Research in International Business and Finance 56 (2021) 101385

Contents lists available at ScienceDirect

Research in International Business and Finance

journal homepage: www.elsevier.com/locate/ribaf

Full length Article

Volatility spillovers between WTI and Brent spot crude oil prices: an analysis of granger causality in variance patterns over time

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ARTICLE INFO

JEL classification:
C22
G15
Q41
Q43
Q47

Keywords:
Oil prices
Volatility spillovers
Granger-causality
Energy economics

ABSTRACT

There has been an increase in price volatility in oil prices during and since the global financial crisis (GFC). This study investigates the Granger causality patterns in volatility spillovers between West Texas International (WTI) and Brent crude oil spot prices using daily data. We use Hafner and Herwartz's (2006) test and employ a rolling sample approach to investigate the changes in the dynamics of volatility spillovers between WTI and Brent oil prices over time. Volatility spillovers from Brent to WTI prices are found to be more pronounced at the beginning of the analysis period, around the GFC, and more recently in 2020. Between 2015 and 2019, the direction of volatility spillovers runs unidirectionally from WTI to Brent oil prices. In 2020, however, a Granger-causal feedback relation between the volatility of WTI and Brent crude oil prices is again detected. This is due to the uncertainty surrounding how the COVID-19 pandemic will evolve and how long the economies and financial markets will be affected. In this uncertain environment, commodities markets participants could be reacting to prices and volatility signals on both WTI and Brent, leading to the detection of a feedback relation.

1. Introduction

Crude oil is not only one of the most traded commodities in the world, but also one of the most important energy inputs in production processes. Hence, fluctuations in crude oil prices significantly affect global economic activity through various channels. Shock increases in oil prices are well known to be associated with economic slowdowns and high inflation rates in oil-importing countries. Furthermore, crude oil prices can serve as a leading indicator for predicting the course of business activities and financial markets. Specifically, the empirical literature shows that crude oil price volatility is an important leading indicator of stock market volatility and financial stress.

From an empirical point of view, which oil price to use in an economic or financial model still needs further clarification. Most papers in the literature use West Texas International (WTI) or Brent oil prices in their models, although other oil price variables, such as Dubai, Sahara, Maya, Lloyd, and Bonny, have also been used, but seldom. WTI and Brent crude oil have the largest trading volume in global crude oil markets, hence providing further reasons for research to focus on them. Technically, WTI and Brent crude oil are the

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https://doi.org/10.1016/j.ribaf.2021.101385
Received 4 May 2020; Received in revised form 14 December 2020; Accepted 1 January 2021
Available online 10 January 2021
0275-5319/

most widely used types of oil in industry and they are classified as light due to their low sulfur content. Higher-sulfur crudes are classified as medium or heavy. Their different chemical compositions make them less than perfect substitutes for refining and processing. Ghoshray and Trifonova (2014) provide further details on the properties of different types of oil traded on commodities markets and their price differences.

Globalization in the oil market was first emphasized in the literature by Wiener (1991). Wiener argues that the world oil market is “one great pool,” and supply and demand shocks in oil prices in one region will rapidly spread to other regions, and hence the prices of crude oils that have the same quality will move together. Quality discounts, transportation costs, and time discounts are considered reasons for price spreads in the global oil market. Since WTI and Brent crude oil have a similar sulfur content, the price spread between them is expected to be small or constant over time. On the other hand, empirical studies show that the price spread between WTI and Brent is not stable over time, and it has significantly increased since the global financial crisis (GFC) (Ghoshray and Trifonova, 2014; Schalck and Chenavaz, 2015; and Coronado et al., 2017).

The increased spread between WTI and Brent prices has important economic implications, and hence it has attracted the attention of policymakers and academic professionals. For instance, developments in global oil prices are very important for petroleum-related firms, because they consider global oil prices a guide for their oil-related business decisions. Corbet et al. (2020) have found that volatility in crude oil prices under the COVID-19 environment has also been important for other energy-related companies, such as those in coal and renewables sectors. However, it is also important for policymakers to determine their national energy policies. Furthermore, Fattouh (2011) indicates that increased spreads between WTI and Brent have raised doubts on WTI as a global oil price benchmark. Fattouh (2011) examines the reasons for the spread between WTI and Brent and emphasizes the importance of logistic and storage issues for WTI. The capacity situation in Cushing, Oklahoma, is found to be very important for WTI, because that is where the pipeline system ends. Hence, oil supply constraints in Cushing directly affect WTI prices. In addition to the fundamentals behind oil price formation in the markets, there could also exist behavioral considerations. Li et al. (2015) investigate the effects of traders' Google searches on crude oil prices and find a one-week leading relation between Google search volumes and oil prices between 2004 and 2014.

