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RESEARCH ARTICLE

Determinants of the WTI-Brent price spread revisited

Jerome Geyer-Klingeberg | Andreas W. Rathgeber

Institute of Materials Resource Management, University of Augsburg, Augsburg, Germany

Correspondence
Jerome Geyer-Klingeberg and Andreas W. Rathgeber, Institute of Materials Resource Management, University of Augsburg, Werner-von-Siemens-Straße 6, Augsburg 86159, Germany.
Email: jerome.geyer-klingeberg@mrm.uni-augsburg.de and andreas.rathgeber@mrm.uni-augsburg.de

Abstract

Using autoregressive distributed lag modeling and structural break testing, we explore the drivers of the oil price spread between West Texas Intermediate and Brent in a data set from 1995 to 2019. We find a major structural break in December 2010 and minor breaks in 2005 and 2012. Important spread determinants are the convenience yield, as a proxy for crude oil inventories, the trading activity in crude oil paper markets, shipping costs, as well as the stock market development in the United States and Europe. After the break in 2010, the paper market activity, open interest, and shipping costs have become more important spread drivers.

KEYWORDS

Brent, convenience yield, crude oil, structural break, West Texas Intermediate

1 | INTRODUCTION

Due to its strategic importance for the global economy, crude oil is the world's most actively traded commodity. However, not all traded crude oils are alike. Although there are multitudes of varieties and blends from hundreds of different oil production spots,[1] there are only a few crude oil benchmarks used for oil pricing. The most prevalent global benchmarks for (light) crude oil are West Texas Intermediate (WTI) and North Sea Brent crude (Brent).[2] Although the quality characteristics of Brent and WTI are similar, WTI is somewhat lighter, which makes it more valuable for refining (Energy Intelligence Group, 2011).

The local market price of crude oil, like any other tradable commodity, is determined by supply and demand. When price differences between various local markets increase, demand and supply can spill over from one market to another market. This concept of market integration was first proposed by Adelman (1984) and the hypothesis of a global oil market. The degree of market integration depends on the interchangeability between regional markets and transaction costs (Kleit, 2001), the capacity to transport oil across the supply chain, and the ability of suppliers to change the supply line (George & Breul, 2014). As an implication of integrated crude oil markets, the price of crude oil with similar quality characteristics, like WTI and Brent, should manifest a common movement (Fattouh, 2010b).

Figure 1 shows the spot prices for WTI and Brent crude oil, as well as their price spread.[3] The price of WTI has historically traded at a premium of around $1.3 per barrel against Brent (on average), which approximately represents

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[1]The International Crude Oil Market Handbook (Energy Intelligence Group, 2011) lists more than 190 different crude oil streams.

[2]WTI is a blend of several American domestic crude streams with its major trading spot in Cushing, Oklahoma. Brent oil covers four crude streams pumped in the North Sea.

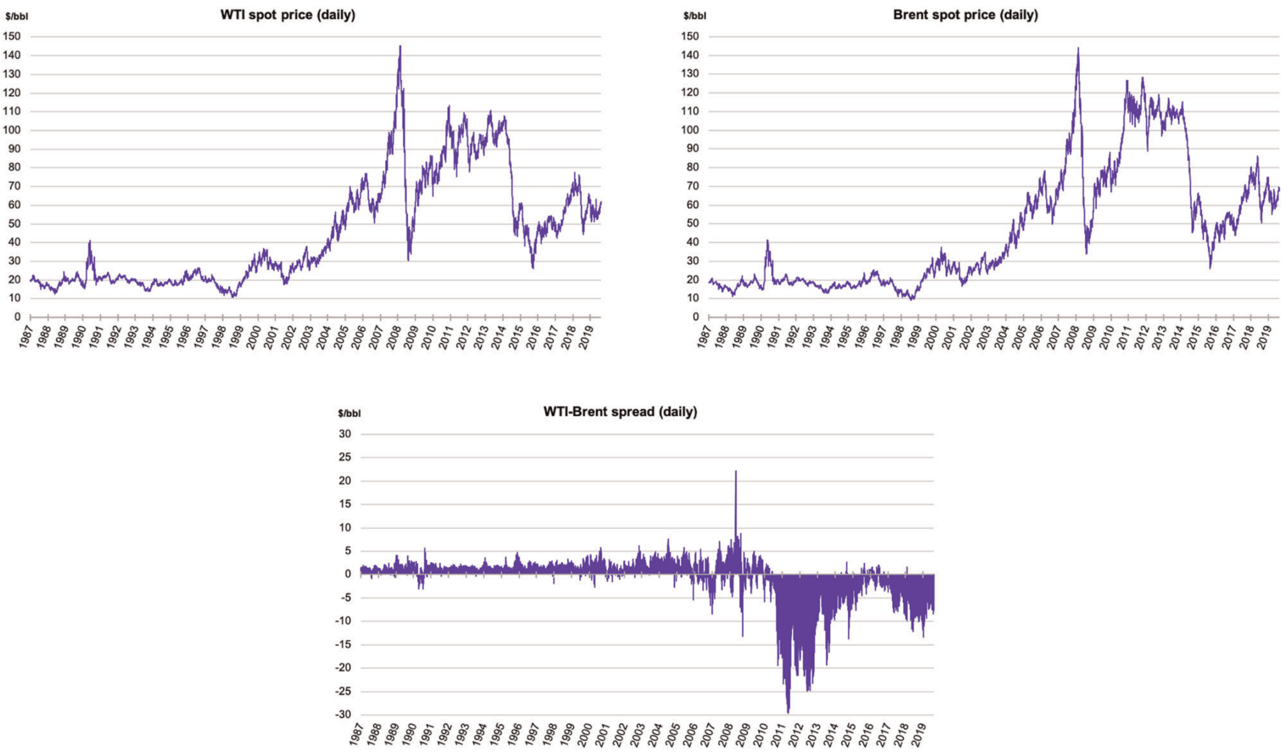

FIGURE 1 West Texas Intermediate and Brent spot prices and price spread. Data retrieved from U.S. Energy Information Administration [Color figure can be viewed at https://wileyonlinelibrary.com]

the transportation costs of moving oil from the North Sea to refineries along the U.S. Gulf Coast (Kaminski, 2014). Beginning in 2006, the volatility of the WTI-Brent spread increased with alternating periods of positive and negative price spreads. Since 2010, WTI and Brent started to decouple. The result is an increasing discount of WTI against Brent, which peaked in September 2011 with a spread of −\$29.59 per barrel.

The volatility of the WTI-Brent spread creates economic and policy implications, as firms and governmental institutions rely on global oil benchmarks to define their business strategy and energy policy. When global markets are integrated, producers with the lowest costs provide the supply and consumers can rely on the signaling and allocation function of prices (Kleit, 2001). Otherwise, when local prices diverge and spreads are volatile, transaction costs rise and the balancing mechanism between markets decreases (Gülen, 1999). Depending on whether oil markets are fragmented or unified, local policy interventions can have regional or global effects (Weiner, 1991). Moreover, various authors argue that the wide price spread illustrates that WTI no longer reflects the world oil supply-demand balance and thus loses its eligibility as global oil price benchmark (Bentzen, 2007; Fattouh, 2010a; Kaufmann & Ullman, 2009). In addition, abnormal WTI-Brent price differences result in revenue declines of U.S. oil producers and other oil-exporting countries, because oil imports to the United States are priced on the basis of WTI (Janzen & Nye, 2013). If, as a consequence, upstream oil producers lower their production levels, also the transport volumes and thus midstream sector's earnings decrease. Finally, the negative WTI-Brent price gap affects contractual agreements where WTI is the reference price and thus has implications on the instruments used for financial risk management (Kaminski, 2014).

While a long line of literature examines structural breaks and cointegration of the WTI-Brent price spread (among others, Chen et al., 2015; Fattouh, 2010b; Hammoudeh et al., 2008; Kao & Wan, 2012), only a few authors analyze the determinants of crude oil price differentials (especially, Büyüksahin et al., 2013; Milonas & Henker, 2001). The goal of this study is to re-examine a broad set of supply and demand factors as drivers for the variation in the WTI-Brent price spread. Thereby, we combine the previous literature on structural break analysis and the determinants of price differentials. Based on a daily data set for the time period between 1995:01 and 2019:12, we identify structural breaks in

[3] In this paper, the WTI-Brent spread is defined as WTI spot (futures) price—Brent spot (futures) price.

TABLE 1 Overview of existing studies on the WTI-Brent price spread

Authors	Sample period	Methodology	Findings
Panel A: Structural breaks			
Bentzen (2007)	1987:04–2004:12	Bai–Perron test for multiple structural breaks	SB: 1999:11
Büyüksahin et al. (2013)	2006:06–2012:07	Chow test	SB: 2008:11, 2010:12
Argua (2015)	2001:01–2014:05	Bai–Perron test for multiple structural breaks	SB: 2003:01, 2005:01, 2007:01, 2009:02, 2011:02
Chen et al. (2015)	1988:01–2014:12	CUSUM of squares-based test	SB: 2010:12
Li et al. (2015)	2004:01–2013:12	Rolling Chow test	SB: 2010:01
Liu et al. (2016)	2004:01–2010:12	Bai–Perron test for multiple structural breaks	SB: 2010:12
Ye and Karali (2016)	1993:12–2016:04	Bai–Perron test for multiple structural breaks	SB: 2005:05, 2010:12, 2013:04
Caporin et al. (2019)	2000:01–2017:12	Gregory-Hansen cointegration test with break	SB: 2010:10, 2011:02, 2014:10
This study	*1995:01–2019:12*	*Hansen, Lee and Strazicich, Perron, Zivot-Andrews*	SB: *2005:02, 2010:12, 2012:11*
Panel B: Spread determinants			
Milonas and Henker (2001)	1991:02–1996:01	OLS regression	Convenience yield explains WTI-Brent futures price spread.
Bacon and Tordo (2004)	2003:01–2004:06	OLS regression	Quality differences and transport costs influence WTI-Brent oil price differences.
Büyüksahin et al. (2013)	2004:04–2012:04	ARDL	Several factors drive the WTI-Brent futures price spread, especially U.S. business climate, storage problems in Cushing, open interest, position of futures traders.
Li et al. (2015)	2004:01–2013:12	Granger causality	Cushing and Midwest's inventories drive WTI-Brent spread before 2010, after 2010 Chinese crude oil demand is the main force.
Caporin et al. (2019)	2000:01–2017:12	VECM	Shale oil production determines changes in WTI and Brent oil prices.
This study	*1995:01–2019:12*	*ARDL*	*Convenience yield, trading activity in paper markets, open interest, shipping costs, and stock market development in the United States and Europe determine the WTI-Brent future price spread.*

Note: This table presents a review of existing studies on crude oil price differentials.

