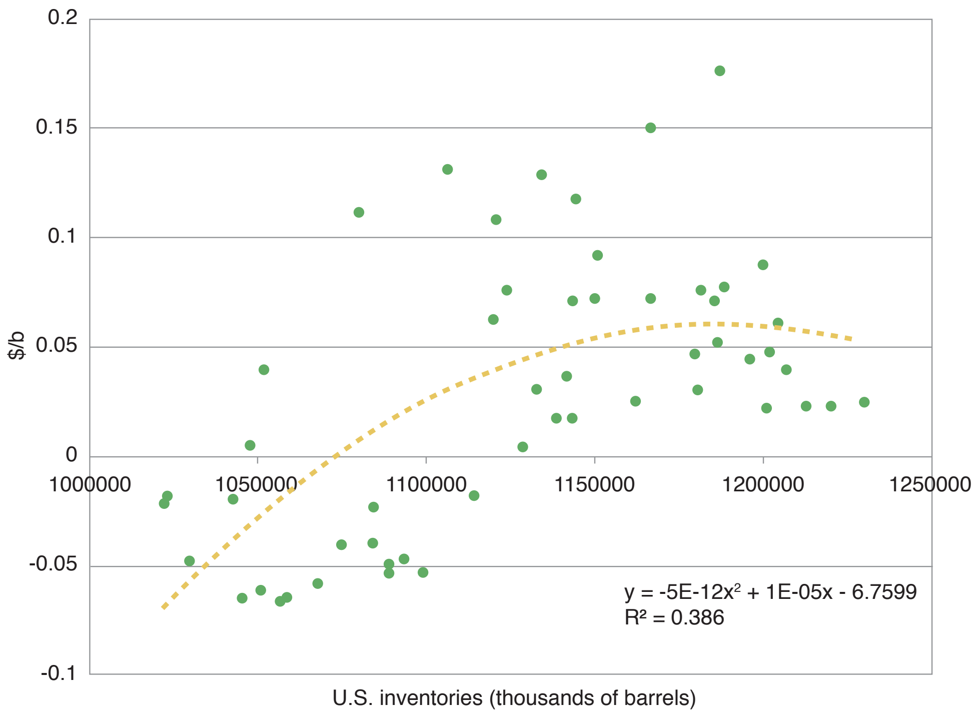
Market participants wishing to buy crude oil for use at a later date, or simply to speculate on the commodity, must pay close attention to the relationship between spot and futures prices. As a result, quantities such as convenience yield and risk premium are implicitly related to price. The relationship between inventory level and market structure will reflect the former's implicit links with convenience yield, cost of carry and options value.

Figure 3 displays a scatter plot of a simple measure of WTI contango versus monthly estimates of U.S. inventories. As expected, the data clearly shows a positive, slightly convex relationship between the degree of contango and inventories.

Hypothesis 1: There is a well-defined quantitative relationship between market structure (contango/backwardation) and inventories.

Hypothesis 2: A spread option formulation yields results that are comparable, and in some instances superior, to models based on conventional storage theory that focus on cost of carry, convenience yield and contango/backwardation.

Figure 3. WTI contango vs U.S. inventories.



Sources: JODI, Bloomberg, Internal KAPSARC Calculations.

The estimated trendline: Contango=y; Inventories=x; Number of observations = 329; R^2=0.7929; The sample period is 03/06/2014 to 06/26/2015.

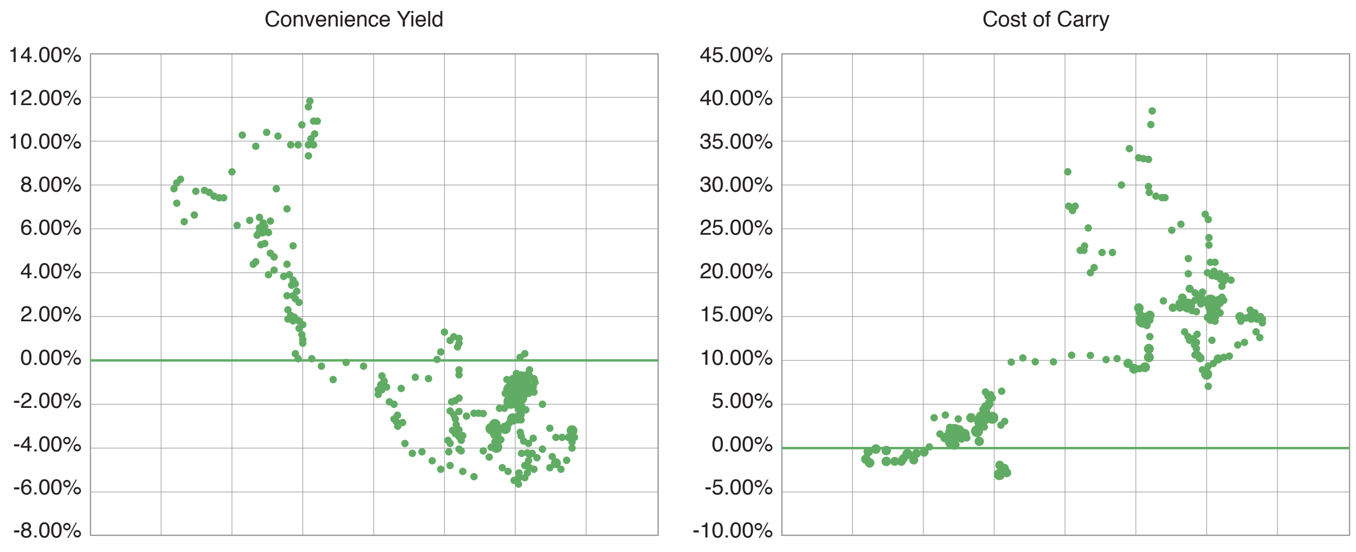
Utilizing the values for convenience yield, contango, cost of carry, and spread options, as estimated from the data and time series listed above, and the formulas stated in Appendix A, we conduct a simple econometric test of the relationship between market structure and inventory levels suggested by storage theory. Specifically, the test examines the relationships between: (i) inventories and the convenience yield, (ii) inventories and the cost of carry, (iii) inventories and the basis and (iv) inventories and the spread options value. The results of this analysis are reported in Table 1. The summary statistics of the underlying variables, structure of the regression equation, and detailed results are reported in appendices B, C and D.

Unsurprisingly, the results for the daily and weekly frequency time series support the conventional storage theory. The coefficients carry all of the correct signs, and suggest a positive relationship between the basis and inventories. As predicted, the estimated coefficients of the inventory variable for the spread option and convenience yield are negative, while those for the level of contango and cost of carry are positive.

The spread option formulation would appear to provide the best fit across all frequencies of data. The estimated coefficient of inventories is statistically significant across daily, weekly and quarterly frequencies of data for one model only, the spread option formulation, which has the highest R-squared (R2).

Figure 4 illustrates a scatter plot of the estimated values for the convenience yield and cost of carry versus daily estimates of inventories at LOOP. Once again, a visual inspection of the estimated time series provides a clear validation of the

Figure 4. Scatterplots of convenience yield and cost of carry vs. inventories.



Source: KAPSARC estimates 2019, Bloomberg and Orbital Insights.

conventional storage theory. There is a negative relationship between the inventory variable for the convenience yield, and a positive relationship between inventories and the cost of carry. Note: the time period of the data sample and value of storage are not disclosed due to the proprietary nature of daily values for LOOP storage provided by Orbital Insights.

The results are robust across different time periods for the lower frequency data. However, monthly and quarterly regressions do not clearly support the conventional theory of storage. In the case of monthly data, only the spread option model has the correct negative sign for the coefficient of inventories. In the case of quarterly data, the cost of carry and spread option models have the correct sign on the inventory coefficient, but only the spread option coefficient can be said to be statistically significant. With the exception of the spread option formulation using quarterly data, we cannot be confident from the data sample employed in this analysis that changes in inventories can explain the variations in market structure at monthly and quarterly frequencies.

Table 1. Regression results for market structure vs. inventories.

Daily	Contango	Convenience yield	Cost of carry	Spread option
Constant	-0.0929**	0.0018	0.0041	2.7512***
Standard error	(0.0406)	(0.0011)	(0.0093)	(0.24519)
Inventory	0.0538	-0.0015	0.0014	-0.4408**
	(0.0436)	(0.0010)	(0.0224)	(0.2276)
Daily	**Contango**	**Convenience yield**	**Cost of carry**	**Spread option**
Constant	-0.6027***	0.0099**	0.0017	2.6742***
Standard error	(0.1459)	(0.0048)	(0.0056)	(0.2596)
Inventory	0.0803*	-0.0022*	0.0027	-0.1458**
	(0.0434)	(0.0011)	0.0016	(0.0701)
Daily	**Contango**	**Convenience yield**	**Cost of carry**	**Spread option**
Constant	0.6562	-0.0355	0.0376	1.4629
Standard error	(0.5376)	(0.0302)	(0.0419)	(0.8266)
Inventory	-0.1500*	0.0019	-0.0019	-0.0198
	(0.0869)	(0.0032)	(0.0079)	-0.1412
Daily	**Contango**	**Convenience yield**	**Cost of carry**	**Spread option**
Constant	-0.2067	-0.0442	0.1344	4.1034***
Standard error	(1.1832)	(0.0557)	(0.1336)	(0.4991)
Inventory	-0.2591	0.0039	0.0079	-0.1233*
	(0.1674)	(0.0072)	(0.0100)	(0.0583)

Source: KAPSARC estimates 2019, Bloomberg and Orbital Insights.