The observed increases in both WTI and Brent price volatility and in the volatility of their price spreads after 2008 necessitate a better understanding of the direction of Granger-causal linkages between the volatility of WTI and Brent prices. Given this background, we aim to examine the presence (or absence) of volatility spillovers between WTI and Brent spot crude oil prices using Granger causality in variance tests, which is the novelty of this paper.

The literature on WTI and Brent crude oil prices focuses on the stability of the price differentials or spreads between these two similar light oils and the potential drivers behind the observed deviations. Nevertheless, only a few studies specifically examine the (Granger-) causal relations between WTI and Brent crude oil prices, and they mostly focus on testing for Granger causality in mean. To the best of our knowledge, the studies of Kang et al. (2011) and Lu et al. (2014) are the only ones that analyze the spillover effects between the second moments of WTI and Brent oil prices. In particular, Kang et al. (2011) investigate the volatility spillover effects between WTI and Brent oil prices using weekly data for the 1990–2009 period. Lu et al. (2014) examine the time-varying volatility spillover effects in the global crude oil market (WTI, Brent, Dubai, and Tapis crudes) for the 2002–2012 period, employing Hong's (2001) Granger causality in variance test and dynamic conditional correlation multivariate generalized autoregressive conditional heteroskedasticity (DCCM-GARCH).

It is well known that volatility spillover effects (or causality in variance) between financial markets variables are important for investors as they indicate a lack of diversification benefits among financial markets. In addition, the volatility spillover effects point to the presence of contagion effects between the financial markets. Hence, volatility spillovers can affect investors' decisions and the construction of optimal portfolios. Moreover, the causality in variance also indicates an information spillover effect among the markets, and hence it allows us to determine which market plays a more dominant role. The literature on volatility spillovers between various crude oil prices is sparse, and the periods investigated in the limited number of studies are rather short. Our study aims to contribute to the literature by testing for causality in variance between WTI and Brent oil prices using daily data for the periods of from May 20, 1987, to August 3, 2020, which is the longest time horizon in the literature to date. The sample period also includes the volatility increase observed in 2020 resulting from the effects of the COVID-19 pandemic. Furthermore, our study incorporates several methodological novelties in this literature, such as the consideration of structural breaks in causality in variance tests. In addition, we employ a rolling version of Hafner and Herwartz (2006) causality in variance test. This approach enables us to detect changes in Granger-causal patterns over time. The rolling sample Granger causality tests provide a comparison of how Granger-causal volatility spillover relations have changed under the COVID-19 environment.

The concept of time-varying Granger causality needs further clarification.[1] The empirical relations observed among the variables of interest operationalized by means of statistical or probabilistic causality concepts, such as Granger causality, can vary over time, due to the changing influence of different environmental variables. There could be various reasons for a change in the nature of the empirical Granger-causal relations. In the case of economic or financial variables, changes in the direction of Granger-causal linkages can arise due to abrupt policy changes, geopolitical risks, or other factors, such as unexpected shocks in the global economy. Schalck and Chenavaz (2015), for instance, find evidence that shifts in global demand and stock market movements had effects on oil commodity returns between 1990 and 2013, especially since 2008. They also argue that these effects are not well captured by a constant-parameter model. Chiaruccia et al. (2017) also find evidence of a structural change in the oil market before 2008.

[1] We thank an anonymous referee for pointing this out.

In the context of this paper, events such as the invasion of Kuwait in 1990 and the Iraq War in 1991, the 1997 Asian crisis, 1998 Russian crisis, the dot.com bubble bursting in 2000, the 9/11 terror attack in 2001, the Iraq War in 2003, the GFC of 2008–2009, and the COVID-19 pandemic are important events that could be associated with break points in oil prices and potentially also a change in the nature and direction of the Granger-causal relations among the prices of different crude oil varieties. We address these questions in Section 4 of this paper.

The remainder of the paper is organized as follows. Section 2 reviews the literature on oil price spreads. Section 3 discusses the data and methodology. Section 4 presents the empirical findings. Section 5 discusses the results and concludes the paper.

2. Literature review

There exists a vast literature on the effects of oil price changes on economic performance. Hamilton (1983, 1996, 2003) and Kilian (2009), among others, are some influential contributions to the literature on oil price movements and macroeconomic performance. A comprehensive review of the literature is given by Barsky and Kilian (2004); Baumeister and Kilian (2016); Dong et al. (2019); Herrera et al. (2019), and Lorusso and Pieroni (2019). Another line of literature on oil prices examines the linkages between oil price movements and their effects on financial markets. The recent works of Kilian and Park (2009); Sari et al. (2010); Wang et al. (2013); Nazlioglu et al. (2015); Çevik et al. (2018); Degiannakis and Filis (2018), Melichar and Atems (2018); Yildirim et al. (2018), and Sakaki (2019) examine the effects of oil price movements on stock market prices or on financial markets in general. Lang and Auer (2020) provide an up-to-date review of the economic and financial markets effects of crude oil prices.