Abbreviations: ARDL, autoregressive distributed lag modeling; OLS, ordinary least square; SB, structural break; VECM, vector error correction modeling.

the time series and estimate an autoregressive distributed lag (ARDL) model to analyze how the impact of the spread determinants changed before/after the breaks.

Our findings confirm a major structural breakpoint in December 2010. The most important determinant of the WTI-Brent spread is the convenience yield, which is a proxy for local crude oil inventories. Moreover, the trading activity in crude oil paper markets, shipping costs, as well as the stock market development in the United States and Europe affect the size of the spread. We find that the impact of the spread determinants changed after the break in 2010. Especially, the influence of paper market trading on the physical spot market heavily increased after 2010. Moreover, evidence can be found that shipping costs are more relevant after the break. The increasing importance and differences in the spread determinants, as well as the amplified variability in the WTI-Brent price spread, reflect the decoupling process of the two oil price benchmarks.

The remainder of this paper is organized as follows. In Section 2, we present a brief overview of the literature. Section 3 explains the data set and the determining factors of the WTI-Brent spread, followed by the methodology outlined in Section 4. The results of the empirical analysis are presented in Section 5. Section 6 includes the discussion, and Section 7 concludes.

2 | LITERATURE REVIEW

There is a wide range of previous studies on the WTI and Brent price differential. Two research streams, which are summarized in Table 1, are closely related to this study.

The first group of studies analyzes structural breaks in the time series of the major oil price spreads. Bentzen (2007) applies Bai and Perron (2003, 1998)'s test for multiple structural breaks and documents a disruption in the WTI-Brent spread in November 1999. This time corresponds to Organization of the Petroleum Exporting Countries political intervention, which moved prices into a target zone of \$22–\$28 per barrel. Büyüksahin et al. (2013) use the structural break test by Chow (1960) and identify two major structural changes in the WTI-Brent spread time series in November 2008 and December 2010. They also break down the WTI-Brent spread into a landlock and a transatlantic spread. Using this approach, they find that the structural break in 2008 is due to a change in the landlock spread, while the second break in 2010 appears to be specific to Brent crude. The structural breakpoint at the end of 2010 is confirmed by several authors like Caporin et al. (2019), Chen et al. (2015), Leybourne et al. (2007), Liu et al. (2016), as well as Ye and Karali (2016). In addition, Li et al. (2015) find another breakpoint in early 2010 when applying the rolling Chow test by Hansen (1997),

The second group of studies examines the determining factors of crude oil price differentials. Milonas and Henker (2001) analyze the convenience yield as a proxy for the local crude oil availability. Using ordinary least square (OLS) regression and daily observations for the period between 1991:02 and 1996:01, the authors show that the convenience yield is a statistically significant factor for the size of the price spread of WTI and Brent futures contracts. Moreover, Bacon and Tordo (2004) conclude from an OLS regression over the period from 2003:01 through 2004:06 that price differences among 56 crude oils can be explained by quality characteristics (gravity, sulfur content, and acidity) and transport costs. Büyüksahin et al. (2013) use an ARDL model to investigate the predictive power of three groups of variables (macroeconomic fundamentals, physical-market conditions, and financial factors) on the observed spread between nearby futures on WTI and Brent crude oil. Based on daily futures prices, but monthly macroeconomic and oil production data between 2004:04 and 2011:12, they find that the climate of the U.S. economy impacts the spread level between WTI and Brent. Among the physical factors, storage problems in Cushing have a significant impact, indicating a decreasing WTI-Brent spread when storage bottlenecks occur. In addition, there is some evidence that Canadian oil shipments to the Midwest lower the spread. The spread is also driven by financial variables such as the open interest, long positions of index traders, and variables measuring the impact of financial crises. In another study, Li et al. (2015) use monthly data between 2004:01 and 2013:12 to examine physical spread determinants of the WTI-Brent. The results of their Granger causality test reveal that inventory levels in Cushing and Midwest drive the pre-2010 spread. After 2010, Chinese demand for crude oil remains the only driving force. Overall, their explanation is restricted to the U.S. market, without providing an explanation for the changes in the Brent price. Caporin et al. (2019) apply vector error correction modeling and impulse response functions to analyze the effects of shale oil production. They find that shale oil supply shocks have a negative impact on the WTI and Brent prices until 2011.

Taken together, the previous literature provides evidence that the price gap between WTI and Brent alternates over time with a major structural break in 2010. Recent publications document that several factors beyond quality differences are drivers of crude oil price differences. In this study, we extend the existing literature by (i) analyzing the change in the spread determinants before and after the structural break(s), (ii) examining the transmission channel between physical and paper markets for crude oil, and (iii) combining a wide range of spread determinants including new variables that have not been examined before (e.g., extreme weather conditions in the Atlantic Ocean and North Sea), and variables that have been investigated in separate studies (e.g., the convenience yield by Milonas & Henker, 2001 and other supply and demand factors by Büyüksahin et al., 2013).

TABLE 2 Variable description and data sources

Variable	Definition	Source
P^{WTI}	Western Texas Intermediate opening spot price (US$ per barrel)	Thomson Reuters
P^{Brent}	UK Brent nominal closing spot price (US$ per barrel)	Bloomberg
F^{WTI}	WTI opening futures crude oil price (US$), various maturities between 1 month and 9 years	NYMEX
F^{Brent}	Brent closing futures crude oil price (US$), various maturities between 1 month and 9 years	ICE
RF	US$ treasury yield on actively traded non-inflation-indexed issues, adjusted to constant maturity, various maturities between 1 and 12 months	Federal Reserve
SC^{WTI}	Logarithmic difference between storage fee ($0.40 per barrel) and P^{WTI}	Ederington et al. (2012)
SC^{Brent}	Logarithmic difference between storage fee ($0.40 per barrel) and P^{Brent}	Ederington et al. (2012)
SPR^{Spot}	Normalized WTI-Brent spot price spread	Own calculation
F^{WTI_3M}	Continuous 3-month WTI futures contract	Own calculation
F^{Brent_3M}	Continuous 3-month Brent futures contract	Own calculation
SPR^{Future}	Normalized WTI-Brent futures price spread for a continuous 3-month futures contract	Own calculation
CY^{WTI}	Convenience yield for continuous 3-month WTI futures contract	Own calculation
CY^{Brent}	Convenience yield for continuous 3-month Brent futures contract	Own calculation
VL^{WTI}	Logarithm of aggregate trading volume for all WTI futures contracts	NYMEX
VL^{Brent}	Logarithm of aggregate trading volume for all Brent futures contracts	ICE
OI^{WTI}	Logarithm of aggregate open interest for all WTI futures contracts	NYMEX
OI^{Brent}	Logarithm of aggregate open interest for all Brent futures contracts	ICE
BD	Baltic dry index divided by 1000 and premultiplied by the sign of the WTI-Brent spread	Baltic Exchange
BDT	Baltic dirty tanker index divided by 1000 and premultiplied by the sign of the WTI-Brent spread	Baltic Exchange
ST^{US}	Arithmetic mean of five sector indices for chemicals, construction and materials, automobiles and parts, utilities, and industrial goods, normalized to an index value of one starting on January 01, 1995	STOXX
ST^{EU}	Arithmetic mean of five sector indices for chemicals, construction and materials, automobiles and parts, utilities, and industrial goods, normalized to an index value of one starting on January 01, 1995	STOXX
ST^{ASIA}	Arithmetic mean of five sector indices for chemicals, construction and materials, automobiles and parts, utilities, and industrial goods, normalized to an index value of one starting on January 01, 1995	STOXX
TP^{US}	Arithmetic mean temperature for Chicago, Dallas, Kansas City, Los Angeles, Miami, New York, and Seattle	National Climatic Data Center
TP^{EU}	Arithmetic mean temperature for Berlin, Central England, Madrid, Nancy, Rotterdam, and Vienna	European Climate Assessment
HT	Heating day, defined as $(TP^{US} - TP^{EU})_{\text{Temperature(US)}<18.3°\text{C}}$	Own calculation
CL	Cooling day, defined as $(TP^{US} - TP^{EU})_{\text{Temperature(US)}>18.3°\text{C}}$	Own calculation
TR	= 1 for the 3 days before and after a tornado occurred in the Cushing area, 0 otherwise	National Weather Service
HR	= 1 for the 3 days before and after a hurricane occurred in the North Sea, 0 otherwise	University of Siegen

Note: This table presents the variables used in the analysis.

3 | DATA

We obtain daily data between January 01, 1995 and December 31, 2019. This period extends previous studies, such as Milonas and Henker (2001), and includes recent events in the global oil markets. In contrast to earlier studies, for example, Büyüksahin et al. (2013), we only consider spread determinants with daily data. Therefore, we match daily observations of the WTI-Brent spread with daily data of the explanatory variables. Table 2 provides an overview of the variables that are analyzed in this study.