Note: *, **, and *** indicate the estimated coefficients in bold is statistically significant at the 10%, 5% and 1% levels respectively. Standard errors are in parentheses. Convenience yield, cost of carry, and contango are calculated as a first difference. The coefficients for the seasonal dummies are not shown.

A Granger causality test was conducted in an effort to determine whether or not changes in inventories can be used to predict variations in market structure, as measured by spread option value. This test determines if shifts in inventories precede, and as a result, Granger cause changes in the options value. In the case of daily data, the causality was found to run both ways, so that the spread option value can be used to predict inventories and vice versa.

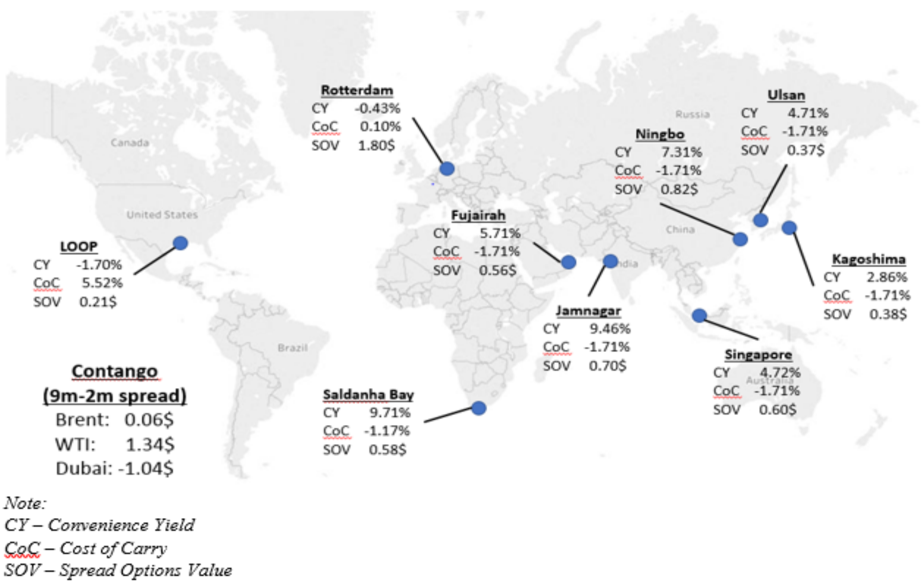
In the case of weekly, monthly and quarterly data, the causality ran only one way: changes in inventories can be used to predict variations in the options value of storage.

To summarize, the weekly frequency time series provides the best evidence that the traditional theories of storage can be used to explain variations in the market structure.

Across daily, weekly, and quarterly data, the spread option model appears the most robust and informative approach. For each of these frequencies, the spread option coefficient on inventory is statistically significant, and the spread option approach provides the best value of R2, and the most reliable model fit for each of the market structures, as measured by the F statistic.

Figure 6 illustrates a snapshot of the calculated values for convenience yield, cost of carry and spread option value on the last day of the sample period, January 25, 2019. On that day, the world oil market appears reasonably well balanced, with inventories trading slightly above their 5-year moving average in the U.S. (LOOP), and slightly below 'average' in Europe (Rotterdam). This was reflected by the market structure, with WTI exhibiting a slight contango of $1.34/b, Brent nearly flat with a contango of $0.06/b, and Middle East and Dubai each with a backwardation of -$1.04/b.

Figure 6. Global crude oil Storage value snapshot, January 25, 2019.



Sources: KAPSARC estimates 2019, Bloomberg, and Orbital Insights.

Note: CY= convenience yield; CoC= cost of carry; SOV= spread options value.

Unsurprisingly, the options value is highest at Rotterdam, indicating the value to be had by shifting supply to Europe; this would push inventories back toward their 5-year moving average. The convenience yield is highest in the Middle East, Asia and Africa, implying that inventories in those areas were significantly below their 5-year moving average. In fact, data from the International Energy Agency (IEA), OECD and the Joint Organizations Data Initiative (JODI) indicate that this was indeed an accurate snapshot of world oil inventories at the time, with commercial crude oil inventories measured at levels above the 5-year moving average in the U.S., and slightly below it in the OECD regions. For the rest of the world, inventories were at just 88% of the 5-year moving average (IEA 2019; JODI 2019).

Conclusion

We seek to determine whether there is a well-defined quantitative relationship between the market structure of crude oil prices and inventory levels. More practically, how steep does contango in crude oil markets have to be for storage to be 'in the money,' thereby guaranteeing rising storage levels?

This paper makes two contributions to existing literature. The first is the analysis of daily data on inventories collected from real-time satellite imagery, facilitating a detailed examination of daily behavior of world oil markets. The second is the application of a spread option-based approach to model the behavior of commodity price responses to the changes in inventory levels.

The prevailing theories of storage assert that there is a well-defined and quantifiable relationship between market structure (i.e., contango/backwardation) and inventory levels. It is a proposition that has proven difficult to validate. Stylized facts, such as a negative relationship between convenience yield and inventory levels, that have generally been accepted by industry are difficult if not impossible to quantify directly. Most of the storage transactions are carried out through bilateral agreements and contracts, meaning the data is not publicly available. The primary variables—convenience yield, cost of carry and risk premiums—are simply unobservable.

The results show that the basic theories of inventory, based on cost of carry and risk premium models, hold for daily and weekly frequencies but become less reliable for longer time frames.

We show that a locational spread option-based model offers a viable alternative to the more traditional methodologies, and can also be used to estimate implied convenience yields and the shadow price of storage. The approach uses all of the information in the futures curves for all major competing crudes, thereby incorporating all relevant information about market expectations as well as accounting for the implied volatility of commodity prices across the entire spectrum of futures curves.

Finally, the three elusive storage variables that drive global crude inventory levels—the cost of carry, convenience yield and spread options value—are calculated for key storage locations, providing a snapshot of global oil inventories at any point in time from December 21, 2015 to January 25, 2019. We estimate these variables for eight primary international storage hubs located at major seaports: Fujairah (UAE), Jamnagar (India), Kagoshima (Japan), Louisiana (U.S.), Ningbo (China), Rotterdam (Netherlands), Saldanha Bay (South Africa), Singapore and Ulsan (South Korea). This snapshot of global inventories will be available on the KAPSARC website, and the underlying dataset is available on request.

Where to now?

The 'snapshot' of global inventories presented in this study provides a unique glimpse into the status of world oil markets. At any given time there may be a 'well balanced' oil market, or regional or global surpluses or shortages of crude. Changes in demand and supply will trigger price reactions that move the market back toward equilibrium, or balance. Yet the potential consequences of any specific political or economic disturbance are unclear and would appear to depend on current market conditions.

As illustrated by the daily estimates of the three primary drivers of inventory levels—convenience yield, spread options value and cost of carry—it is clear that the quantitative relationship between market structure and inventories constantly varies with market conditions across regions and time.

Conclusion

Further examination of the changing nature of these relationships, and the corresponding implications for policymakers, is recommended for future research. Specifically, given a set of underlying market characteristics, it would be interesting to investigate the following questions: (i) How high do inventories have to be before OPEC cutbacks can be said to have successfully rebalanced world oil markets? (ii) How steep does contango in crude oil markets have to be for storage to be ‘in the money,’ thereby triggering rising storage levels? (iii) What are the main characteristics that determine market conditions at any given time, and is there a stable path between different market states?

Appendix A. Data and Key Variables

Contango, convenience yield, cost of carry and spread options estimates

The formulas used for contango, convenience yield, cost of carry and spread option value are as follows:

Contango

Let F(t,T) be the futures price at time t for delivery of crude oil at future time T, and P(t) be the spot price of crude oil at time t.

Contango is calculated as the simple return from purchasing the commodity at time t and selling it for delivery at time T, or F(t,T) – P(t). For the purpose of this analysis P(t) is equal to the price of crude oil at time t=2, essentially the 2-month futures price, and T is equal to the futures price seven months later, or the 9-month futures price. Note: We start at month t=2 instead of t=1 to accommodate for statistical discrepancies arising on the last few days of bid week, the last week before the close of trading on various crude oil futures contracts. To cite one example, WTI crude contracts close on the third business day prior to the twenty-fifth calendar day of the month preceding the delivery month (CME Group 2019).

Note: In futures markets the largest volume of trading usually occurs during the last few days of bid week, when all financial positions must be closed out.

Convenience yield

As mentioned above, the marginal convenience yield C(t,T) is a benefit (or cost) that accrues to the owner of a physical asset, such as a barrel of crude oil. If the spot and futures prices, borrowing costs, and time to maturity are known, the marginal convenience yield can be calculated as the simple difference between the interest rate (borrowing rate) and (1/T) times the natural log of the futures price divided by the spot price (Smith 2019).