A seminal study in this literature is that of Weiner (1991), who asks the question of whether the world oil market is one great pool and finds that price shocks stemming from supply shocks in one region are mostly contained in the same region. Weiner's study uses correlation analyses and switching regressions for the period 1980–1987. Sauer (1994), on the other hand, uses cointegration tests and finds that oil price differences adjust after a time lag, supporting the unified markets—one great pool—hypothesis. Bachmeister and Griffin (2006) and Bentzen (2007) also find a high degree of market integration in the crude oil market between 1998 and 2004. Using daily data from January 3, 2007, to January 7, 2011, Ghoshray and Trifonova (2014) examine the asymmetric dynamic adjustment process across six crude oil varieties. In their sample, the average daily price differential per barrel of WTI and Brent crude oil is USD 1.30, with a standard deviation of USD 1.94. They find evidence in favor of cointegration between all crude oil pairs and that the markets have asymmetric responses to positive and negative shocks. An important conclusion of the Ghoshray and Trifonova is that quality differences between crude oil varieties cannot explain the price differentials and that other factors need to be examined to understand the speed of price adjustment in crude oil markets.

Büyükşahin et al. (2013) relate the futures price spread between WTI and Brent crude oil prices to short-term storage conditions in Cushing, Oklahoma, which is the physical delivery point for WTI futures, to the spot and futures prices of WTI and Brent crude oil and to the price of Louisiana Light Sweet (LLS) oil. The equation can be expressed as follows (Büyükşahin et al., 2013: 131): WTI_f - $Brent_f$ = (WTI_f - LLS_s) + (LLS_s - $Brent_s$) + ($Brent_f$ - $Brent_s$), where the subscripts f and s represent futures and spot prices, respectively. The first component on the right-hand side (RHS) of the equation, WTI_f - LLS_s, represents the landlocked commodity spread between WTI and LLS. The second term, LLS_s - $Brent_s$, stands for the price difference between LLS and Brent and proxies for the shipping cost of Brent across the Atlantic Ocean. The third term, $Brent_f$ - $Brent_s$, proxies for the immediacy of demand for Brent crude oil on the world market. Büyükşahin et al. (2013) provide a framework to explain the futures price differentials between WTI and Brent oil. Their findings point to the importance of the storage conditions in Cushing, Oklahoma, and to macroeconomic conditions in explaining the WTI and Brent futures price differentials. Using an extreme value theory framework with quantile regressions for the period from 1983 to 2013, Aboura and Chevallier (2016) find that the upper and lower levels for a maximum one-day variation in WTI prices that could occur once in a century are, respectively, +23 % and -33 %.

Extending the work of Büyükşahin et al. (2013); Liu et al. (2018) use a structural vector autoregression methodology to investigate the price spread between WTI and Brent crude oil for the period between January 1994 and December 2016. They show a large volatility increase in the WTI–Brent price spreads during and after the GFC. Chen et al. (2015) also obtain similar results. As an underlying fundamental, the results of Liu et al. (2018) from structural vector autoregression impulse response functions indicate that production shocks in the United States mainly drive developments in the WTI–Brent price spread. Nevertheless, the WTI–Brent price spread is also observed to be declining more recently since mid-2019, again pointing to an alteration in price adjustment dynamics.

Among the few studies that specifically examine the (Granger-) causal linkages between WTI and Brent crude oil prices, Coronado et al. (2017) investigate the causal relations between Brent, WTI, and Argus oil prices for the period between January 2013 and October 2015 using daily data. The authors show that the mean oil prices per barrel of WTI and Brent crude oil were USD 88.26 and USD 81.48, respectively, yielding a price spread of USD 6.78 for the sample period. These results are more than five times higher than the USD 1.30 in Ghoshray and Trifonova (2014) sample from January 2007 to January 2011. Coronado et al. (2017) use a nonparametric causality test proposed by Diks and Panchenko (2006), and the results show a bidirectional causality relation between WTI and Brent crude oil prices. Coronado et al. (2017) also find only unidirectional Granger causality from Brent and WTI prices to Argus prices and comment that these findings are in line with current trading patterns in the world oil market.