3.1 | WTI-Brent price spread

We use WTI (Cushing) opening spot prices and Brent closing spot prices. By matching opening U.S. and closing prices in Europe, we consider the time difference between the trading hours of the two markets. We define the WTI-Brent spot spread as the WTI crude oil price P_t^{WTI} minus the Brent price P_t^{Brent}.[4] For our analysis, we use the normalized spread SPR_t, which smooths the time series and reduces heteroscedasticity:

$$SPR_t^{Spot} = \left(P_t^{WTI} - P_t^{Brent}\right)/P_t^{Brent}. \tag{1}$$

3.2 | Convenience yield

Following Milonas and Henker (2001), we investigate the convenience yield as a measure of crude oil availability. This relation is derived from the theory of storage (among many others, Kaldor, 1939; Working, 1927, 1949), which implies that the convenience yield is inversely related to inventories.[5] A high convenience yield indicates low storage volumes and, thus, a high supply risk. Consequently, we assume that an increase in the WTI convenience yield widens the price spread between WTI and Brent (and vice versa for Brent).

For daily estimates of the convenience yield, we follow the cost-of-carry hypothesis (Brennan, 1958). Accordingly, the price of commodity futures contracts is equal to the spot price plus the convenience yield and the cost-of-carry represented by the storage costs (tanker rates, pipeline costs, and insurance fees). In its continuous form, the cost-of-carry pricing formula of a WTI or Brent future $F_{t,T}^{\bullet}$ is given by:

$$F_{t,T}^{\bullet} = P_t^{\bullet} e^{\left(RF_{t,T}+SC_{t,T}^{\bullet}-CY_{t,T}^{\bullet}\right)(T-t)}, \tag{2}$$

where $P_t^{\bullet}$ denotes the corresponding spot price of WTI or Brent, $RF_{t,T}$ represents the risk-free interest rate, $SC_{t,T}^{\bullet}$ denotes the storage costs of WTI or Brent, and $CY_{t,T}^{\bullet}$ is the convenience yield of WTI or Brent. $T - t$ is the time to the contract's maturity. By rearranging Equation (2), we receive the convenience yield:

$$CY_{t,T}^{\bullet} = RF_{t,T} + SC_{t,T}^{\bullet} - \frac{1}{T-t}\left\{\ln\left(F_{t,T}^{\bullet}\right) - \ln\left(P_t^{\bullet}\right)\right\}. \tag{3}$$

Convenience yields are derived from WTI and Brent crude oil futures with 3 months to maturity. Futures with 6 and 12 months to maturity are used for robustness analyses. Futures price data is obtained from the New York Mercantile Exchange (NYMEX) for WTI and the Intercontinental Exchange (ICE) for Brent. As risk-free rate of return, we use 3-month U.S. Treasury bill yields. For better comparability, discrete interest rates are transformed into continuous rates. For the storage costs, we follow Ederington et al. (2012) and assume the "fairly common rough estimate" of $0.40 per barrel per month. In line with Stepanek et al. (2013), storage costs are measured as a logarithmic difference between the storage fee and daily spot prices. For robustness analysis, we also estimate inventory-dependent storage costs.

As there is no continuous 3-month futures contract, we construct a futures contract and the convenience yield with the desired maturity (CY^{WTI} and CY^{Brent}). Our preferred method is an approach that is used to estimate the term structure of yield curves (e.g., Martellini, 2003). First, we calculate the convenience yield from the observed futures prices. Second, we

[4]We calculate the spread only for days with price data available for both WTI and Brent crude oil. Consequently, we remove all days that are public holidays either in the United States or Europe.

[5]Many authors find empirical evidence for this inverse relationship for various commodities (Fama & French 1987; Geman & Ohana 2009; Geman & Smith 2013; Stepanek et al. 2013).

interpolate all data points (maturity and convenience yield) with the help of a cubic spline function. Third, we evaluate the spline function at the respective maturity. This is our preferred methodology due to the nonlinear construction of the futures price for the required maturity. As robustness test, we define and test alternative roll-over strategies.

3.3 | Trading volume and open interest

As the liquidity in derivatives markets could influence spot market segmentation, we follow Büyüksahin et al. (2013) and include the aggregate open interest (OI^{WTI}, OI^{Brent}) for all crude oil futures traded at NYMEX (for WTI) and ICE (for Brent). We also add the aggregated trading volumes in WTI and Brent paper markets (VL^{WTI}, VL^{Brent}). As increased futures trading amplifies the pressure of paper markets on physical trading in the spot markets, we hypothesize a positive impact of WTI (Brent) open interest and trading volume on the respective spot price, which therefore decreases (increases) the WTI-Brent spread when prices adjust to the theoretically correct quality spread of 1.2.

3.4 | Freight rates

The transportation costs of crude oil determine its interchangeability between physical markets and therefore also its price gap. Transportation costs are mainly determined by the freight rate for shipping. Freight rates increase with decreasing shipping space and port capacity. For example, when freight rates are high, it is more expensive to ship crude oil from Europe to North America[6] (Lanza et al., 2005). As a result, the balancing mechanism between regional physical markets is hampered when transportation costs are high. Therefore, we expect an increasing absolute price spread between WTI and Brent when freight rates rise. As a proxy variable for the crude oil freight rates, we define BD as the Baltic Dry Index, which is a broad index for different goods, vessel types, and routes. Since the freight rates influence the absolute spread, they are premultiplied by the sign of the spread. In addition, we also use the Baltic Dirty Tanker index (BDT), which is an index for shipping of crude oil and thus a more accurate measure of the transportation costs. For the empirical analyses, we provide results for both indices, since the time series for BDT is only available since 2002, while BD is available for the full sample period.

3.5 | Economic conditions

On the demand side, we consider the economic situation in North America, Europe, and Asia. A growing economy is accompanied by an increasing industrial demand for commodities, which leads to rising prices in local crude oil markets. We expect an increasing (decreasing or even negative) price difference when the U.S. (European or Asian) economy grows. As a proxy for the industrial crude oil demand, we construct an aggregated oil consumer stock index. We use performance index time series for different (super)sectors from the Industry Classification Benchmark (ICB), which were chosen with regard to their high crude oil consumption: chemicals (ICB-1350), construction & materials (ICB-2350), automobiles & parts (ICB-3350), industries utilities (ICB-7000), and industrial goods (ICB-2700). Data is retrieved from STOXX. We then construct ST^{US} and ST^{EU} as arithmetic mean of the five aforementioned indices. Both time series are normalized to a value of one on January 01, 1995. Analogously, we define ST^{ASIA} for robustness analysis measuring the impact of the emerging markets in Asia.

3.6 | Heating and cooling

To account for crude oil consumption for heating and cooling,[7] we create two temperature indices. For the United States (TP^{US}), we take the arithmetic mean of the daily temperature in the following cities across the continent: Chicago, Dallas, Kansas City, Los Angeles, Miami, New York, and Seattle.[8] Weather data is retrieved from the National

[6] Exports of WTI crude oil from North America to Europe can rather be neglected due to rigid export restrictions for over 40 years by the U.S. government until January 2016.

[7] While crude oil is directly used for heating, it is indirectly connected to cooling through electricity production.

Climatic Data Center. For Europe (TP^{EU}), we use temperatures recorded in the following cities: Berlin, Central England, Madrid, Nancy, Rotterdam, and Vienna. The data is retrieved from the European Climate Assessment & Data set. Crude oil demand for heating HT is measured by $(TP^{US} - TP^{EU})_{TP^{US}<18.3°C}$ and cooling CL is approximated by $(TP^{US}\text{-}TP^{EU})_{TP^{US}>18.3°C}$, which is the difference between the mean temperature in North America and Europe when the difference is below (above) the threshold value of 18.3°C and zero otherwise. The threshold of 18.3°C is commonly used to identify heating and cooling days (Hall & Basara, 2006).

3.7 | Extreme weather conditions

Crude oil supply could also be affected by weather anomalies that hamper oil production and transportation. For WTI, weather anomalies are tornados in the Cushing area. For Brent, hurricanes in the North Sea might change crude oil supply. Weather data for tornados is collected from the National Weather Service. Data for hurricanes in the North Sea production areas is provided by the database of the University of Siegen.[9] We define two dummy variables for extreme weather conditions. Three days before and after a tornado occurs in the Cushing area, TR is equal to one. Equivalently, HR equals one when hurricanes appear in the North Sea. Both weather anomalies are expected to have a negative influence on the supply situation leading to an increase of the respective crude oil price. We expect the WTI-Brent spread to increase when a Tornado occurs and to decrease for hurricanes. Since weather effects are not influenced by the other endogenous variables, we classify TR and HR as exogenous variables in the further analysis.

4 | METHODOLOGY

We apply the ARDL methodology developed by Pesaran and Shin (1999) to explore the long-run relationship between the WTI-Brent spread and its determinants. The ARDL model is widely used in empirical research due to several preferable aspects (among many others, Ahmad & Du, 2017; Büyüksahin & Robe, 2014; Ozturk & Acaravci, 2013). First, it allows to disentangle the short-run and long-run dynamics of regressors. Second, the ARDL model provides unbiased estimates for the long-run effects even if some of the model regressors are endogenous (Narayan, 2005). Third, the ARDL bounds test by Pesaran et al. (2001) is more flexible compared to other traditional cointegration techniques, such as Johansen and Juselius (1990), as it does not require the input variables to be integrated of the same order. Indeed, the ARDL bounds test can deal with mixed order of integration. Thus, it can even be employed when some variables are stationary in levels, that is, they are $I(0)$, and others are stationary in first differences, that is, $I(1)$. Finally, the ARDL procedure allows that the variables in the model have different lengths of optimal lags, which is not possible in conventional cointegration approaches.

In our model, the normalized WTI-Brent price spread SPR_t is regressed on its lags, as well as present and lagged values of the spread determinants. The ARDL $(p, q_1, ..., q_n)$ model with optimal lags is estimated via OLS and can be described by the following unrestricted error correction representation:

$$\Delta SPR_t = a_0 + a_1 t + \sum_{i=1}^{p-1} \psi_{1,i} \Delta SPR_{t-i} + \sum_{j=1}^{n} \sum_{i=0}^{q_j-1} \psi_{j+1,i}\, \Delta X_{j,t-i} + \lambda_1 SPR_{t-1} + \sum_{j=1}^{n} \lambda_{j+1} X_{j,t-1} + \sum_{k=1}^{m} \delta_k Z_{k,t} + u_t, \tag{4}$$

where a_0 is the error drift component, $t = \max(p, q_1, ..., q_n), ..., T$ is the time trend component, $X = [CY^{WTI}, CY^{Brent}, VL^{WTI}, VL^{Brent}, OI^{WTI}, OI^{Brent}, BD, ST^{US}, ST^{EU}, HT, CL]$ represents the $n = 11$ spread determinants described in Section 3, $Z = [TR, HR]$ captures the $m = 2$ exogenous dummy regressors for weather anomalies, u_t is the white noise error term. $\psi_1,...,\psi_n$ symbolize the error correction dynamics, and $\lambda_1, ..., \lambda_n$ represent the long-run relationship among the variables.