Y.1) $$F(t,T) = \mathrm{S(t)} * e^{((R(t,T)-C(t,T))*T)}$$

So that:

Y.2) $$C(t,T) = R(t,T) - \left(\frac{1}{T}\right) * ln\left(\frac{F(t,T)}{\mathrm{S(t)}}\right)$$

Cost of carry

The cost of carry refers to the total costs incurred as a result of holding a commodity in storage, or equivalently the net yield from carrying the underlying asset. It can be estimated by the basis, or in percentage terms as (F(t,T)-S(T))/S(T) and includes the physical expenses of storing the commodity at a given point in time, any necessary insurances, and relevant interest expenses (such as for bonds, margin accounts, or loans) and the opportunity cost associated with taking the position (Chen 2018).

Y.3) $F(t,T) = \mathrm{S(t)} * e^{((R(t,T)+W(t,T)-C(t,T))*T)}$

So that:

Y.4) $CC(t,T) = R(t,T) + W(t,T) - \left(\frac{1}{T}\right) * ln\left(\frac{F(t,T)}{\mathrm{S(t)}}\right)$

Where CC(t,T) is the cost of carry.

Spread option value

The calculation of the spread option value follows the methodology outlined in the KAPSARC paper "Placing a Value on Spot Sales from a Joint Oil Stockpiling Facility" (Considine, Wu, Al-Fawzan, and Six 2019). The value reflects how much a market player would pay to secure the right to purchase crude oil from a major benchmark supplier, at the nearest major international 'port' storage hub (Carmona 2003). This, in turn, will depend on the price of crude oil supplies from other global competitors and can be estimated as a simple European spread option.

The price p is defined as the fair market value of the European spread option, and is given by the following equation:

$$\mathrm{p} = \mathrm{e}^{-\mathrm{rT}} \iint (\mathrm{s}_2 - \mathrm{s}_1 - \mathrm{K})^{+} \mathrm{f}_{\mathrm{T}}(\mathrm{s}_1 \mathrm{s}_2) \mathrm{d}_{\mathrm{s}_1} \mathrm{d}_{\mathrm{s}_2}$$

Where:

1. K=The exercise price level: set equal to zero.

2. T=The expiration date: the option is expected to expire two months after the value or settlement date.

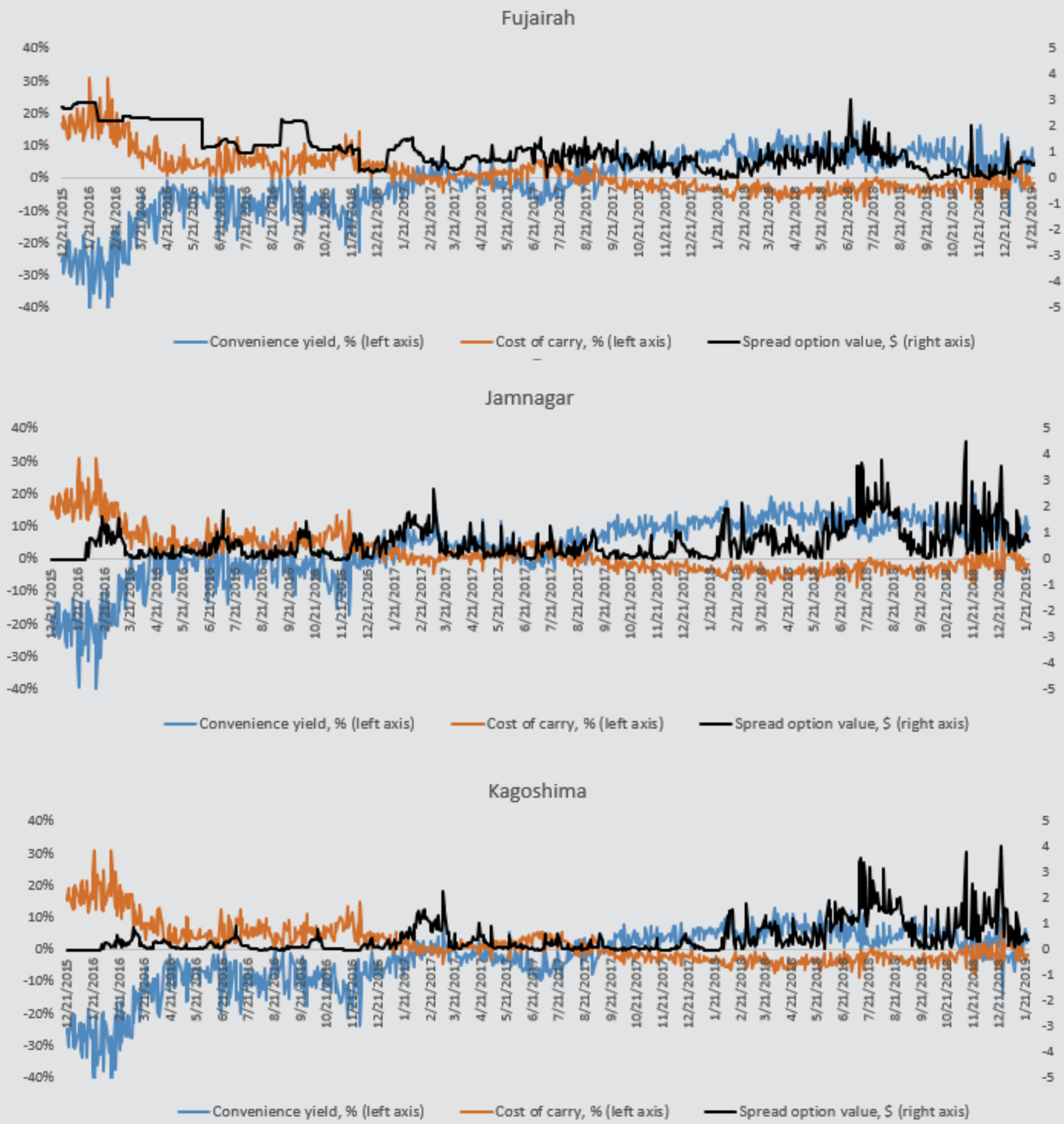
3. s_1=The price of a major benchmark crude free on board (FOB) at the location of the closest major storage hub plus transportation costs.

4. s_2=The price of all competing crudes of comparable API FOB at the storage facility at time t, plus transportation costs (The American Petroleum Industry [API] gravity is the standard measure of how light or heavy a petroleum liquid is when compared to water).

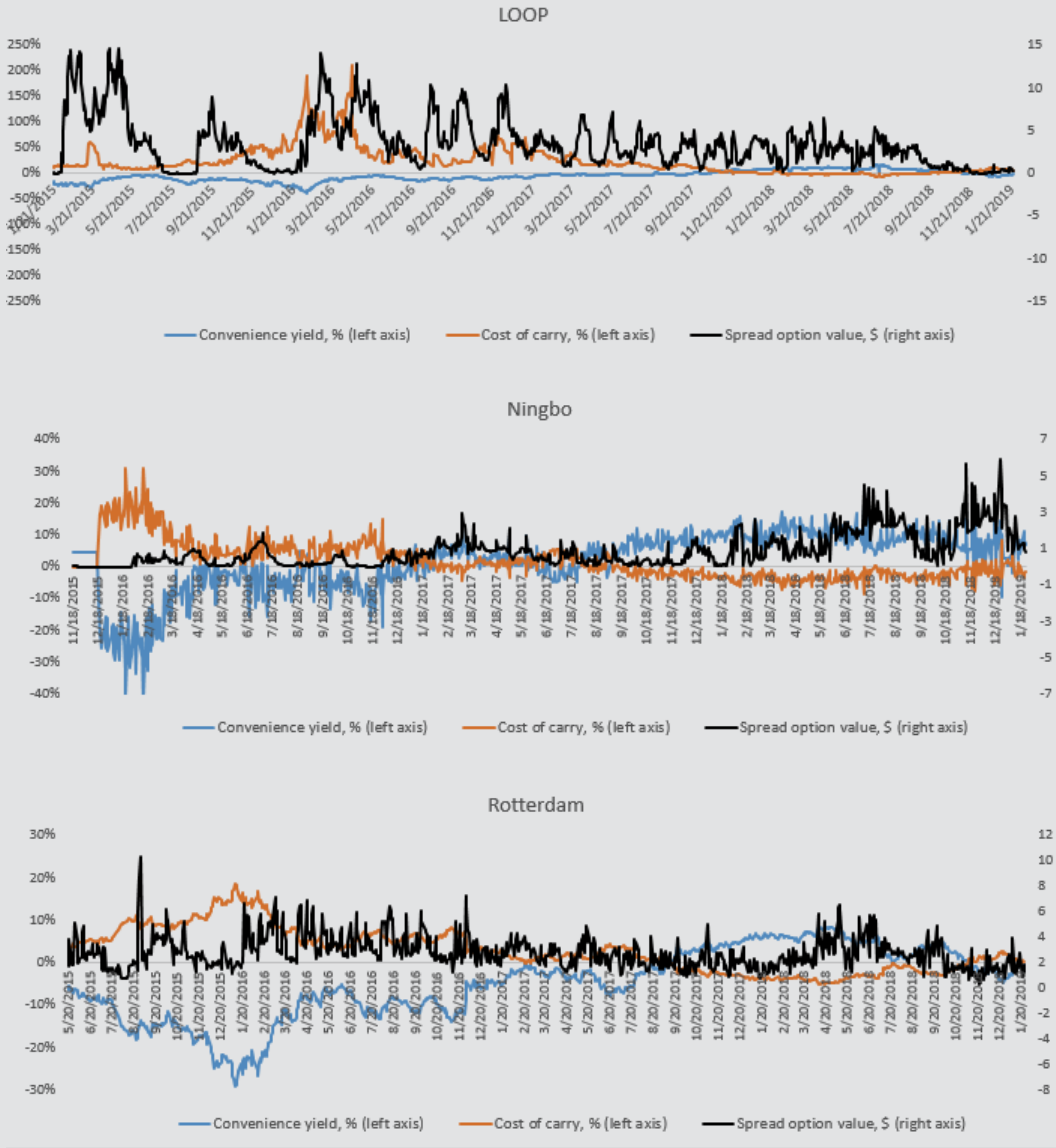
5. r=The short-term risk-free interest rate.