The literature on the relations between the dynamics of WTI and Brent crude prices and price differentials mostly examines only Granger causality in mean. To the best of our knowledge, Kang et al. (2011) and Lu et al. (2014) are the only one to analyze the spillover effects between the second moments of WTI and Brent oil prices. In particular, Kang et al. (2011) investigate the volatility spillover effects between WTI and Brent oil prices using weekly data for 1990–2009. They identify five sudden change points in the variance of the WTI and Brent return series via the iterative cumulative sum of squares (ICSS) algorithm. Multivariate GARCH (MGARCH) model estimations indicate an information and volatility spillover effect from WTI to Brent when structural breaks are

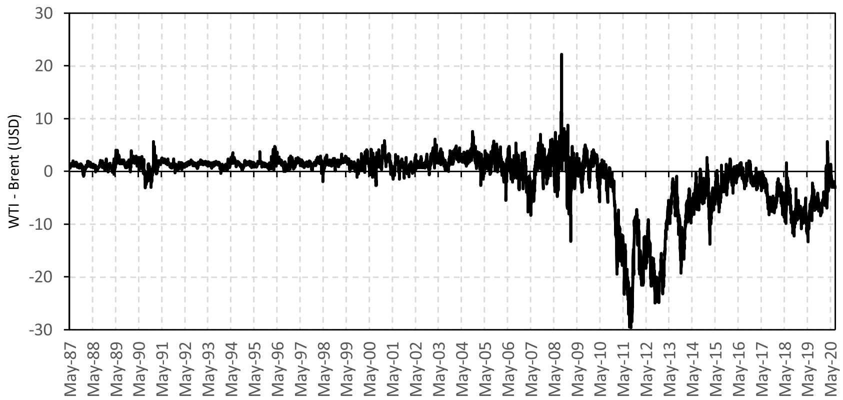

Fig. 1. WTI and Brent Spot Crude Oil Price Spreads.
May 20, 1987, to August 03, 2020

taken into account in the model estimation. Lu et al. (2014) examine time-varying volatility spillover effects in the global crude oil market (WTI, Brent, Dubai, and Tapis crude) for 2002–2012 using Hong's (2001) Granger causality in variance test and DCCM-GARCH. They find evidence in favor of spillover effects among global crude oil markets. Moreover, the test results suggest that causality relations tend to change over time and that there are significant instantaneous Granger-causal effects between WTI and Brent volatility. On the other hand, the authors conclude that Dubai and Tapis crude cannot dominate the global crude oil markets.

Given the lack of studies investigating the Granger-causal volatility spillovers between WTI and Brent crude oil prices, we aim to contribute to the literature in several ways. First, our methodology differs from Kang et al. (2011)'s and Lu et al. (2014)'s. We employ the causality in variance test proposed by Hafner and Herwartz (2006). Second, we employ the structural break in variance test proposed by Sanso et al. (2004) to determine the presence of structural breaks in the variance of the series. Note that Kang et al. (2011) employ the structural break in variance test suggested by Inclan and Tiao (1994) when they examine volatility spillovers between the Brent and WTI return series. However, Sanso et al. (2004) show that the test procedure Inclan and Tiao suggest is susceptible to the distributional properties of the series, and the testing procedure tends to find oversized sudden change points when the series exhibits an autoregressive conditional heteroskedasticity (ARCH) effect. Third, we use a longer time period than those employed by the two earlier studies, and we use daily data. Last, our sample includes 2020 data and provides a first look into the effects of the COVID-19 pandemic on volatility spillovers between WTI and Brent crude oil prices.

3. Data and methods

3.1. Data

We use daily data from May 20, 1987 to August 3, 2020, on WTI and Brent spot crude oil prices, yielding 8501 observations. We collected daily prices for WTI and Brent from the International Energy Agency. The data span in our study is larger than that of the previous studies. Fig. 1 presents the daily spot price spread between the WTI and Brent crude oil prices.

The average price spread between WTI and Brent for the sample period is found to be US -1.191, that is, the price per barrel for Brent oil trades by about USD 1 more than for WTI. The WTI–Brent spread is mostly positive until 2008, averaging about USD 1.436. However, the WTI–Brent price spread turns out to be USD -5.545 for the period from January 1, 2019, to August 3, 2020. The overall volatility of the spread measured in standard deviations also increases from USD 1.276 in 1987–2007 to USD 6.945 in the post-2008 period.

3.2. Econometric framework

Two main approaches in the literature have been used to determine the existence of volatility spillovers. The first approach relies on MGARCH models. The presence of volatility spillovers is tested by imposing constraints on specific parameters. On the other hand, a large number of studies criticize the MGARCH models because the estimation method entails multiple constraints for parameters to ensure covariance stationarity.