Whether a long-run cointegration relationship exists between SPR_t and the spread determinants X is examined by the ARDL bounds test. In this test, the null hypothesis of no cointegration, $H_0^F: \lambda_1 = \cdots = \lambda_{n+1} = 0$, is evaluated using a common F-statistic. Since the distribution of the test statistic is nonstandard under the null hypothesis, critical values

[8] For each city, we took weather stations close to the city center.

[9] https://www.bau.uni-siegen.de/fwu/wb/publikationen/sturmflutarchiv/?lang=de

must be obtained by stochastic simulation. Pesaran et al. (2001) present asymptotic lower and upper bound critical values for large sample sizes. The lower bound critical values consider that the variables are $I(0)$, whereas the upper bounds assume that the variables are $I(1)$. When the estimated F-statistic exceeds the upper bound, the null hypothesis is rejected, and we can conclude a cointegration relation among the variables. In contrast, if the test statistic falls under the lower bound, we cannot reject the null and cannot infer the existence of a cointegration relation. A drawback of the bounds by Pesaran et al. (2001) is that they are only available for a range of $k \in [0,10]$ long-run forcing variables. Kripfganz and Schneider (2018) present asymptotic critical values for the lower and upper bounds, which are independent of the number of long-run variables. As the number of spread determinants exceeds the range available from Pesaran et al. (2001), we use the critical values by Kripfganz and Schneider (2018).

If a long-run relationship exists, the error correction model can be reformularized as follows:

$$\Delta SPR_t = a_0 + a_1 t + \sum_{i=1}^{p-1} \psi_{1,i} \Delta SPR_{t-i} + \sum_{j=1}^{n} \sum_{i=0}^{q_j-1} \psi_{j+1,i} \, \Delta X_{j,t-i} + \sum_{k=1}^{m} \delta_k Z_{k,t} + \phi ECT_{t-1} + u_t, \tag{5}$$

where ECT_{t-1} is the error correction term and ϕ indicates the speed of adjustment to the long-run equilibrium after a shock in the system. If the value of the bounds test falls in-between the two critical bounds, the results are inconclusive and the decision depends on the error correction term ECT_{t-1} (Banerjee et al., 1998; Kremers et al., 1992). If ECT_{t-1} is significant with a negative sign, it implies long-run cointegration of the estimated variables. Otherwise, cointegration must be neglected.

TABLE 3 Summary statistics

	Mean	Median	*SD*	Min.	Max.	*N*
SPR^{Spot}	−0.0026	0.0082	0.0855	−0.2498	0.3470	6062
SPR^{Future}	−0.0037	0.0086	0.0825	−0.2413	0.2284	6062
CY^{WTI}	0.1300	0.0995	0.2180	−1.3395	1.2963	6062
CY^{Brent}	0.1399	0.1084	0.1890	−0.4825	1.1224	6062
VL^{WTI}	12.7369	12.9017	0.9080	9.7730	15.1189	6062
VL^{Brent}	12.0060	12.2479	1.4464	5.1120	14.7942	6062
OI^{WTI}	13.7720	13.9877	0.6259	12.6411	14.8139	6062
OI^{Brent}	13.2976	13.2436	0.9177	11.7484	14.8222	6062
BD	2.1190	1.4340	1.8904	0.2900	11.7930	6062
BDT	0.9833	0.8250	0.4177	0.4530	3.1940	4373
ST^{US}	2.2664	2.0214	0.8958	0.9041	4.7082	6062
ST^{EU}	2.5987	2.3664	1.0440	0.9223	4.8118	6062
ST^{ASIA}	1.1291	1.0412	0.2722	0.6181	1.8211	6062
HT	0.5685	0	1.4756	−3.7625	8.2286	6062
CL	1.4924	0	3.2333	−12.0417	15.6563	6062
TR	0.0102	0	0.1006	0	1	6062
HR	0.0063	0	0.0789	0	1	6062

Note: This table presents summary statistics for the full sample period from January 01, 1995 through December 31, 2019. Variable definitions can be obtained from Table 2.

TABLE 4 Unit root test

	ADF test		PP test	
	Levels	First differences	Levels	First differences
SPR^{Spot}	−8.79***	−35.62***	−11.28***	−108.69***
SPR^{Future}	−5.83***	−41.74***	−19.46***	−187.07***
CY^{WTI}	−5.72***	−33.24***	−8.01***	−91.21***
CY^{Brent}	−6.07***	−44.95***	−7.05***	−90.48***
VL^{WTI}	−5.29***	−34.96***	−44.13***	−218.16***
VL^{Brent}	−3.27*	−18.26***	−13.72***	−183.99***
OI^{WTI}	−3.27*	−14.22***	−3.01	−90.79***
OI^{Brent}	−4.11***	−25.87***	−5.15***	−115.39***
BD	−3.10**	−12.25***	−2.75*	−27.09***
BDT	−5.17***	−12.20***	−4.83***	−37.36***
TR	−23.18***	−30.06***	−27.35***	−94.87***
HR	−19.94***	−29.94***	−23.06***	−85.17***
ST^{US}	−0.17	−56.74***	−0.21	−80.32***
ST^{EU}	−2.69	−54.59***	−2.66	−76.08***
ST^{ASIA}	−2.55	−58.54***	−2.66	−84.16***
HT	−11.00***	−32.46***	−35.78***	−150.52***
CL	−23.21***	−20.12***	−24.30***	−109.42***

Note: ADF is the Augmented Dickey-Fuller test (Dickey & Fuller, 1981) and PP is the Phillips and Perron (1988) unit root test. The lag order for the tests are selected by the Schwartz–Bayesian Information Criterion. All unit root tests regressions include an intercept and drift. The tests for the spot and futures spread also include a structural break component.

***, **, and * denote statistical significance at the 1%, 5%, and 10% level, respectivley.

5 | EMPIRICAL ANALYSIS

5.1 | Summary statistics and unit root test

Table 3 presents the summary statistics for the WTI-Brent spread and the spread determinants.

Although ARDL can handle mixed orders of integration, it must be ensured that none of the variables is integrated with an order greater than one. Otherwise, the critical bounds by Kripfganz and Schneider (2018) are not valid. Table 4 reports the results of the Augmented Dickey–Fuller (Dickey & Fuller, 1981) and the Philipps and Perron (Phillips & Perron, 1988) test for nonstationarity in the time series. For both tests, we include a constant and time trend. The optimal lag length is selected by the Schwartz–Bayesian Information Criterion (SBC).

According to the unit root tests, we can infer that the time series for OI^{WTI}, ST^{US}, ST^{EU}, and ST^{ASIA} have a unit root at levels. All variables are stationary in first differences.

5.2 | Structural break identification

To identify structural breaks, we (i) determine the number of potential breakpoints, (ii) detect the dates when the time series changes abruptly, and (iii) analyze the robustness of the breakpoints while controlling for the WTI-Brent spread determinants.

In the first step, we perform Hansen (2000)'s test for breakpoint detection, as it accounts for heteroscedasticity through conditional distributions and compared to other approaches like the Chow test, the test does not foster the

TABLE 5 Structural break detection in WTI-Brent price spread

Break point 1	December 08, 2010	December 08, 2010	December 08, 2010
Break point 2		November 09, 2012	November 09, 2012
Break point 3			February 17, 2005
Min t_β by Zivot and Andrews (1992)	188.44	188.39	188.39
Max $\lvert t_d \rvert$ by Perron (1997)	6.87	6.87	6.87
min SBC by Lee and Strazicich (2001)	−8.35	−8.35	−8.35
min BIC	−25,941	−25,932	−25,932
Lags	3	3	3

Note: This table reports the results of the structural break tests.

identification of an excessive number of breaks. This method identifies three potential breakpoints: two are significant at the 1% level and a third breakpoint is significant at the 5% level.

In the second step, we apply several parametric tests to locate the position of the three break points (Bai & Perron, 2003; Busetti & Harvey, 2001; Harvey & Terence, 2003; Lee & Strazicich, 2001; Perron, 1997; Zivot & Andrews, 1992). Comparing the results of all tests, we find a cluster around three dates in the WTI-Brent spread series. All tests detect a first break point in 2010. Some tests determine additional break points in 2012 and 2005. In the following, we focus on three methods (Lee & Strazicich, 2001; Perron, 1997; Zivot & Andrews, 1992). The general idea is to include a crash dummy,[10] a shift dummy, or a trend in the autoregressive equation of the inspected variable, which is in our case the WTI-Brent spread. In the Zivot and Andrews (1992)'s test, the minimum t-statistic of the regression coefficient of the lagged variable is the relevant test statistic. Perron (1997) suggests the maximum absolute t-statistic of the regression coefficient of the break point dummy variable. Lee and Strazicich (2001) use the Schwarz Bayesian criterion to identify the optimal break point. In addition, we conduct a minimum BIC search. All models show similar three breakpoints (Table 5). Our favorite model by Lee and Strazicich (2001) uncovers a major break in December 2010. This finding is in line with previous literature (Chen et al., 2015; Leybourne et al., 2007; Liu et al., 2016; Ye & Karali, 2016). Two other but minor breaks are in November 2012 and February 2005.

In the third step, we include the determinants of the WTI-Brent spread as controls in the autoregressive equation. Hence, we receive a time series of residuals, which are tested for the structural breaks. Again, we find a major break point in December 2010.