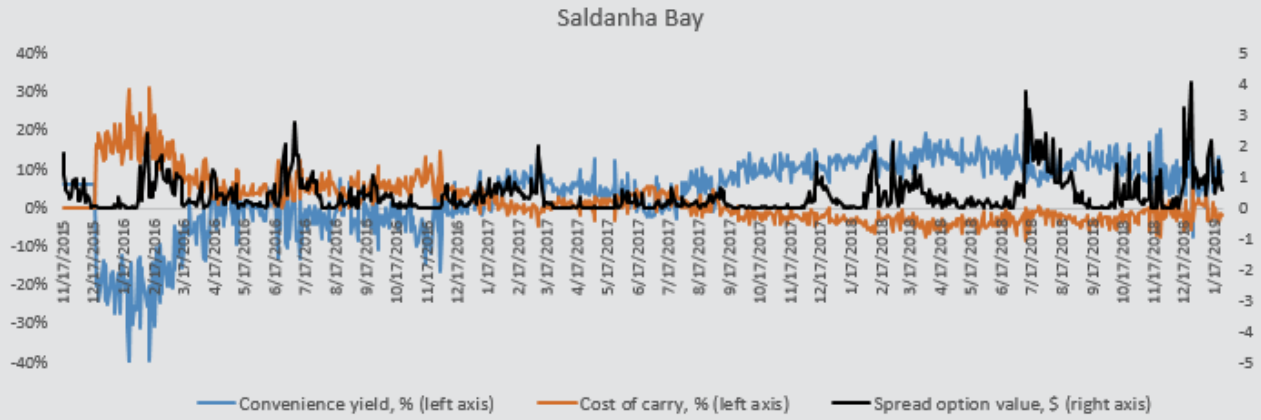
Note: A spread option derives its value from the difference in prices between two or more assets. They are generally traded over the counter, rather than on an exchange. In commodity markets, spread options are often based on the difference in asset prices in two or more locations, points in the calendar, grades or quality, and inputs vs. outputs in the production process, such as spark spreads, and crack spreads (Durrleman 2003). This particular example is based on the location spread, so that the value of the spread call option reflects the fair market value of the right, but not the corresponding obligation, to purchase spot sales FOB at a major storage hub at a future date. The exercise or strike price here is set equal to zero, as the cost of transporting the crude oil to the major international storage hub at future date t is included in S1(0) and S2(0).

Figure A1. Convenience yield, cost of carry and real options value estimations.



Appendix A. Data and Key Variables




Saldanha Bay
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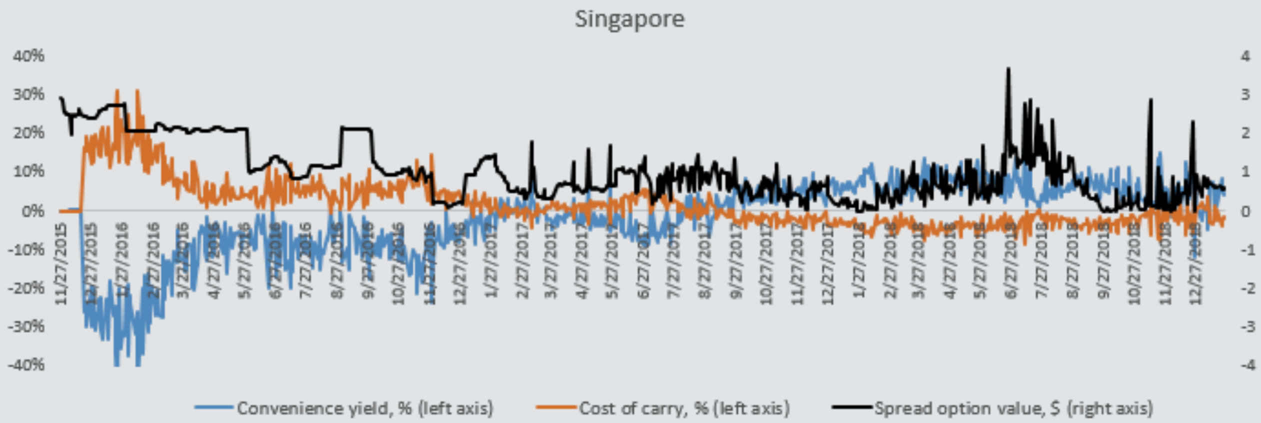
Convenience yield, % (left axis)
Cost of carry, % (left axis)
Spread option value, $ (right axis)


Singapore
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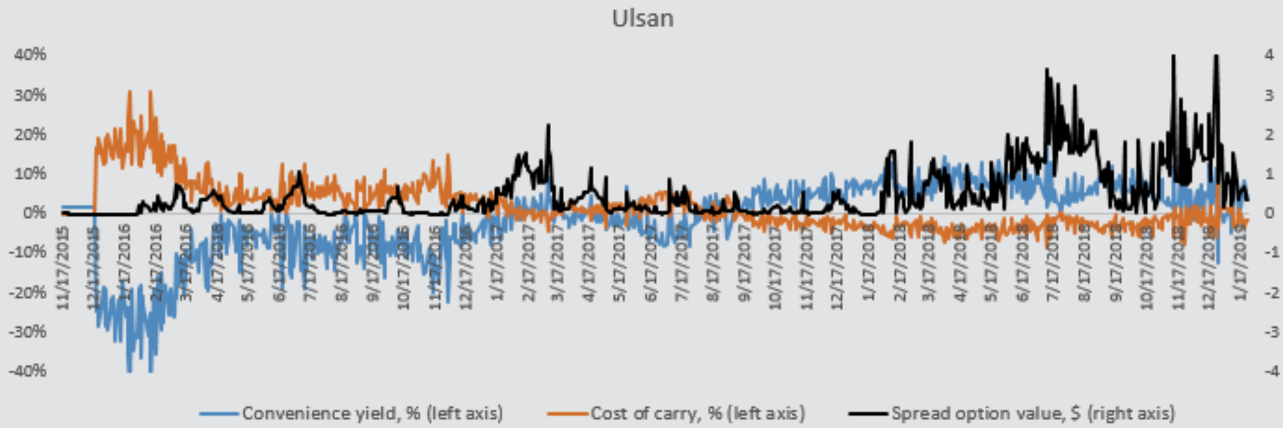
Convenience yield, % (left axis)
Cost of carry, % (left axis)
Spread option value, $ (right axis)


Ulsan
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Convenience yield, % (left axis)
Cost of carry, % (left axis)
Spread option value, $ (right axis)

Appendix A. Data and Key Variables

Table A1. Convenience yield.

Location	Inputs	Data Description	Sources
Fujairah	9-months crude oil future price, $/b	DKI9 Dubai crude oil index	Bloomberg (2019)
Fujairah	2-months crude oil future price, $/b	DKI2 Dubai crude oil index	Bloomberg (2019)
Fujairah	Cost of capital, %	The Central Bank of the United Arab Emirates key rate	Trading Economics (2019)
Jamnagar	9-months crude oil future price, $/b	DKI9 Dubai crude oil index	Bloomberg (2019)
Jamnagar	2-months crude oil future price, $/b	DKI2 Dubai crude oil index	Bloomberg (2019)
Jamnagar	Cost of capital, %	The Central Bank of India key rate	Triami Media (2019)
Kagoshima	9-months crude oil future price, $/b	DKI9 Dubai crude oil index	Bloomberg (2019)
Kagoshima	2-months crude oil future price, $/b	DKI2 Dubai crude oil index	Bloomberg (2019)
Kagoshima	Cost of capital, %	JY0001M index: Japanese yen LIBOR 1-month rate	Bloomberg (2019)
LOOP	9-months crude oil future price, $/b	CL9 WTI crude oil index	Bloomberg (2019)
LOOP	2-months crude oil future price, $/b	CL2 WTI crude oil index	Bloomberg (2019)
LOOP	Cost of capital, %	The Federal Reserve System key rate	Triami Media (2019)
Ningbo	9-months crude oil future price, $/b	DKI9 Dubai crude oil index	Bloomberg (2019)
Ningbo	2-months crude oil future price, $/b	DKI2 Dubai crude oil index	Bloomberg (2019)
Ningbo	Cost of capital, %	The People's Bank of China key rate	Triami Media (2019)
Rotterdam	9-months crude oil future price, $/b	CO9 Brent crude oil index	Bloomberg (2019)
Rotterdam	2-months crude oil future price, $/b	CO2 Brent crude oil index	Bloomberg (2019)
Rotterdam	Cost of capital, %	EUR BS175 BVAL Crv ZR index: 1-year zero coupon bond rate	Bloomberg (2019)
Saldanha Bay	9-months crude oil future price, $/b	DKI9 Dubai crude oil index	Bloomberg (2019)
Saldanha Bay	2-months crude oil future price, $/b	DKI2 Dubai crude oil index	Bloomberg (2019)
Saldanha Bay	Cost of capital, %	The South African Reserve Bank key rate	Triami Media (2019)
Singapore	9-months crude oil future price, $/b	DKI9 Dubai crude oil index	Bloomberg (2019)
Singapore	2-months crude oil future price, $/b	DKI2 Dubai crude oil index	Bloomberg (2019)
Singapore	Cost of capital, %	Singapore Average Overnight interest rate	Trading Economics (2019)
Ulsan	9-months crude oil future price, $/b	DKI9 Dubai crude oil index	Bloomberg (2019)
Ulsan	2-months crude oil future price, $/b	DKI2 Dubai crude oil index	Bloomberg (2019)
Ulsan	Cost of capital, %	Bank of Korea key rate	Triami Media (2019)

Source: KAPSARC.