The second approach is less complex than the MGARCH model, and it requires the estimation of a univariate GARCH model. In the investigation of the causality in variance using the univariate GARCH model approach, two different testing procedures have come to the fore. The first testing procedure, suggested first by Cheung and Ng (1996) and modified by Hong (2001), depends on the cross-correlation functions of squared standardized residuals that are derived from the first-stage GARCH model. However, Hafner and Herwartz (2006) show via Monte Carlo simulations that, in the case of small and medium sample sizes, the testing procedure of Cheung and Ng (1996) suffers from significant oversizing if the innovations underlying a conditionally heteroskedastic process are leptokurtic. Furthermore, the cross-correlation function testing procedure has been criticized in the literature as it could be sensitive to lag and lead order selection. Hafner and Herwartz (2006) suggest a testing procedure where the Lagrange multiplier (LM) principle is considered for investigating causality in variance between the variables of interest and show that the LM test outperforms reasonably. Hafner and Herwartz define the null hypothesis of no causality in variance as follows:

$$H_0 = Var\left(\varepsilon_{it}\middle|\mathrm{I}_{t-1}^{(j)}\right) = Var(\varepsilon_{it}|\mathrm{I}_{t-1}) \tag{1}$$

where $i, j = 1, 2, \ldots, N, i \neq j$, and $I_t^{(j)} = I_t\middle|\sigma(\varepsilon_{jr}, \tau \leq t)$.

Since Hafner and Herwartz (2006) testing procedure depends on the residuals of the GARCH model, the following GARCH models suggested by Bollerslev (1986) should be estimated:

$$\begin{aligned} r_{it} &= \mu_{it} + \varepsilon_{it}, \\ \varepsilon_{it} \setminus (\varepsilon_{it-1},\ \varepsilon_{it-2}, \ldots,\ r_{it-1},\ r_{it-2}, \ldots) &\sim GED\left(0,\ \sigma_{it}^2\right) \\ \sigma_{it}^2 &= \omega + \alpha_i\varepsilon_{it-1}^2 + \beta_i\sigma_{it-1}^2 \end{aligned} \tag{2}$$

$$\begin{aligned} r_{jt} &= \mu_{jt} + \varepsilon_{jt}, \\ \varepsilon_{jt} \setminus \left(\varepsilon_{jt-1},\ \varepsilon_{jt-2}, \ldots,\ r_{jt-1},\ r_{jt-2}, \ldots\right) &\sim GED\left(0,\ \sigma_{jt}^2\right) \\ \sigma_{jt}^2 &= \omega + \alpha_j\varepsilon_{jt-1}^2 + \beta_j\sigma_{jt-1}^2 \end{aligned} \tag{3}$$

In the context of this paper, μ_{it} and μ_{jt} are the means and ε_{it} and ε_{jt} stand for the innovation processes for the return series of WTI and Brent crude oil prices, respectively. The null hypothesis of no causality is tested by using the LM test statistic as follows:

$$\lambda_{LM} = \frac{1}{4T}\left(\sum_{t=1}^{T}\left(\xi_{it}^2 - 1\right)z_{jt}^{'}\right)V(\theta_i)^{-1}\left(\sum_{t=1}^{T}\left(\xi_{it}^2 - 1\right)z_{jt}\right) \xrightarrow{d} \chi^2 \tag{4}$$

where ξ_{it} denotes the standardized residuals obtained from the GARCH model, $V(\theta_i) = \frac{\kappa}{4T}\left[\sum_{t=1}^{T} z_{jt}z'_{jt} - \sum_{t=1}^{T} z_{jt}x'_{it}\left(\sum_{t=1}^{T} x_{it}x'_{it}\right)^{-1}\sum_{t=1}^{T} x_{jt}z'_{jt}\right]$,

where $\kappa = \frac{1}{T}\sum_{t=1}^{T}\left(\xi_{it}^2 - 1\right)^2$, $z_{jt} = \left(\varepsilon_{jt-1}^2, \sigma_{jt-1}^2\right)'$, $x_{it} = \sigma_{it}^{-2}\left(\partial\sigma_{it}^2/\partial\theta_i\right)$, and $\theta_i = (\omega_i, \alpha_i, \beta_i)'$.

The steps of the causality in variance test are defined by Hafner and Herwartz (2006) as follows:

1 Determine the residuals (ε_{it}, ε_{jt}) and standardized residuals (ξ_{it}), employ a GARCH(1,1) model, and then calculate the derivatives x_{it} and the volatility process σ_{jt}^2 entering z_{jt}.
2 Regress $\xi_{it}^2 - 1$ on x'_{it} and on the misspecification indicators in z'_{jt}.
3 Calculate λ_{LM} as T x R^2, where R^2 is obtained from the regression in step 2.

Hafner and Herwartz (2006) show that the asymptotic distribution of the test statistic is a χ^2 distribution and the number of misspecification variables in z_{jt} is considered the number of degrees of freedom.