5.3 | Cointegration analysis

After the break point detection, we analyze cointegration. To find the optimal lag length, we follow Toda and Yamamoto (1995). For the cointegration analysis, we define a VAR model as follows:

$$(1-L)y_t = Cy_{t-1} + B_1(1-L)y_{t-1} + \cdots + B_q(1-L)y_{t-q} + c_0 + c_1 t + e_t, \tag{6}$$

where $y_t = (Brent_t, WTI_t)^T$. To test for the long-run relationship among WTI and Brent crude oil prices, we apply the cointegration tests by Engle and Granger (1987) as well as Johansen and Juselius (1990). Within the Engle–Granger framework, we use two implementation strategies: (i) an exogenous WTI-Brent spread at the delivery spread of \$0.30 (CME Group, 2018), and (ii) we estimate the spread within the cointegration test. Consequently, in the second case, the test statistics must be changed to the Engle–Granger statistics with a constant and trend.

[10]Due to the large number of observations in our daily time series, we define the crash dummy to be one in a period of 10 days.

TABLE 6 Cointegration test between WTI and Brent spot price

	Before structural	After structural break	Full period with structural break
Engle–Granger test			
Fixed spread ($0.30)	−5.73***	−1.47	−5.91***
Endogenous spread	−9.42***	−3.99**	−6.81***
Johansen–Juselius test			
Trace test with $r = 0$	95.75***	19.61	38.91***
λ max test with $r = 0$	89.90***	16.70	37.28***
Trace test with $r \leq 1$	5.85	2.91	1.63*
λ max test with $r \leq 1$	5.85	2.91	1.63*
Lags	2	3	4

Note: This table shows the results from Engle and Granger (1987) and Johansen and Juselius (1990) test for cointegration. Number of lags are selected by Schwartz–Bayesian Information Criterion. The number of conintegrating vectors is indicated by *r*. The structural break point is December 8, 2010.
***, **, and * denote rejection of the null hypothesis at the 1%, 5%, and 10% level.

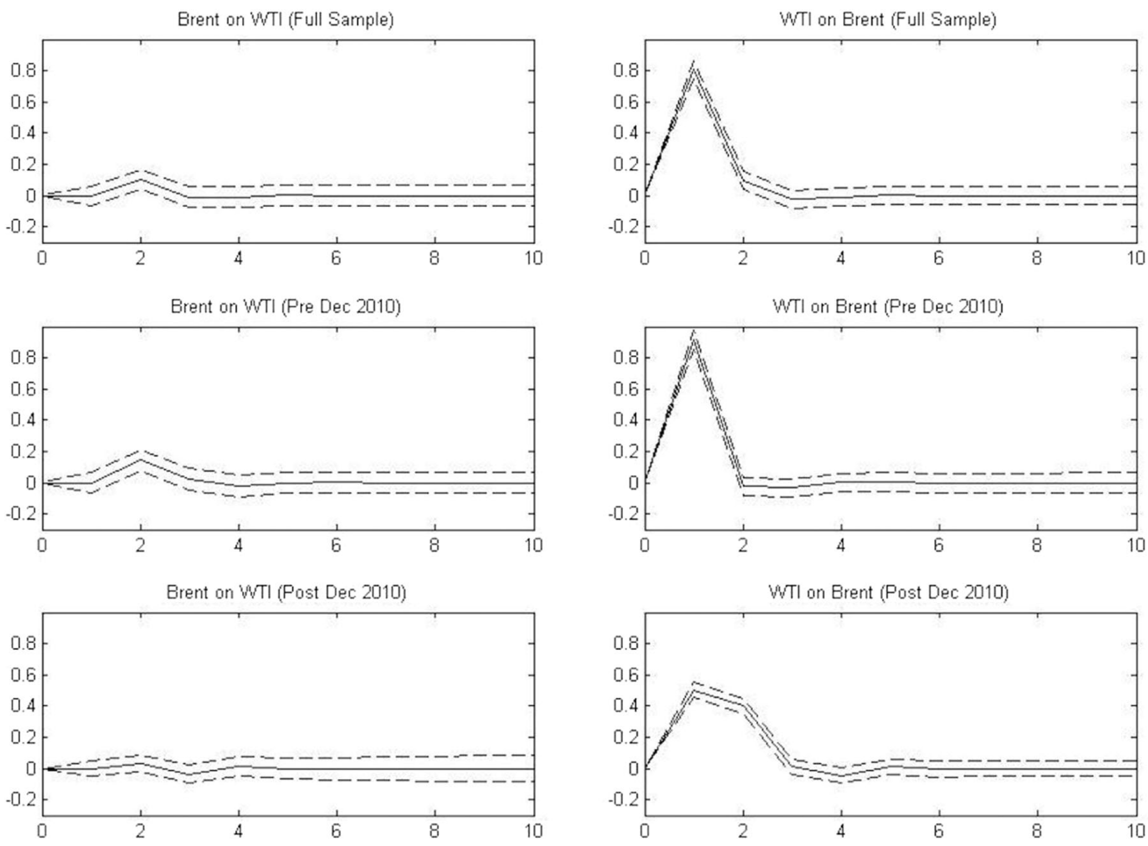

FIGURE 2 Impulse response functions. The figure depicts the orthogonalized impulse response function of Brent on WTI (left column) and WTI on Brent (right column) for the first 10 days after a one standard deviation shock in WTI (Brent) spot price. The first row refers to the entire time period (January 01, 1995–December 31, 2019), the second row refers to the time period before the structural break (January 01, 1995–December 07, 2010), and the third row refers to the time period after the structural break (December 08, 2010–December 31, 2019). Dashed lines represent 99% confidence bands. WTI, West Texas Intermediate

Due to the structural break discovered in the previous section, we extend both cointegration tests by a structural break dummy. For the Engle–Granger test we follow Gregory and Hansen (1996) and introduce a shift variable in cointegration. Hence, the time series for the fixed delivery spread is adjusted by the dummy variable multiplied by the regression coefficient. This time series serves as input for the standard ADF test. In the second case, the spread is estimated by the Engle–Granger test. Here, we include the dummy in the estimation equation and apply the test statistic proposed by Gregory and Hansen (1996). Johansen et al. (2000) present a methodology to include structural breaks in the rank tests. They introduce a shift dummy in their VEC framework and estimate the rank statistics. To derive the critical values, they apply a gamma distribution, where their first two moments are estimated by a of fourth-degree rational function. Table 6 reports the corresponding results of the cointegration tests.

For the time series before the structural break in 2010, both tests indicate cointegration. The same applies to the full sample. Accordingly, there is a common stochastic trend in both oil price time series before the structural break. This changes when we look at the time series from 2010 onwards. Both Johansen and Engle–Granger tests with the delivery spread show insignificant results, whereas the Engle–Granger test with endogenous spread does imply cointegration. Hence, we can conclude that there is a clear tendency towards a decoupling of the crude oil prices after 2010. This finding is supported by the results from impulse response function analysis. We estimate the stable and invertible VAR model in Equation (6) in differences and generate impulse response functions with a Cholesky one standard deviation shock in the Brent (WTI) innovations.

Figure 2 shows a rather small response of WTI to a Brent price shock before 2010. After the break in 2010, there is almost no response. In contrast, the Brent price reacts strongly to a WTI price shock. After the break point in 2010, the reaction is much smaller. In particular, the fact that WTI does not react to Brent price shocks underlines the discussion whether WTI still reflects the international oil supply-demand balance or whether WTI is strongly driven by local factors such as the inventories in Cushing (Bentzen, 2007; Fattouh, 2010a; Kaufmann & Ullman, 2009).

After the structural break identification and cointegration analysis, we update the vector of exogenous variables from Equation (4) to $Z = [TR, HR, D_{2010}]$ for the baseline models with the major break point in 2010 and $Z = [TR, HR, D_{2010}, D_{2005}, D_{2012}]$ for the models including the weaker break points as well.

5.4 | ARDL model: Bounds test

The first step of the ARDL estimation is the selection of the lag orders. Following Pesaran and Shin (1999), we use the SBC to select the appropriate lag orders of p and q for the ARDL model. Next, we estimate the regression parameters of Equation (4) via OLS with an unrestricted intercept and unrestricted trend. Table 6 reports the F-statistics of the ARDL bounds test, the t-statistics of the error correction term in the ARDL model, and the Kripfganz and Schneider (2018) critical values for the significance levels. Again, results are reported for the full sample and the time period before/after the break in 2010.

According to the results, we can reject the null hypothesis of no cointegration at the 1% level for the full sample and the pre-2010 period because the F-statistics are above the upper bound critical value. Accordingly, we can infer that there is strong evidence for a long-run economic relationship among the regressors and the WTI-Brent price spread in the full sample period and in the period before the break. In the post-2010 period, the F-statistic is only significant at the 10% level. Accordingly, the evidence for cointegration is weaker after the break. This finding indicates that the relationship between the determinants and the spread changed after 2010.

5.5 | ARDL model: Long-run elasticities

Table 8 presents the long-run elasticities of the ARDL model. As model diagnostics indicate that we cannot reject the null hypothesis of no serial correlation from Durbin's test and also not the null hypothesis of a constant variance in the residuals from Breusch–Pagan test for heteroscedasticity, we apply the Newey–West procedure to estimate robust standard errors (Newey & West, 1987). Table 8 reports the interaction terms of the spread determinants and the 2010 break dummy for all variables driving the balancing mechanisms between the physical spot market and the paper markets (VL^{WTI}, VL^{Brent}, OI^{WTI}, OI^{Brent}, BD, and BDT).

In Model (1), we see a strong and statistically significant impact of the WTI and Brent convenience yield on the spread values, whereas the coefficient is positive for WTI and negative for Brent. Hence, high levels of the WTI (Brent) convenience yield increase (lower) the size of the spread. As the convenience yield is an indicator for inventories, our findings imply that the storage level of the two crude oil benchmarks is a key driver of the price spread.

In addition, we can see that the trading volume and open interest in Brent paper markets explain spread variation. Due to the negative sign of the long-run coefficient for Brent trading volume, extended trading of Brent futures lowers the price differential between WTI and Brent. We do not find evidence of the WTI futures trading to impact the spread. In addition, the number of outstanding Brent contracts (measured by the open interest) determines the spread. Accordingly, a larger open interest increases the spread.