Table A2. Cost of carry.

Location	Inputs	Data Description	Sources
Fujairah	Delivered crude oil spot price, $/b	Dubai Oman PGCRDUBA index; shipping cost to the location	Bloomberg (2019), Clarksons Research (2019), KAPSARC research
Fujairah	Cost of capital, %	The Central Bank of the United Arab Emirates key rate	Trading Economics (2019)
Jamnagar	Delivered crude oil spot price, $/b	Dubai Oman PGCRDUBA index; shipping cost to the location	Bloomberg (2019), Clarksons Research (2019), KAPSARC research
Jamnagar	Cost of capital, %	The Central Bank of India key rate	Triami Media (2019)
Kagoshima	Delivered crude oil spot price, $/b	Dubai Oman PGCRDUBA index; shipping cost to the location	Bloomberg (2019), Clarksons Research (2019), KAPSARC research
Kagoshima	Cost of capital, %	JY0001M index: Japanese yen LIBOR 1-month rate	Bloomberg (2019)
LOOP	Delivered crude oil spot price, $/b	WTI USCRWTIC index; LPS1 LOOP Storage Cost index	Bloomberg (2019)
LOOP	Cost of capital, %	The Federal Reserve System key rate	Triami Media (2019)
Ningbo	Delivered crude oil spot price, $/b	Dubai Oman PGCRDUBA index; shipping cost to the location	Bloomberg (2019), Clarksons Research (2019), KAPSARC research
Ningbo	Cost of capital, %	The People's Bank of China key rate	Triami Media (2019)
Rotterdam	Delivered crude oil spot price, $/b	Brent EUCRBRDT index, shipping cost to the location	Bloomberg (2019), Clarksons Research (2019), KAPSARC research
Rotterdam	Cost of capital, %	EUR BS175 BVAL Crv ZR index: 1-year zero coupon bond rate	Bloomberg (2019)
Saldanha Bay	Delivered crude oil spot price, $/b	Dubai Oman PGCRDUBA index; shipping cost to the location	Bloomberg (2019), Clarksons Research (2019), KAPSARC research
Saldanha Bay	Cost of capital, %	The South African Reserve Bank key rate	Triami Media (2019)
Singapore	Delivered crude oil spot price, $/b	Dubai Oman PGCRDUBA index; shipping cost to the location	Bloomberg (2019), Clarksons Research (2019), KAPSARC research
Singapore	Cost of capital, %	Singapore Average Overnight interest rate	Trading Economics (2019)
Ulsan	Delivered crude oil spot price, $/b	Dubai Oman PGCRDUBA index; shipping cost to the location	Bloomberg (2019), Clarksons Research (2019), KAPSARC research
Ulsan	Cost of capital, %	Bank of Korea key rate	Triami Media (2019)
Ulsan	9-months crude oil future price, $/b	DKI9 Dubai crude oil index	Bloomberg (2019)

Source: KAPSARC.

Table A3. Spread option.

Location	Inputs	Data Description	Sources
Fujairah	Benchmark crude oil delivered, $/b	Dubai Oman PGCRDUBA index; shipping cost to the location	Bloomberg (2019), Clarksons Research (2019), KAPSARC research
Fujairah	Alternative crudes delivered, $/b	URALS Med CIF URAMM K18 BFVD index; Arab Medium to Asia; USCRHLSE Index; shipping cost to the location	Bloomberg (2019), Clarksons Research (2019), KAPSARC research
Fujairah	Cost of capital, %	The Central Bank of the United Arab Emirates key rate	Trading Economics (2019)
Jamnagar	Benchmark crude oil delivered, $/b	Arab Light to Asia; shipping cost to the location	Bloomberg (2019), Clarksons Research (2019), KAPSARC research
Jamnagar	Alternative crudes delivered, $/b	URALS Med CIF URAMM K18 BFVD index; Brent EUCRBRDT index; Kozmino EUCRESPO index; USCRLLSS index; shipping cost to the location	Bloomberg (2019), Clarksons Research (2019), KAPSARC research
Jamnagar	Cost of capital, %	The Central Bank of India key rate	Triami Media (2019)
Kagoshima	Benchmark crude oil delivered, $/b	Arab Light to Asia; shipping cost to the location	Bloomberg (2019), Clarksons Research (2019), KAPSARC research
Kagoshima	Alternative crudes delivered, $/b	URALS Med CIF URAMM K18 BFVD index; Brent EUCRBRDT index; Kozmino EUCRESPO index; USCRLLSS index; shipping cost to the location	Bloomberg (2019), Clarksons Research (2019), KAPSARC research
Kagoshima	Cost of capital, %	JY0001M index: Japanese yen LIBOR 1-month rate	Bloomberg (2019)
LOOP	Benchmark crude oil delivered, $/b	USCRHLSE index; LPS1 LOOP Storage Cost index	Bloomberg (2019)
LOOP	Alternative crudes delivered, $/b	URALS Med CIF URAMM K18 BFVD index; Brent EUCRBRDT index; Kozmino EUCRESPO index; Arab Light to US; shipping cost to the location	Bloomberg (2019), Clarksons Research (2019), KAPSARC research
LOOP	Cost of capital, %	The Federal Reserve System key rate	Triami Media (2019)
Ningbo	Benchmark crude oil delivered, $/b	Arab Light to Asia; shipping cost to the location	Bloomberg (2019), Clarksons Research (2019), KAPSARC research
Ningbo	Alternative crudes delivered, $/b	URALS Med CIF URAMM K18 BFVD index; Brent EUCRBRDT index; Kozmino EUCRESPO index; USCRLLSS index; shipping cost to the location	Bloomberg (2019), Clarksons Research (2019), KAPSARC research
Ningbo	Cost of capital, %	The People's Bank of China key rate	Triami Media (2019)
Rotterdam	Benchmark crude oil delivered, $/b	Brent EUCRBRDT index; shipping cost to the location	Bloomberg (2019), Clarksons Research (2019), KAPSARC research
Rotterdam	Alternative crudes delivered, $/b	URALS Med CIF URAMM K18 BFVD index; Arab Light to EU; USCRLLSS index; shipping cost to the location	Bloomberg (2019), Clarksons Research (2019), KAPSARC research
Rotterdam	Cost of capital, %	EUR BS175 BVAL Crv ZR index: 1-year zero coupon bond rate	Bloomberg (2019)

Location	Inputs	Data Description	Sources
Saldanha Bay	Benchmark crude oil delivered, $/b	Arab Light to EU; shipping cost to the location	Bloomberg (2019), Clarksons Research (2019), KAPSARC research
Saldanha Bay	Alternative crudes delivered, $/b	URALS Med CIF URAMM K18 BFVD index; Brent EUCRBRDT index; Kozmino EUCRESPO index; USCRLLSS index; shipping cost to the location	Bloomberg (2019), Clarksons Research (2019), KAPSARC research
Saldanha Bay	Cost of capital, %	The South African Reserve Bank key rate	Triami Media (2019)
Singapore	Benchmark crude oil delivered, $/b	Dubai Oman PGCRDUBA index; shipping cost to the location	Bloomberg (2019), Clarksons Research (2019), KAPSARC research
Singapore	Alternative crudes delivered, $/b	URALS Med CIF URAMM K18 BFVD index; Arab Medium to Asia; Kozmino EUCRESPO index; USCRHLSE index; shipping cost to the location	Bloomberg (2019), Clarksons Research (2019), KAPSARC research
Singapore	Cost of capital, %	Singapore Average Overnight interest rate	Trading Economics (2019)
Ulsan	Benchmark crude oil delivered, $/b	Arab Light to Asia; shipping cost to the location	Bloomberg (2019), Clarksons Research (2019), KAPSARC research
Ulsan	Alternative crudes delivered, $/b	URALS Med CIF URAMM K18 BFVD index; Brent EUCRBRDT index; Kozmino EUCRESPO index; USCRLLSS index; shipping cost to the location	Bloomberg (2019), Clarksons Research (2019), KAPSARC research
Ulsan	Cost of capital, %	Bank of Korea key rate	Triami Media (2019)

Source: KAPSARC.