An extensive literature focuses on the effect of structural breaks on the GARCH model, and structural breaks in variance are found to lead to the overestimation of the GARCH parameters. Hillebrand (2005) shows that structural breaks in the variance cause spurious integrated GARCH processes. Galeano and Tsay (2010) find that breaks in the variance produce overestimated GARCH parameters. This finding is significant for testing volatility spillovers between the series, because Javed and Mantalos (2011) emphasize that causality in variance test results are directly affected by the GARCH model specification. Furthermore, Van Dijk et al. (2005) and Rodrigues and Rubia (2007) determine that Hong's (2001) causality in variance test suffers from severe size distortions when there are breaks in the variances of the series in question. It should be noted that these findings are very important in calculating LM test statistics as the test statistics depend on the GARCH parameter estimation. Hence, we employ the structural-breaks-in-variance test of Sanso et al. (2004), which employs the ICSS procedure to examine the existence of breaks in the unconditional variance of the series.

On the other hand, a well-documented literature shows that the causality relation between crude oil markets changes over time, and the presence of time-varying causality relation should therefore also be considered (Arouri et al., 2010; Lu et al., 2014; Çevik et al., 2018). In other words, the presence of causal links in the crude oil market tends to change over periods of recession and expansion. We thus also calculate the time-varying LM statistic by using the rolling GARCH model. The first step of the time-varying causality in variance test is to determine an appropriate rolling sample size. It should be noted that a very small rolling sample size leads to a convergence problem in the GARCH model, because the GARCH model estimation requires a large sample size. However, when the subsample is large, it can cause a longer lag effect in determining changes in Granger causality. Hence, we consider that the rolling sample size is 1000 days in the estimation of the rolling GARCH model.[2] Then, the time-varying LM test is calculated by using Hafner

[2] Ng and Lam (2006) examine the impact of sample sizes on the GARCH model estimation. They find that, if the sample size is less than 700, the maximum likelihood (ML) estimation procedure provides erroneous optimal solutions. The authors therefore recommend using a sample size of 1, 000 observations for the GARCH model estimation.

Table 1
Descriptive Statistics on WTI and Brent Daily Return Series: May 20, 1987 to August 3, 2020.

	WTI	Brent
Mean	0.008	0.010
Median	0.000	0.000
Max	42.583	41.202
Min	−42.363	−64.370
Std. Dev.	2.717	2.543
Skewness	−0.540	−1.860
Kurtosis	38.664	74.099
Jarque–Bera	45,930 [0.000]	1,795,500 [0.000]
ARCH(5)	403.66 [0.000]	244.13 [0.000]
$Q(20)$	123.752 [0.000]	193.026 [0.000]
$Q_s(20)$	6228.01 [0.000]	2217.18 [0.000]
ADF	−16.729***	−15.397***
PP	−95.284***	−91.124***
KPSS	0.059***	0.062***

Notes: The figures in square brackets show the probability (p-value) of rejecting the null hypothesis; ARCH(5) indicates the LM conditional variance test; and $Q(20)$ and $Q_s(20)$ indicate Box–Pierce serial correlation tests for the return and squared return series, respectively. *** indicates stationarity at the 1% significance level.

Table 2
Tests of Structural Breaks in Variance.

WTI: 8 Breaks	BRENT: 6 Breaks
21.05.1990	19.11.2012
22.03.1991	26.11.2014
25.11.1991	01.12.2016
8.01.1996	29.10.2018
26.06.2003	05.03.2020
08.04.2016	
05.03.2020	24.06.2020
30.04.2020	

and Herwartz (2006) test procedure (from step 1 through step 3) defined above for each rolling sample.

It should be noted that Rossi and Wang (2019) suggest a time-varying Granger causality test procedure that performs well in the case of instabilities. However, the procedure suggests examining causality in mean between the series. The testing methodology seems to be more suited to small sample sizes. In this paper, we examine time-varying Granger causality in variance using Hafner and Herwartz's procedure in a rolling sample. We report the results of Rossi and Wang (2019) procedure for Granger causality in mean for the overall sample in the Appendix.

4. Empirical results

We first calculate the logarithmic daily return series of WTI and Brent spot crude oil prices. The total number of observations is 8,501. We present the descriptive statistics for the return series in Table 1. The returns (daily percentage price changes) on WTI exhibit higher volatility than Brent for the overall sample according to the standard deviation criterion. All return series have negative skewness and high excess kurtosis, and these results suggest that the distributions of the return series are not normally distributed. The Jarque–Bera normality test confirms this finding. The null hypothesis of normality is strongly rejected. Box–Pierce Q-statistics suggest evidence in favor of autocorrelation in both returns and squared returns for WTI and Brent. LM test statistics show that the variances of all the return series are not constant, and ARCH effects are detected. We also find evidence in favor of stationarity for the return series according to augmented Dickey-Fuller (ADF), Phillips–Perron (PP), and the Kwiatkowski–Phillips–Schmidt–Shin (KPSS) tests.