The shipping costs measured by the Baltic dry index determine the spread as well. Larger transportation costs lead to an increasing absolute spread. Moreover, the elasticity estimates for the economic condition reveal that an increase in the U.S. stock index widens the spread, while a surge in the European stock markets decreases the size of the price gap. Finally, there is no evidence for oil demand from heating/cooling to impact the spread, and also extreme weather conditions in the Atlantic and North Sea do not explain variation.

Regarding the impact of the structural breaks, we observe in Models (1) and (2) that the major break in 2010 is highly significant, with a negative sign indicating a decline in the spread after 2010. For the other two minor break points, we find a significant change in the spread after 2012. However, no significant impact can be confirmed for the break in 2005. In terms of statistical significance and the size of the economic effect represented by the reported long-run elasticities, the break in 2010 is the most dominant break point.

When interacting the spread determinants with the major break dummy (D_{2010}), it becomes apparent that the impact of two determinants changed after 2010. First, the results uncover a significant positive impact of Brent open interest on the spread before 2010 (Model 4). The impact of Brent open interest increased after 2010. The open interest in WTI futures after 2010 is also a significant driver of the price spread. In addition, we can see that transportation costs measured by the Baltic Dry index (BD) have explanatory power. When using the Baltic Dirty Tanker index (BDT) in Model (6), which is the better proxy for the transportation costs of crude oil, we find that the influence of shipping costs increased after 2010. This might be due to the fact that when shipping between both markets becomes more expensive, it will be more difficult to reduce price differentials between both crudes by transporting it from one physical market to the other. However, as discussed in Section 3, a disadvantage of this alternative measure is that the time series is shorter, as BDT data is not available for the entire sample period. Summing up, we confirm the results from the bounds test and find evidence for change in the underlying dynamics of the spread determinants after 2010.

Model (7) tests the interactions among the physical market (spot) and the paper markets (futures) by including the WTI-Brent futures price spread as an explanatory factor in the ARDL model. The results imply a positive impact from the paper market on the spot market. This effect reinforces after the break in 2010, indicating pressure from the paper

TABLE 7 Bounds test for cointegration in ARDL model

Model: $F(SPR^{Spot} \mid CY^{WTI}, CY^{Brent}, VL^{WTI}, VL^{Brent}, OI^{WTI}, OI^{Brent}, BD, ST^{US}, ST^{EU}, HT, CL)$				
	Optimal lag structure	**F**	**t**	**Inference**
Before structural break	(3,3,3,0,0,1,0,1,0,0,0,0)	7.22***	−8.49***	Cointegration
After structural break	(5,5,4,0,0,1,0,2,1,0,0,0)	3.22*	−5.63**	Weak cointegration
Full sample	(6,6,5,0,0,0,0,1,0,0,0,0)	6.65***	−8.34***	Cointegration
Critical value bounds	***F***	***F***	***t***	***t***
Significance level (%)	$I(0)$	$I(1)$	$I(0)$	$I(1)$
1	2.68	3.91	−3.96	−5.99
5	2.22	3.36	−3.41	−5.39
10	1.99	3.08	−3.13	−5.06

Note: The ARDL models are estimated according to Equation (4) with unrestricted intercept and unrestricted trend. The F-statistics refer to a joint test of the long-run coefficients from Equation (4) ($H_0^F: \lambda_1 = \cdots = \lambda_{n+1}$). The t-statistics refer to the test of the error correction term from Equation (5) ($H_0^t: \phi = 0$). The rejection of both null hypotheses indicates a long-run relationship. Critical values for the lower $I(0)$ and upper $I(1)$ bounds are taken from Kripfganz and Schneider (2018). The structural break point is in December 2010.

***, **, and * denotes rejection of the null of no cointegration for $I(1)$ at the 1%, 5%, and 10% level.

TABLE 8 Long-run elasticities from ARDL model

		SPR^{Spot}							
Model		**(1) One break**	**(2) Three breaks**	**(3) CY with break**	**(4) OI with break**	**(5) VL with break**	**(6) BDT with break**	**(7) SPR^{Future} with break**	**(8) Asia index included**
Dependent variable									
Constant		−0.0252	−0.0294	−0.0196	−0.0141	0.0010	−0.0246	−0.0442***	−0.0197
		(−1.46)	(−1.63)	(−1.19)	(−0.90)	(0.26)	(−0.87)	(−3.28)	(−1.20)
Trend		−0.0001***	−0.0001***	−0.0001***	−0.0001***	−0.0001*	−0.0001**	−0.0001***	−0.0001***
		(−3.73)	(−3.81)	(−3.76)	(−3.19)	(−1.89)	(−2.11)	(−5.12)	(−3.70)
CY^{WTI}	+	0.3898***	0.3444***	0.3798***	0.3634***	0.3813***	0.2672***	0.2326***	0.3796***
		(7.89)	(7.53)	(6.29)	(5.81)	(5.24)	(3.71)	(13.80)	(6.33)
$CY^{WTI} \times D_{2010}$				0.0375	0.0449	0.0637	0.1043	−0.1243***	0.0352
				(0.24)	(0.28)	(0.34)	(0.77)	(−4.10)	(0.23)
CY^{Brent}	−	−0.4506***	−0.3976***	−0.4641***	−0.4260***	−0.4461***	−0.2856***	−0.2393***	−0.4561***
		(−6.98)	(−7.01)	(−5.96)	(−5.41)	(−4.85)	(−2.60)	(−11.55)	(−5.86)
$CY^{Brent} \times D_{2010}$				0.0465	0.0975	−0.0684	−0.0702	0.0792***	0.0343
				(0.32)	(0.60)	(−0.42)	(−0.46)	(2.60)	(0.23)
SPR^{Future}	+							0.5964***	
								(14.79)	
$SPR^{Future} \times D_{2010}$								0.3322***	
								(6.26)	
VL^{WTI}	−	0.0128	0.0145	0.0145		0.0122	0.0115	0.0026	0.0141
		(1.14)	(1.45)	(1.17)		(1.11)	(0.84)	(1.10)	(1.14)
$VL^{WTI} \times D_{2010}$						−0.0357			
						(−0.80)			
VL^{Brent}	+	−0.0128***	−0.0120***	−0.0130***		−0.0089**	−0.0069**	−0.0037***	−0.0130***
		(−4.24)	(−4.33)	(−3.86)		(−2.32)	(−2.11)	(−4.14)	(−3.88)
$VL^{Brent} \times D_{2010}$						0.0188			
						(0.53)			
OI^{WTI}	−	−0.0496	−0.0141	−0.0719*	0.0074		−0.1064**	0.0092	−0.0678*
		(−1.26)	(−0.38)	(−1.76)	(0.20)		(−2.16)	(1.17)	(−1.66)
$OI^{WTI} \times D_{2010}$					−0.2433**				
					(−2.09)				
OI^{Brent}	+	0.1082***	0.0703***	0.1254***	0.0343		0.1561***	0.0190***	0.1217***
		(3.46)	(2.64)	(3.75)	(1.28)		(3.60)	(3.23)	(3.60)
$OI^{Brent} \times D_{2010}$					0.1993***				
					(3.02)				
BD	+	0.0028**	0.0028***	0.0035***	0.0040***	0.0034**		0.0008***	0.0034***
		(2.53)	(2.92)	(3.09)	(3.69)	(2.57)		(3.01)	(2.97)
BDT	+						0.0123		
							(1.24)		
$BDT \times D_{2010}$							0.0214***		
							(3.54)		
ST^{US}	+	0.0384***	0.0277**	0.0365**	0.0273	0.0568***	0.0217	0.0193***	0.0393**
		(2.74)	(2.20)	(2.39)	(1.62)	(3.49)	(1.22)	(5.72)	(2.55)
ST^{EU}	−	−0.0359**	−0.0389**	−0.0331*	−0.0400**	−0.0436***	−0.0133	−0.0207***	−0.0303
		(−1.98)	(−2.49)	(−1.69)	(−2.07)	(−2.66)	(−0.63)	(−4.90)	(−1.51)
ST^{ASIA}	−								−0.0168
									(−0.74)

TABLE 8 (Continued)

Model		SPR^{Spot}							
		(1) One break	(2) Three breaks	(3) CY with break	(4) OI with break	(5) VL with break	(6) BDT with break	(7) SPR^{Future} with break	(8) Asia index included
HT	+	−0.0033	−0.0027	−0.0037	−0.0035	−0.0046	−0.0012	−0.0007*	−0.0037
		(−1.41)	(−1.33)	(−1.48)	(−1.37)	(−1.53)	(−0.47)	(−1.78)	(−1.48)
CL	+	0.0003	0.0004	0.0006	0.0005	0.0010	−0.0005	0.0002	0.0006
		(0.24)	(0.43)	(0.55)	(0.40)	(0.75)	(−0.42)	(0.81)	(0.58)
Exogenous variables									
TR	+	−0.0010	−0.0010	−0.0012	−0.0012	−0.0012	−0.0017	−0.0003	−0.0012
		(−0.61)	(−0.64)	(−0.70)	(−0.71)	(−0.73)	(−0.97)	(−0.20)	(−0.72)
HR	–	0.0030	0.0029	0.0031	0.0030	0.0030	0.0032	0.0009	0.0031
		(1.47)	(1.41)	(1.48)	(1.47)	(1.41)	(1.43)	(1.11)	(1.48)
D_{2005}			−0.0004						
			(−0.59)						
D_{2010}		−0.0047***	−0.0060***	−0.0043***	0.0224	0.0047	−0.0055***	−0.0003	−0.0044***
		(−4.43)	(−5.05)	(−4.51)	(0.61)	(0.30)	(−4.76)	(−0.44)	(−4.60)
D_{2012}			0.0031***						
			(3.74)						
ECT_{t-1}		−0.0442***	−0.0512***	−0.0393***	−0.0380***	−0.0329***	−0.0489***	−0.1483***	−0.0396***
		(−5.39)	(−5.80)	(−5.46)	(−5.63)	(−4.69)	(−5.66)	(−10.52)	(−5.48)
N		6056	6056	6055	6055	6055	4367	6055	6055
		0.63	0.63	0.66	0.66	0.66	0.56	0.82	0.66

Note: This table reports the long-run coefficients estimated from the ARDL model. Variables are defined in Table 2. *t*-statistics (in parentheses) are based on Newey and West (1987) adjusted standard errors to account for serial correlation and heteroscedasticity. ***, **, * denote statistical significance at the 1%, 5% or 10% level.

market on the physical spot market. Model (8) includes the stock market activity in Asia as a proxy for emerging markets and the dramatic increase of crude oil imports. However, we do not find an influencing effect on the WTI-Brent price, which might be driven by the fact that China's oil imports come mainly come from as Russia and the Middle East.