Inventory Data: Savitzky-Golay Smoothing Filters

Daily inventory data was obtained from Orbital Insights. The Savitzky-Golay filter was used to smooth the noise introduced by the satellite data gathering procedure, and maximize the signal to noise ratio (Press 1996).

The general equation for the Savitzky-Golay filter is:

$$Filtx_t = \frac{1}{h}\left[\sum_{i=-\frac{n_{p-1}}{2}}^{\frac{n_{p-1}}{2}} (a_i x_{t-i})\right]$$

Where:

$Filtx_t$= the filtered value of x_t

h= given in Table A.4

a_i= the coefficients of the polynomial

n_p= the number of data points used for the smoothing

x_t= the unfiltered time series

Table A4. Polynomial smoothing (cubic polynomials)

NP	h	a0	a1	a2	a3	a4	a5	a6	a7	a8	a9	a10	a11	a12
5	35	17	12	-3	0	0	0	0	0	0	0	0	0	0
7	21	7	6	3	-2	0	0	0	0	0	0	0	0	0
9	231	59	54	39	14	-21	0	0	0	0	0	0	0	0
11	429	89	84	69	44	9	-36	0	0	0	0	0	0	0
13	143	25	24	21	16	9	0	-11	0	0	0	0	0	0
15	1105	167	162	147	122	87	42	-13	-78	0	0	0	0	0
17	323	43	42	39	34	28	18	7	-6	-21	0	0	0	0
19	2261	269	264	249	224	189	144	89	24	-51	-136	0	0	0
21	3059	329	324	309	284	249	204	149	84	9	-76	-171	0	0
23	805	79	78	75	70	63	54	43	30	15	-2	-21	-42	0
25	5175	467	462	447	422	387	343	287	222	147	62	-33	-138	-253

Note: The coefficients of the polynomial are symetric so that only the positive coefficients are listed, ai = a-i.

Source: KAPSARC.

Appendix B. Summary Statistics

Table B1 reports some basic statistics for the levels of contango, crude oil inventories, convenience yield, and the spread option value for daily, weekly, monthly and quarterly frequencies.

For the daily and weekly time series, the mean of contango, the cost of carry, convenience yield and spread option are all positive, and have very high standard deviations. The skewness of contango, cost of carry and the spread option are all positive suggesting a heavier right tail, while the skewness for inventories and convenience yield are negative, suggesting a heavier left tail.

For all of the time series, kurtosis is quite high, suggesting fat-tailed distributions for all of the variables. The Jarque-Bera test rejects the null hypothesis that any of the time series are normally distributed.

Table B1. Summary statistics for daily time series.

	Inventories	Contango	Cost of carry	Convenience yield	Spread option
Mean	166.2728	5.5800	0.1948	-0.0452	3.4173
Median	164.5142	4.6600	0.1278	-0.0488	2.9731
Maximum	184.0706	15.9400	2.1094	0.1542	12.5639
Minimum	144.7955	0.3300	-0.0752	-0.3864	-0.4186
Std. dev.	9.0729	2.8435	0.2815	0.1045	2.8498
Skewness	-0.2211	0.8217	2.2817	-0.3223	1.1700
Kurtosis	2.3207	3.3953	10.3230	2.5195	4.0851
Jarque-Bera	31.8869	138.6857	3604.6450	31.3192	322.9623
Probability	0.0000	0.0000	0.0000	0.0000	0.0000
Sum	193707.8000	6500.6430	226.3955	-52.5538	3981.2050
Sum sq. dev.	95817.5700	9411.7530	92.0266	12.6795	9453.5640
Observations	1165	1165	1162	1162	1162

Source: Internal KAPSARC calculations.

Note: The spread option and inventories values are smoothed and filtered for noise using the Savitzky-Golay filter described in Appendix A.

Appendix B. Summary Statistics

Table B2. Summary statistics for weekly time series.

	Inventories	Contango	Cost of carry	Convenience yield	Spread option
Mean	166.2711	5.6066	0.1950	-0.0456	3.4106
Median	164.4110	4.6440	0.1304	-0.0497	3.0339
Maximum	183.7490	14.8420	1.7162	0.1389	12.1209
Minimum	144.9884	0.8740	-0.0676	-0.3660	-0.1247
Std. dev.	9.0945	2.8333	0.2806	0.1048	2.8284
Skewness	-0.2180	0.8090	2.1899	-0.3255	1.1650
Kurtosis	2.3061	3.3235	9.3333	2.5238	4.0735
Jarque-Bera	6.8001	27.5656	600.3492	6.5868	66.6354
Probability	0.0334	0.0000	0.0000	0.0371	0.0000
Sum	40403.8700	1362.4040	47.3954	-11.0765	828.7806
Sum sq. dev.	20015.6700	1942.6100	19.0501	2.6557	1935.9440
Observations	243	243	243	243	243

Note: The spread option and inventories values are smoothed and filtered for noise using the Savitzky-Golay filter described in Appendix A.

Source: Internal KAPSARC calculations.

For the monthly time series, the standard deviations are all slightly lower, as expected. All of the time series have fat tails, but the Jarque-Bera test cannot reject the null hypothesis that the level of inventories and convenience yields are normally distributed.

Table B3. Summary statistics for monthly time series.

	Inventories	Contango	Cost of carry	Convenience yield	Spread option
Mean	166.1618	5.5909	0.1942	-0.0451	3.4272
Median	164.1658	4.6514	0.1346	-0.0434	3.1719
Maximum	182.6546	13.3625	1.1803	0.1125	10.4239
Minimum	146.1536	0.9461	-0.0635	-0.3022	-0.0126
Std. dev.	9.0857	2.7785	0.2723	0.1049	2.5272
Skewness	-0.2130	0.8309	1.8858	-0.2930	0.8497
Kurtosis	2.3018	3.3032	6.9736	2.3398	3.2877
Jarque-Bera	1.5608	6.6578	70.0332	1.8180	6.9322
Probability	0.4582	0.0358	0.0000	0.4029	0.0312
Sum	9305.0630	313.0905	10.8753	-2.5284	191.9246
Sum sq. dev.	4540.1970	424.5887	4.0782	0.6049	351.2706
Observations	56	56	56	56	56

Note: The spread option and inventories values are smoothed and filtered for noise using the Savitzky-Golay filter described in Appendix A.

Source: Internal KAPSARC calculations.

For the quarterly time series, the Jarque-Bera test statistic suggests that all of the time series are normally distributed. Once again, the mean of contango, the cost of carry, convenience yield and spread option are all positive, and have very high standard deviations. The skewness of contango, cost of carry and the spread option are all positive, suggesting a heavier right tail, while the skewness for inventories and convenience yield are negative, suggesting a heavier left tail.

For all of the time series, kurtosis is quite high, suggesting fat-tailed distributions for all of the variables.

Appendix B. Summary Statistics

Table B4. Summary statistics for quarterly time series.

	Inventories	Contango	Cost of carry	Convenience yield	Spread option
Mean	165.8345	5.6374	0.1790	-0.0381	3.3282
Median	164.7094	4.7115	0.1183	-0.0392	2.9279
Maximum	180.1008	12.0879	0.8643	0.1108	6.8082
Minimum	148.3084	1.5690	-0.0626	-0.2327	0.0668
Std. dev.	9.0892	2.6120	0.2468	0.1035	1.7940
Skewness	-0.2326	0.7433	1.2949	-0.2466	0.2486
Kurtosis	2.2944	2.9288	4.1296	2.0399	2.3119
Jarque-Bera	0.5953	1.8460	6.6526	0.9708	0.6006
Probability	0.7426	0.3973	0.0359	0.6154	0.7406
Sum	3316.6900	112.7482	3.5807	-0.7613	66.5640
Sum sq. dev.	1569.6590	129.6284	1.1570	0.2037	61.1525
Observations	20	20	20	20	20

Source: Internal KAPSARC calculations.

Note: The spread option and inventories values are smoothed and filtered for noise using the Savitzky-Golay filter described in Appendix A.

Appendix C. Unit Root Tests

The first step in the econometric analysis is to conduct unit root tests on all the variables. Table C.1 reports the results of these tests for contango, inventory levels, convenience yield, and the spread option value for daily, weekly, monthly and quarterly frequencies. The test statistics are estimated for the Augmented Dickey Fuller, and Phillips-Peron tests. The lag length for the Augmented Dickey Fuller (ADF) tests are selected according to the Schwartz Information Criteria. The results show that most of the variables have unit roots at 1%, 5% and 10% significance levels.

The results for the spread option variables suggest that we can reject the null hypothesis of a unit root at the 5% level of significance for all frequencies of data.

For the cost of carry, the results for the weekly frequency are ambiguous, as the ADF suggests that we can reject the null hypothesis at the 5% level while the Philips-Peron (PP) value suggests that we cannot reject the null at even the 10% level.

Based on the results of the various unit root tests, we can reject the unit root hypothesis for the spread option at all frequencies, and for the cost of carry at daily and weekly frequencies. The first difference was taken and each time series was retested before its inclusion in the regression analysis. In all cases, the first difference of the new time series was found to be stationary.

Table C1. Unit root tests.