We employ the modified ICSS test suggested by Sanso et al. (2004) to determine the presence of structural breaks in variance. The test results are presented in Table 2 and Fig. 2. Note that Panels (a) and (b) of Fig. 2 illustrate the return series for WTI and Brent prices, respectively, with the structural breakpoints and ± 3 standard deviations. The results in Table 2 indicate the existence of structural breaks in the variance of the return series. Overall, WTI daily return series has contained eight sudden change points, and Brent daily return series has six regime shifts in variance. Table 2 also shows that five out of eight breaks in the WTI return series occurred before 2008, while all breaks in the Brent return series occurred after 2008. The test results also imply the effect of COVID-19 pandemic on oil prices because we obtain a sudden change point at the beginning of March 2020.

When we examine the break dates for the variance of the WTI return series, the first period is related to the invasion of Kuwait in 1990 and the Iraq War in 1991. After the Gulf War, the volatility of oil prices significantly decreased until 1996. Still, it increased again between 1996 and 2003 due to several global imbalances (e.g., 1996–1997 Asian crisis, the 1998 Russian crisis, the dot.com bubble bursting in 2000, the 9/11 terror attack in 2001, and the second Iraq War in 2003). Fig. 2 shows that the volatility of the WTI decreased

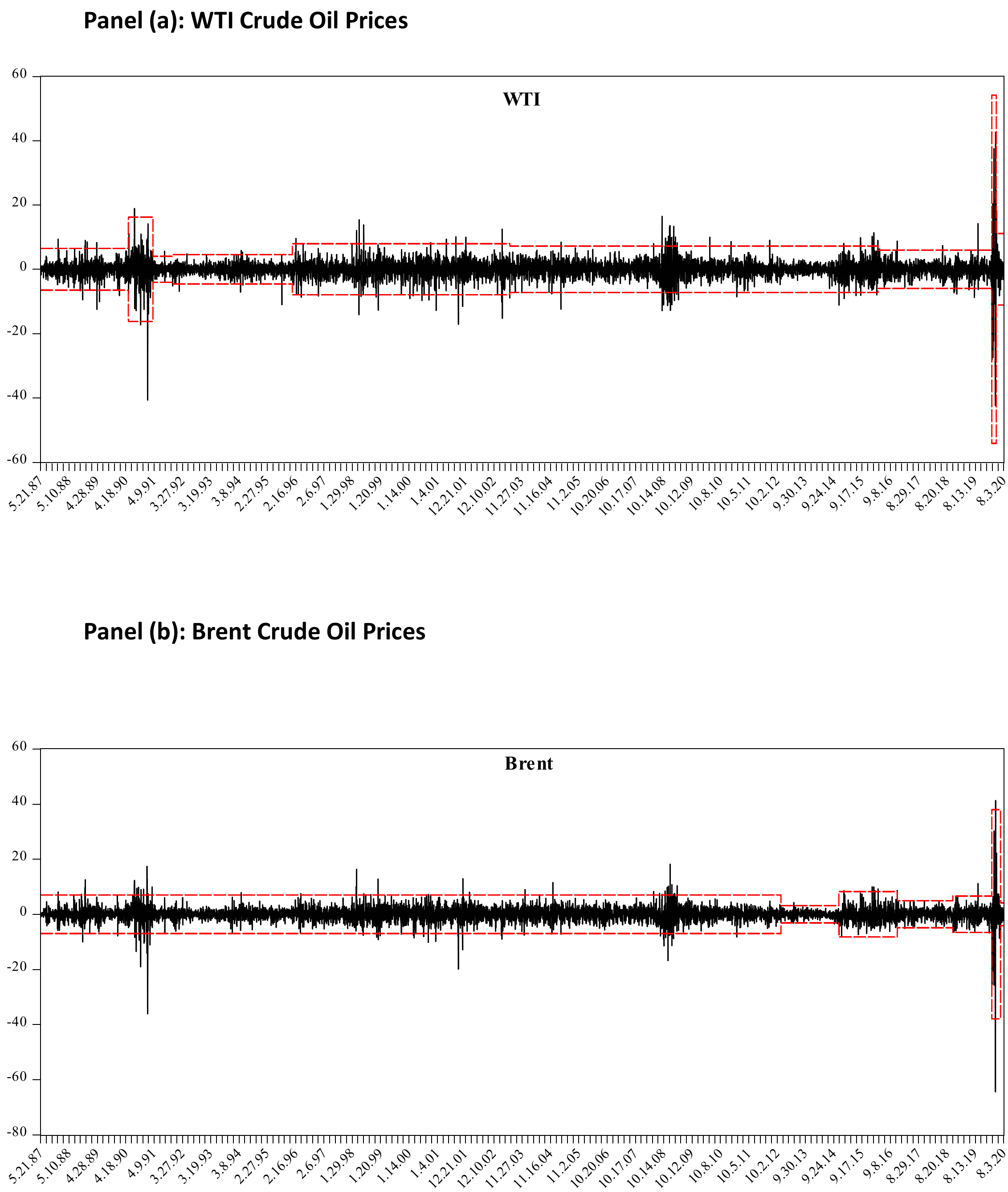

Fig. 2. Daily Return Series of WTI and Brent Crude Oil Prices (% change).
Panel (a): WTI Crude Oil Prices
Panel (b): Brent Crude Oil Prices

during 2004–2014, except for the GFC period. On the other hand, the results of the structural break tests for the Brent crude oil prices indicate that the variance of Brent is more stable than the variance of WTI. We do not detect a sudden change point before 2012. The results in Fig. 2 show that the volatility in oil prices significantly increases at the beginning of 2020 due to the COVID-19 pandemic. In this context, we determine two structural break points in the variance of both the WTI and Brent return series from March 2020 to August 2020. It is also noteworthy that the WTI oil future prices became negative in April 2020, falling to as low as near USD -40 on April 20, 2020. Using hourly price data from May 1, 2019, to May 12, 2020, Corbet et al. (2020) investigate the transmission of volatility shocks around the time of the negative WTI event across the energy sector and energy-focused corporations. Their results indicate positive volatility spillovers on coal and renewables.