Table 7 reports the coefficients of the error-correction term ECT_{t-1} from Equation (5), which measures how quickly variables converge to the equilibrium. As the coefficient is statistically significant with a negative sign in all models, we can confirm the presence of an established long-run relationship in the full sample. The significant speed of adjustment suggests convergence of the model dynamics from short-run to a long-run equilibrium. Deviations from the equilibrium are corrected by 3.80% per day in Model (4) up to 14.83% in Model (7).

5.6 | Robustness analysis

In addition to the ARDL results presented in the previous section, we performed various robustness tests with alternative variable definitions and model specifications (Table 9).

We calculate the convenience yields for contracts with 6 and 12 months to maturity (Models 11 and 12), which are a proxies for the expected long−term storage (Weymar, 1966). The magnitude of the long-run elasticity increases for both WTI ($\lambda_{CY(6M)^{WTI}} = 0.6098^{***}$; $\lambda_{CY(12M)^{WTI}} = 0.9759^{***}$) and Brent ($\lambda_{CY(6M)^{Brent}} = -0.7108^{***}$; $\lambda_{CY(12M)^{Brent}} = -1.0941^{***}$).

Moreover, we extend the estimation of the convenience yield by two alternative methods (Models 13 and 14). First, we construct a 3-month futures contract by the weighted average of the futures prices with a shorter and a longer maturity. The weights are defined linearly as difference between the 3 months and the maturity of the respective future divided by the maturity difference between both (longer and shorter maturity). This implies a daily roll-over from the short-term future to the long-term future (Hammerschmid, 2018; Szymanowska et al., 2014). Second, we simply use

TABLE 9 Long-run elasticities from ARDL model: Robustness analysis

		SPR^{Spot}										SPR^{Future} (3 months)		SPR^{Future} (6 months)	SPR^{Future} (12 months)
Model		(9) Three breaks	(10) Futures spread (3 months)	(11) CY (6 months)	(12) CY (12 months)	(13) CY (Average maturity)	(14) CY (Rolling maturity)	(15) Term spread	(16) Future spread (6 months)	(18) Storage costs (linear)	(19) Storage costs (logistic)	(20) Future spread	(21) Future spread	(22) Future spread	(23) Future spread
Dependent variable															
Constant		−0.0242	−0.0550***	−0.0274	−0.0268	−0.0201	−0.0192	−0.0337*	−0.0429***	−0.0175	−0.0168	−0.0889***	0.1324***	0.0843***	−0.0182
		(−1.38)	(−3.60)	(−1.64)	(−1.54)	(−1.22)	(−1.11)	(−1.90)	(−3.11)	(−1.08)	(−1.03)	(−2.61)	(4.29)	(3.31)	(−0.83)
Trend		−0.0001***	−0.0001***	−0.0001***	−0.0001***	−0.0001***	−0.0001***	−0.0001***	−0.0001***	−0.0001***	−0.0001***	−0.0001***	0.0001**	0.0001	−0.0001***
		(−3.97)	(−4.41)	(−3.93)	(−3.79)	(−3.81)	(−3.28)	(−4.43)	(−4.53)	(−3.75)	(−3.83)	(−4.58)	(2.21)	(0.46)	(−2.93)
CY^{WTI}	+	0.4548***	0.1774***	0.6098***	0.9759***	0.3843***	0.3530***		0.2901***	0.3771***	0.3701***	0.2341***	−0.1569***	−0.2549***	−0.2347***
		(9.46)	(17.01)	(6.83)	(6.68)	(6.21)	(5.80)		(32.26)	(6.17)	(6.26)	(4.97)	(−20.12)	(−48.25)	(−18.93)
CY^{WTI} x D_{2010}		0.2657	−0.0568***	0.1374	0.0826	0.0337	0.0202		−0.0618***	0.0450	0.0697	0.1199	0.0833***	0.0462***	0.0102
		(1.32)	(−2.66)	(0.77)	(0.35)	(0.21)	(0.13)		(−3.08)	(0.29)	(0.45)	(1.49)	(9.03)	(6.60)	(0.58)
CY^{WTI} x D_{2012}		−0.2037													
		(−0.84)													
CY^{WTI} x D_{2005}		−0.2492**													
		(−2.53)													
CY^{Brent}	−	−0.5549***	−0.1801***	−0.7108***	−1.0941***	−0.4681***	−0.4198***		−0.2906***	−0.4579***	−0.4538***	−0.2498***	0.1487***	0.2437***	0.2245***
		(−8.64)	(−14.05)	(−7.00)	(−6.88)	(−5.92)	(−5.44)		(−25.71)	(−5.81)	(−5.86)	(−4.19)	(16.18)	(41.96)	(14.94)
CY^{Brent} x D_{2010}		−0.2036	0.0110	−0.0943	−0.0861	0.0606	0.0348		0.0592***	0.0394	0.0473	−0.0207	−0.0137	−0.0334***	−0.0574***
		(−0.55)	(0.57)	(−0.53)	(−0.35)	(0.41)	(0.24)		(3.34)	(0.28)	(0.34)	(−0.23)	(−1.34)	(−4.86)	(−3.41)
CY^{Brent} x D_{2012}		0.1001													
		(0.27)													
CY^{Brent} x D_{2005}		0.3551***													
		(2.69)													
TS^{WTI}	−							−1.4086***							
								(−5.29)							
TS^{WTI} x D_{2010}								−0.1188							
								(−0.23)							
TS^{Brent}	+							1.6207***							
								(6.33)							
TS^{Brent} x D_{2010}								0.0062							
								(0.01)							
SPR^{Spot}	+												1.0316***	0.9652***	0.7405***
													(93.47)	(119.38)	(32.32)
SPR^{Future}	+		0.8563***						0.8334***						
			(38.84)						(25.78)						
SPR^{Future} x D_{2010}									0.1397***						
									(3.65)						
VL^{WTI}	−	0.0128	0.0014	0.0166	0.0210*	0.0154	0.0040	0.0246**	0.0020	0.0163	0.0160	0.0217**	0.0013	0.0011	0.057***

TABLE 9 (Continued)