Daily	**Inventories**	**Contango**	**Cost of carry**	**Convenience yield**	**Spread option**	**Critical values**	**ADF**	**PP**
Augmented Dickey Fuller	-2.1990	-2.4717	-3.6247	-1.8265	-3.9133	1% level	-3.435831	-3.435753
Prob.*	0.2069	0.1227	0.0055	0.3678	0.0020	5% level	-2.863848	-2.863814
Philips-Perron	-2.3309	-2.3934	-3.5443	-1.8661	-4.3286	10% level	-2.56805	-2.568031
Prob.*	0.1624	0.1438	0.0071	0.3486	0.0004			
Weekly	**Inventories**	**Contango**	**Cost of carry**	**Convenience yield**	**Spread option**	**Critical values**	**ADF**	**PP**
Augmented Dickey Fuller	-2.1779	-2.2217	-2.8998	-2.1350	-3.6336	1% level	-3.457865	-3.457286
Prob.*	0.2150	0.1992	0.0468	0.2312	0.0058	5% level	-2.873543	-2.873289
Philips-Perron	-2.4005	-2.0255	-2.5607	-2.0304	-3.6982	10% level	-2.573242	-2.573106
Prob.*	0.1427	0.2758	0.1027	0.2737	0.0047			
Monthly	**Inventories**	**Contango**	**Cost of carry**	**Convenience yield**	**Spread option**	**Critical values**	**ADF**	**PP**
Augmented Dickey Fuller	-2.5362	-1.8288	-2.3232	-1.8403	-4.9536	1% level	-3.557472	-3.555023
Prob.*	0.1128	0.3630	0.1685	0.3576	0.0001	5% level	-2.916566	-2.915522
Philips-Perron	-2.4616	-1.9394	-2.2945	-1.8823	-3.5722	10% level	-2.596116	-2.595565
Prob.*	0.1303	0.3123	0.1773	0.3381	0.0095			

Appendix C. Unit Root Tests

Quarterly	Inventories	Contango	Cost of carry	Convenience yield	Spread option	Critical values	ADF	PP
Augmented Dickey Fuller	-0.8576	-1.8042	-1.6581	-1.7006	-3.1568	1% level	-3.886751	-3.831511
Prob.*	0.7760	0.3672	0.4352	0.4110	0.0391	5% level	-3.052169	-3.02997
Philips-Perron	-2.2722	-1.9314	-1.6808	-1.9716	-4.2336	10% level	-2.666593	-2.655194
Prob.*	0.1900	0.3120	0.4244	0.2956	0.0047			

Source: Internal KAPSARC calculations.

Note: The reported values are the test statistics, and the probability of the null hypothesis of a unit root.

*MacKinnon (1996) one-sided p-values.

Appendix D. Methodology and Empirical Results

We investigate the relationships between market structure, inventories and oil prices by examining a large dataset of crude oil spot and futures prices, interest rates, and inventory levels. A description of the dataset is provided above in the section "Data and Key Variables."

To determine the relationship between market structure and inventories, we estimate separate regression equations of the market structure on inventories, and seasonal dummy variables for a number of dependent variables—including the convenience yield, contango, cost of carry, and the spread option value—at daily, weekly, monthly and quarterly frequencies.

The respective regressions follow the work done by Kucher and Kurov (2014), Omura and West (2015) and Fattouh (2009) and are represented as:

$$MS_t = \alpha_o + \beta_1 \Delta Inv_t + \sum_{i}^{N} \left(\gamma_{i_t} * D_{i_t}\right) + \varepsilon_t$$

Where:

MS_t≡ Market structure as defined by the following list of dependent variables

A. Convenience yield

B. Cost of carry

C. Contango

D. Spread option

ΔInv_t≡ Padd3 Inventories

D_i ≡ Seasonal dummy variables

A. Monthly seasonal dummy variables for daily, weekly and monthly frequencies

B. Quarterly seasonal dummy variables for quarterly frequencies

$\alpha_o, \beta_1, \gamma_{i_t}$ ≡ Estimated parameters

Appendix D. Methodology and Empirical Results

The regressions were estimated using ordinary least squares (OLS) with heteroskedasticity- and autocorrelation-consistent (HAC) standard errors and covariance (Bartlett kernel, Newey-West fixed bandwidth=6.0). The results are given in tables D.1-D.4.

Table D.1 shows the estimated relationship between inventory and market structure for daily time series. The sample length for the daily regressions is 412, and included daily data from October 3, 2016 to October 30, 2018. (Note: The sample was shortened to accommodate disruptions to the data set attributed to the addition of new satellites, and coverage by Orbital Insight.) Consistent with the conventional theory of storage, the estimated coefficients on the inventory variable for the spread option and convenience yield are negative, while the coefficients for the level of contango and cost of carry are positive. The estimated coefficient on inventory is statistically significant for one model only, the spread option formulation, which has the highest R2.

In the case of the convenience yield and spread option formulations, the Dubin Watson statistic showed clear signs of autocorrelation. The regressions were re-run using an alternative formulation, a generalized linear model (Newton-Raphson/Marquardt steps), which improved the significance of the estimated coefficient significantly for the spread option model. The results for the convenience yield formulation were not as good, and the p-values were reduced for both the constant and the change in inventories. As there is no change in the estimated coefficients, the results are not reported here.

The F statistic and Wald F statistics suggest that we can reject the null hypothesis that none of the estimated coefficients in the regressions using the cost of carry and spread option as dependent variables are significant. The F-values for the convenience yield model are a bit ambiguous, but suggest that we can reject the null hypothesis at the 10% level of significance. The results for the convenience yield suggest that we cannot reject the null hypothesis that none of the independent variables have an effect on the level of crude oil inventories.

A Granger causality test using 15 lagged observations suggests that we can reject the null hypothesis that changes in inventories do not Granger cause changes in the spread option variable at the 5% level, and we can reject the hypothesis that the spread option value does not Granger cause changes in inventories. In the case of quarterly frequency, the Granger causality can run both ways, from inventories to the spread option value.

Table D1. Regression results for market structure vs. inventories daily data.

Daily	Contango	Convenience yield	Cost of carry	Spread option
Constant	**-0.0929****	0.0018	0.0041	**2.7512*****
Standard error	(0.0406)	(0.0011)	(0.0093)	(0.24519)
Inventory	0.0538	-0.0015	0.0014	**-0.4408****
	(0.0436)	(0.0010)	(0.0224)	(0.2276)
N	412	408	409	412
R-squared	0.0393	0.0205	0.1276	0.2547
Adjusted R-squared	0.0104	-0.0092	0.1012	0.2323
S.E. of regression	0.3364	0.0071	0.0889	1.0882
Sum squared resid	45.1581	0.0198	3.1262	472.4617
F-statistic	1.3612	0.6902	4.8274	11.3641
Prob (F-statistic)	0.1819	0.7612	0.0000	0.0000
Prob (Wald F-statistic)	0.0861	0.5775	0.0000	0.0000
Mean dependent var	0.0136	0.0002	0.0582	2.6356
S.D. dependent var	0.3382	0.0070	0.0937	1.2419
Durbin-Watson stat	1.9828	1.8722	0.0333	0.0865
Wald F-statistic	1.6101	0.8704	4.7631	5.0457

Source: Internal KAPSARC calculations.

Note: *, **, and *** indicate the estimated coefficients in bold is statistically significant at the 10%, 5% and 1% levels respectively. Standard errors are in parentheses. Convenience yield and contango are calculated as a first difference. The coefficients for the seasonal dummies are not shown.

Table D.2 shows the estimated relationship between inventory levels and market structure for weekly time series. The sample length for the weekly regressions is 87, and included weekly data from October 3, 2016 to October 30, 2018. (Note: The sample was shortened to accommodate disruptions to the data set attributed to the addition of new satellites, and coverage by Orbital Insight.) The regressions were estimated using OLS with HAC standard errors and covariance (Bartlett kernel, Newey-West fixed bandwidth=4.0). Once again, the results are consistent with the conventional theory of storage, the estimated coefficients on the inventory variable for the spread option and the convenience yield are negative, while the coefficients for the level of contango and cost of carry are positive. The estimated coefficient on inventory is statistically significant for contango and the spread option formulation. Once again the spread option formulation has the highest R2.

In the case of the spread option formulations, the Dubin Watson statistic showed clear signs of autocorrelation. Once again the regression was re-estimated using a generalized linear model (Newton-Raphson/Marquardt steps) which reduced the significance of the estimated coefficient. The p-value for the inventory coefficient was increased to 0.08 implying significance at the 10% level. As there is no change in the estimated coefficients, the results are not reported here.

The F statistic suggests that we can reject the null hypothesis that none of the variables in the regressions using the contango as dependent variables are significant at the 10% level. Meanwhile, the Wald F statistics indicate that we can reject the null hypothesis that none of the variables in the regressions for any of the models are significant at the 10% level. The null is rejected at the 1% level for the contango and spread option formulations. The Wald F-values for the convenience yield and cost of carry models are ambiguous, but they suggest that we can reject the null hypothesis at the 10% level of significance. The F-test results for the convenience yield and cost of carry models suggest that we cannot reject the null hypothesis that none of the independent variables have an effect on the level of crude oil inventories.

A Granger causality test using five lagged observations suggests that we can reject the null hypothesis that changes in inventories do not Granger cause changes in the spread option variable at the 5% level, but we cannot reject the hypothesis that the spread option value does not Granger cause changes in inventories. In the case of the quarterly frequency, the Granger causality runs only one way, from inventories to the spread option value.