		SPR^{Spot}										SPR^{Future} (3 months)		SPR^{Future} (6 months)	SPR^{Future} (12 months)
Model		(9) Three breaks	(10) Futures spread (3 months)	(11) CY (6 months)	(12) CY (12 months)	(13) CY (Average maturity)	(14) CY (Rolling maturity)	(15) Term spread	(16) Future spread (6 months)	(18) Storage costs (linear)	(19) Storage costs (logistic)	(20) Future spread	(21) Future spread	(22) Future spread	(23) Future spread
		(1.23)	(0.76)	(1.54)	(1.94)	(1.24)	(0.32)	(2.51)	(1.35)	(1.34)	(1.34)	(2.18)	(1.17)	(1.38)	(2.90)
VL^{Brent}	+	−0.0085**	−0.0016**	−0.0105***	−0.0105***	−0.0127***	−0.0126***	−0.0130***	−0.0022***	−0.0130***	−0.0130***	−0.0111***	0.0001	0.0001	−0.0007
		(−2.15)	(−2.46)	(−3.60)	(−3.68)	(−3.79)	(−3.67)	(−5.13)	(−3.77)	(−3.91)	(−4.02)	(−2.74)	(0.07)	(0.25)	(−1.09)
OI^{WTI}	−	−0.0299	0.0002	−0.0378	−0.0189	−0.0755*	−0.0658	−0.0462	0.0063	−0.0764*	−0.0753*	−0.0428	−0.0113***	−0.0092***	0.0156***
		(−0.79)	(0.04)	(−1.07)	(−0.54)	(−1.83)	(−1.58)	(−1.50)	(1.30)	(−1.89)	(−1.91)	(−1.30)	(−2.89)	(−3.45)	(2.67)
OI^{Brent}	+	0.0817***	0.0197***	0.0974***	0.0725***	0.1295***	0.1267***	0.0996***	0.0100***	0.1234***	0.1204***	0.1238***	−0.0052*	0.0002	−0.0153***
		(3.08)	(4.43)	(3.42)	(2.68)	(3.81)	(3.73)	(4.26)	(2.65)	(3.77)	(3.72)	(4.67)	(−1.72)	(0.07)	(−3.23)
BD	+	0.0044***	0.0003	0.0031***	0.0024**	0.0035***	0.0036***	0.0025**	0.0003**	0.0036***	0.0035***	0.0025**	0.0001	0.0001	−0.0006***
		(3.62)	(1.60)	(2.94)	(2.33)	(3.05)	(3.06)	(2.46)	(1.99)	(3.15)	(3.19)	(2.09)	(0.87)	(1.16)	(−2.79)
ST^{US}	+	0.0247*	0.0103***	0.0532***	0.0611***	0.0363**	0.0359**	0.0343***	0.0081***	0.0326**	0.0307**	0.0336***	−0.0073***	−0.0009	0.0139***
		(1.89)	(4.67)	(3.96)	(4.51)	(2.38)	(2.33)	(2.86)	(3.73)	(2.17)	(2.08)	(2.85)	(−5.23)	(−0.97)	(5.48)
ST^{EU}	−	−0.0347**	−0.0108***	−0.0535***	−0.0601***	−0.0330*	−0.0332*	−0.0332**	−0.0098***	−0.0295	−0.0273	−0.0363**	0.0078***	0.0030***	−0.0121***
		(−2.11)	(−3.93)	(−3.11)	(−3.52)	(−1.69)	(−1.69)	(−2.15)	(−3.66)	(−1.53)	(−1.46)	(−2.38)	(4.55)	(2.62)	(−4.00)
HT	+	−0.0028	−0.0005	−0.0025	−0.0016	−0.0038	−0.0038	−0.0025	−0.0004*	−0.0036	−0.0036	−0.0033*	−0.0001	0.0001	0.0005
		(−1.31)	(−1.50)	(−1.15)	(−0.74)	(−1.50)	(−1.50)	(−1.31)	(−1.72)	(−1.43)	(−1.48)	(−1.84)	(−0.06)	(0.64)	(1.53)
CL	+	0.0007	0.0001	0.0010	0.0012	0.0006	0.0002	0.0004	0.0001	0.0005	0.0005	−0.0005	−0.0001	0.0001	0.0003*
		(0.82)	(0.71)	(1.03)	(1.24)	(0.50)	(0.21)	(0.52)	(0.65)	(0.47)	(0.48)	(−0.54)	(−0.44)	(0.58)	(1.69)
Exogenous variables															
TR	+	−0.0018	−0.0009	−0.0011	−0.0013	−0.0013	−0.0017	−0.0009	0.0001	−0.0011	−0.0012	−0.0008	−0.0006	−0.0020	−0.0009
		(−1.17)	(−0.63)	(−0.67)	(−0.79)	(−0.78)	(−1.09)	(−0.47)	(0.06)	(−0.65)	(−0.69)	(−0.26)	(−0.25)	(−1.20)	(−0.50)
HR	−	0.0029	0.0025*	0.0031*	0.0022	0.0029	0.0028	0.0023	0.0006	0.0031	0.0033	0.0027	−0.0008	0.0013	−0.0043**
		(1.42)	(1.67)	(1.67)	(1.24)	(1.40)	(1.34)	(1.17)	(0.67)	(1.48)	(1.59)	(0.93)	(−0.42)	(0.93)	(−2.11)
D_{2005}		−0.0010													
		(−1.19)													
D_{2010}		−0.0052***	−0.0038***	−0.0039***	−0.0033***	−0.0043***	−0.0045***	−0.0052***	−0.0009	−0.0043***	−0.0044***	−0.0108***	0.0022*	−0.0003	−0.0004
		(−3.14)	(−4.65)	(−3.96)	(−3.37)	(−4.59)	(−4.74)	(−5.39)	(−1.11)	(−4.53)	(−4.61)	(−7.24)	(1.73)	(−0.28)	(−0.33)
D_{2012}		0.0029*													
		(1.71)													
ECT_{t-1}		−0.0469***	−0.2466***	−0.0429***	−0.0432***	−0.0391***	−0.0396***	−0.0509***	−0.2407***	−0.0396***	−0.0406***	−0.0918***	−0.6968***	−0.8328***	−0.3257***
		(−5.67)	(−14.27)	(−5.01)	(−4.96)	(−5.40)	(−5.39)	(−6.73)	(−11.75)	(−5.48)	(−5.56)	(−9.50)	(−28.14)	(−42.26)	(−14.48)
N		6055	6055	6055	6055	6055	6055	6057	6055	6055	6055	6055	6055	6058	6058
$Adj.\ R^2$		0.67	0.73	0.68	0.69	0.66	0.65	0.65	0.82	0.66	0.66	0.39	0.55	0.60	0.53

Note: This table reports the long-run coefficients estimated from the ARDL model. Variables are defined in Table 2. *t*-statistics (in parentheses) are based on Newey and West (1987) adjusted standard errors to account for serial correlation and heteroscedasticity.

***, **, and * denote statistical significance at the 1%, 5%, and 10% level.

the futures contract with the closet maturity to three months to calculate the convenience yield (Geman & Nguyen, 2005; Gibson & Schwartz, 1990; Milonas & Henker, 2001). When applying these alternative methods, the ARDL results remain stable and we can confirm the previous findings from Table 7.

We include the term spread TS^{WTI} and TS^{Brent} (defined as difference between the futures and the spot price) as an alternative proxy for the convenience yield (Model 15). The findings confirm the outcomes from the analysis of the convenience yield, with a significant impact of the Brent and WTI term spread.

In the previous models, we assume fixed storage costs in the calculation of the convenience yield. We extend this by estimating dynamic storage costs. In Model (18), we assume a linear relation between storage costs and crude oil storage levels. In Model (19), the relation between storage costs and crude oil storage levels is estimated by a logistic function.

As an extension of Model (7), we include the futures price spread (3, 6, and 12 months to maturity) instead of the spot price spread as dependent variable and treat the spot price spread as explanatory factor (Model 20–23). This analysis shows that the impact of the physical market on the paper market (Model 21: $\lambda_{SPR^{Spot}} = 1.0316^{***}$) is much stronger than vice versa (Model 10: $\lambda_{SPR^{Future}} = 0.8563^{***}$), which coincide with previous evidence, for example, by Lautier et al. (2018).

6 | DISCUSSION

Consolidating the findings from this study leads to the conclusion that the WTI-Brent spread is positively correlated with the convenience yield obtained from a 3-month WTI futures contract and negatively correlated with the Brent oil convenience yield. This finding is in line with the theory of storage according to Working, (1927, 1949) and Brennan (1958). Accordingly, the convenience yield is a surrogate for the availability of a commodity and a high convenience yield implies a critical supply situation, which leads to increasing spot prices and a larger spread. Although this finding in line with Milonas and Henker (2001), who find a significant impact of WTI convenience yield at the 10% or 5% level (depending on the maturity of the futures used for the spread calculation), we obtain stronger effects in terms of statistical significance (all at the 1% level and even lower) and also in terms of economic significance as shown by the long-run elasticities from the ARDL estimation. This result could be reasoned by the different data samples. Milonas and Henker (2001) examine the period from 1991 to 1995, which is a time period when the WTI-Brent spread was more or less negligible. Another crucial difference is that we apply an alternative method for the computation of the convenience yield and also include other supply and demand factors as controls in the ARDL model.

Comparing the findings for the other spread determinants with the previous literature shows some interesting differences. Similar to Büyüksahin et al. (2013), we find a significant effect of the U.S. economy on the WTI-Brent spread. However, the sign of the effect is different. The positive effect resulting from the ARDL model in Table 7 is in line with the predicted sign, but in contrast to the negative sign reported in Büyüksahin et al. (2013). An explanation could be the difference in the variable definition, as Büyüksahin et al. (2013) use the U.S. Business Climate index, whereas we create a dedicated stock index for oil-dependent industries. For the variables measuring the extent of paper markets trading, we confirm the significant effect for the open interest as reported in Büyüksahin et al. (2013) for the Brent market and after 2010 also for WTI. In addition, we analyze the determinants of crude oil market segmentation through the Baltic Dry and the Baltic Dry Tanker index. While Büyüksahin et al. (2013) find no effect of shipping rates, we find a significant and positive impact. This implies that high freight rates cause higher barriers to transport oil, which leads to larger spreads.

7 | CONCLUSION

This study investigates the determinants of the price differential between WTI and North Sea Brent crude oil for the time period between January 01, 1995 and December 31, 2020. Our analysis consists of three steps: (i) Structural break analysis of the WTI-Brent time series, (ii) examination of the cointegration relation among WTI and Brent, and (iii) exploration of the spread determinants within an ARDL model.

For the structural break analysis, we apply several methods and detect a major break in December 2010, which is in line with previous literature. From the cointegration analysis, we find that the strong long-run relationship between WTI and Brent becomes weaker after 2010. The results from impulse response analysis suggest that Brent reacts much stronger to WTI shocks than vice versa. After 2010, there is no more response of WTI to a Brent price shock, which illustrates the decoupling of the two oil prices.

The results from the ARDL model reveal that the convenience yield, as proxy for crude oil inventories, is the most important spread determinant. Moreover, we find a strong positive influence of the convenience yield for WTI, which is an indicator for the crude oil supply situation in the United States. There is also a strong negative influence of the convenience yield for Brent. Both results are in line with the theory of storage, that is, low storage volumes and thus high convenience yield strongly influence the size of the price gap between WTI and Brent. Moreover, the trading activity in crude oil paper markets, transportation costs for crude oil shipping, as well as the stock market development in the United States and Europe determine the size of the spread. Unlike other papers, we find that the impact of the spread determinants changed after the major break in 2010. Especially, the importance of open interest in WTI and Brent futures markets, as well as the shipping costs, gained in importance after 2010. In addition, the influence of the paper market on the physical spot market heavily increased after 2010. Accordingly, we find evidence that the balancing mechanism between both crudes changed over time and paper markets became more important for equalizing price differentials between WTI and Brent.

While we focus on WTI and Brent as crude oil classifications, an interesting subject for future research would be the examination of the determinants of alternative crude oil spreads like the price gap between WTI or Brent and Dubai crude. Another possible direction for further research is whether the same variables, which drive the WTI-Brent spread, also affect other commodities (e.g., cacao or wheat). Finally, with increasing U.S. oil exports and declining North Sea output, the U.S. crude market is replacing the North Sea market in pricing international crude oil, and the key market for oil pricing is now in Houston (Sider, 2017). In contrast to WTI Cushing, WTI Houston closely follows Brent (PEM, 2017).[11] However, futures price data for WTI Houston is only available since 2018. Future research could investigate if the determinants detected in this study also hold for WTI Houston.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from Bloomberg, European Climate Assessment, Federal Reserve, Intercontinental Exchange, National Climatic Data Center, National Weather Service, New York Mercantile Exchange, STOXX, Thomson Reuters Datastream, and the University of Siegen. Restrictions apply to the availability of the data sets, which were used under license for this study.

ORCID

Jerome Geyer-Klingeberg http://orcid.org/0000-0001-6615-7439
Andreas W. Rathgeber http://orcid.org/0000-0002-6996-5631

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