Table D2. Regression results for market structure vs. inventories weekly data.

Weekly	Contango	Convenience yield	Cost of carry	Spread option
Constant	**-0.6027*** **	**0.0099** **	0.0017	**2.6742*** **
Standard error	(0.1459)	(0.0048)	(0.0056)	(0.2596)
Inventory	**0.0803***	**-0.0022***	0.0027	**-0.1458** **
	(0.0434)	(0.0011)	0.0016	(0.0701)
N	87	87	87	87
R-squared	0.2336	0.1239	0.1292	0.2731
Adjusted R-squared	0.1094	-0.0182	-0.0120	0.1552
S.E. of regression	0.6118	0.0138	0.0231	1.1081
Sum squared resid	27.7007	0.0140	0.0393	90.8691
F-statistic	1.8799	0.8719	0.9150	2.3171
Prob (F-statistic)	0.0508	0.5782	0.5365	0.0142
Prob (Wald F-statistic)	0.0000	0.0560	0.0282	0.0006
Mean dependent var	0.0766	0.0002	-0.0025	2.6184
S.D. dependent var	0.6483	0.0136	0.0229	1.2057
Durbin-Watson stat	1.6751	1.6076	1.7145	0.9900
Wald F-statistic	4.6178	1.8454	2.0839	3.3962

Source: Internal KAPSARC calculations.

Note: *, **, and *** indicate the estimated coefficients in bold is statistically significant at the 10%, 5% and 1% levels respectively. Standard errors are in parentheses. Convenience yield, cost of carry, and contango are calculated as a first difference. The coefficients for the seasonal dummies are not shown.

Sample (adjusted): 04.2014–10.2018

Table D.3 shows the estimated relationship between inventory and market structure for the monthly time series. The sample length for the monthly regressions is 55 and includes monthly data from April, 2014 to November, 2018. (Note: A dummy variable was added to accommodate disruptions to the data set attributed to the addition of new satellites, and coverage by Orbital Insight, but it was not found to be statistically significant at the monthly level.) The regressions were estimated using OLS with HAC standard errors and covariance (Bartlett kernel, Newey-West fixed bandwidth=4.0). Once again, the results are generally not statistically significant, and do not provide statistical evidence of the conventional theory of storage. The estimated coefficients on the inventory variable for the convenience yield, the level of contango and the cost of carry are the wrong sign. The estimated coefficient on inventory for the spread option is the right sign, but not statistically significant at the 10% level. Again, the spread option formulation has the highest R2.

In the case of the spread option formulations, the Dubin Watson statistic showed clear signs of autocorrelation. Once again the regression was re-estimated using a generalized linear model (Newton-Raphson / Marquardt steps), which reduced the significance of the estimated coefficient slightly for the spread option model. The p-value for the inventory coefficient was reduced to 0.12, implying significance at the 12% level. As there is no change in the estimated coefficients, the results are not reported here.

The F statistic suggests that we cannot reject the null hypothesis that none of the variables in the regressions can be used to explain the variation in the dependent variable at the 10% level. The Wald F statistics indicate that we cannot reject the null hypothesis that none of the variables in the regressions for any of the models are significant at the 10% level, with the possible exception of the convenience yield specification, which is valid at the 5% level.

A Granger causality test using two lagged observations suggests that we can reject the null hypothesis that changes in inventories do not Granger cause changes in the spread option variable at the 10% level, but we cannot reject the hypothesis that the spread option value does not Granger cause changes in inventories. In the case of the quarterly frequency, the Granger causality runs only one way, from inventories to the spread option value.

Table D3. Regression results for market structure vs. inventories monthly data.

Monthly	Contango	Convenience yield	Cost of carry	Spread option
Constant	0.6562	-0.0355	0.0376	1.4629
Standard error	(0.5376)	(0.0302)	(0.0419)	(0.8266)
Inventory	**-0.1500***	0.0019	-0.0019	-0.0198
	(0.0869)	(0.0032)	(0.0079)	-0.1412
N	55	55	55	55
R-squared	0.2479	0.2744	0.1686	0.3080
Adjusted R-squared	0.0330	0.0671	-0.0689	0.1103
S.E. of regression	1.4063	0.0420	0.1683	2.4055
Sum squared resid	83.0666	0.0739	1.1902	243.0267
F-statistic	1.1538	1.3237	0.7098	1.5578
Prob (F-statistic)	0.3461	0.2418	0.7332	0.1422
Prob (Wald F-statistic)	0.2678	0.0405	0.7083	0.4330
Mean dependent var	0.0609	-0.0017	0.0013	3.4322
S.D. dependent var	1.4302	0.0434	0.1628	2.5502
Durbin-Watson stat	1.8531	1.5851	2.6305	1.0331
Wald F-statistic	1.2766	2.0768	0.7365	1.0392

Source: Internal KAPSARC calculations.

Note: *, **, and *** indicate the estimated coefficients in bold is statistically significant at the 10%, 5% and 1% levels respectively. Standard errors are in parentheses. Convenience yield, cost of carry, and contango are calculated as a first difference. The coefficients for the seasonal dummies are not shown.

Table D.4 shows the estimated relationship between inventory levels and market structure for the quarterly time series. The sample length for the quarterly regressions is 19 and includes quarterly data from Q2 2014 to Q4 2018. (Note: A dummy variable was added to accommodate disruptions to the data set attributed to the addition of new satellites, and coverage by Orbital Insight, but it was not found to be statistically significant at the quarterly level.) The regressions were estimated using OLS with HAC standard errors and covariance (Bartlett kernel, Newey-West fixed bandwidth=3.0). At the quarterly frequency, the results are generally not statistically significant, and for the convenience yield and contango variables not consistent with the conventional and risk premium theories of storage. The estimated coefficients on the inventory variable for the convenience yield and level of contango are the wrong signs. The estimated coefficients on inventory for contango and spread option are the right signs. The spread option coefficient on inventory is statistically significant at the 5% level. The spread option formulation has the highest R2.

In the case of the spread option formulations, the Dubin Watson statistic showed no clear signs of autocorrelation. The F and Wald-F statistics for the convenience yield and cost of carry market structures suggest that we cannot reject the null hypothesis that none of the variables in the regressions can be used to explain the variation in the dependent variable at the 10% level. The contango variable is unclear, with the Wald F statistic suggesting that the null hypothesis can be rejected at the 10% level. For the spread option formulation, both the Wald F and the F statistic suggest that the null hypothesis can be rejected at the 10% level.

A Granger causality test using one lagged observation suggests that we can reject the null hypothesis that changes in inventories do not Granger cause changes in the spread option variable at the 10% level, but we cannot reject the hypothesis that the spread option value does not Granger cause changes in inventories. In the case of quarterly frequency, the Granger causality runs only one way, from inventories to the spread option value.

Table D4. Regression results for market structure vs. inventories quarterly data.

Quarterly	Contango	Convenience yield	Cost of carry	Spread option
Constant	-0.2067	-0.0442	0.1344	**4.1034*** **
Standard error	(1.1832)	(0.0557)	(0.1336)	(0.4991)
Inventory	-0.2591	0.0039	0.0079	**-0.1233***
	(0.1674)	(0.0072)	(0.0100)	(0.0583)
N	19	19	19	19
R-squared	0.3523	0.3053	0.3265	0.4229
Adjusted R-squared	0.1672	0.1068	0.1341	0.2580
S.E. of regression	2.0411	0.0740	0.1650	1.5873
Sum squared resid	58.3276	0.0766	0.3811	35.2741
F-statistic	1.9037	1.5381	1.6970	2.5645
Prob (F-statistic)	0.1658	0.2450	0.2065	0.0845
Prob (Wald F-statistic)	0.0725	0.2431	0.2805	0.0925
Mean dependent var	0.1762	-0.0049	0.0037	3.3374
S.D. dependent var	2.2367	0.0783	0.1773	1.8427
Durbin-Watson stat	2.0960	1.9406	1.8822	1.4116
Wald F-statistic	2.7202	1.5451	1.4135	2.4726

Source: Internal KAPSARC calculations.

Note: *, **, and *** indicate the estimated coefficients in bold is statistically significant at the 10%, 5% and 1% levels respectively. Standard errors are in parentheses. Convenience yield, cost of carry, and contango are calculated as a first difference. The coefficients for the seasonal dummies are not shown.

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About the Project

The purpose of this project is to provide a snapshot of global oil inventories at any given time and to identify whether the global or regional markets can be considered balanced. This will help identify the potential regional or global surpluses (or shortages) of crude oil supplies and inventories that can trigger a price reaction and the subsequent rebalancing of world oil markets.

The equilibrium 'market balancing' level of world oil inventories could have changed significantly in recent decades under the influence of factors, including: (a) the shale revolution and the resulting rapid response of shale oil supplies to changes in world oil prices; (b) the expansion of global oil refining and consuming centers; and (c) the buildup of strategic petroleum reserves in non-OECD countries. Therefore, it is essential to determine the optimal level of inventories that would rebalance world oil markets under the new market paradigm. The project aims to answer the following questions: 1) How high do inventories have to be before the world oil markets become over-supplied? 2) Are current inventory levels so high that they have put the market at risk of another price shock?

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