Table 3
GARCH Model Results.

	WTI			Brent		
	Without dummies	With dummies	With significant dummies	Without dummies	With dummies	With significant dummies
ω	0.079 [0.000]	0.096 [0.000]	0.086 [0.000]	0.052 [0.000]	0.081 [0.000]	0.080 [0.000]
α	0.082 [0.000]	0.069 [0.000]	0.069 [0.000]	0.080 [0.000]	0.076 [0.000]	0.077 [0.000]
β	0.906 [0.000]	0.911 [0.000]	0.912 [0.000]	0.911 [0.000]	0.907 [0.000]	0.907 [0.000]
ν	1.259 [0.000]	1.353 [0.000]	1.352 [0.000]	1.289 [0.000]	1.298 [0.000]	1.296 [0.000]
d_1		0.729 [0.000]	0.724 [0.000]		−0.052 [0.000]	−0.051 [0.000]
d_2		−0.047 [0.174]	−0.050 [0.072]		0.118 [0.021]	0.119 [0.021]
d_3		−0.047 [0.071]	−0.050 [0.002]		−0.011 [0.607]	
d_4		0.097 [0.005]	0.094 [0.000]		0.057 [0.118]	0.060 [0.096]
d_5		0.003 [0.880]			−0.879 [0.075]	−1.151 [0.003]
d_6		0.003 [0.914]			−0.196 [0.138]	
d_7		22.041 [0.002]	21.991 [0.002]			
d_8		−0.189 [0.090]	−0.192 [0.077]			
AIC	4.307	4.302	4.301	4.197	4.194	4.194
SBIC	4.320	4.322	4.320	4.211	4.213	4.211
HQ	4.311	4.309	4.308	4.201	4.201	4.200
Ln(L)	−18268.45	−18239.43	−18239.44	−17979.87	−17780.52	−17781.88
Q **(50)**	42.817 [0.754]	42.859 [0.753]	42.859 [0.753]	56.958 [0.232]	56.483 [0.246]	58.854 [0.234]
Q_s **(50)**	51.452 [0.417]	53.519 [0.341]	53.542 [0.340]	51.130 [0.429]	62.241 [0.115]	65.516 [0.069]

Note: The figures in square brackets show the p-values; ν indicates GED parameter, and d_i is the dummy variable corresponding to the structural breaks; $Q(50)$ and $Q_s(50)$ indicate Ljung–Box serial correlation test values for the return and squared return series, respectively; and AIC, SBIC, and HQ indicate the Akaike, Schwarz, and Hannan–Quinn model information criteria, respectively.

Table 4
Causality in Variance Test Results.

Causality direction	Breaks ignored	Breaks accounted for dummies	Breaks accounted for significant dummies
WTI →Brent	32.606 [0.000]	36.757 [0.000]	37.453 [0.000]
Brent → WTI	11.750 [0.002]	2.618 [0.270]	2.585 [0.274]

Notes: → indicates the direction of causality. The figures in square brackets show the p-values.

It should be noted that the structural break test results are slightly different from those in previous studies, specifically in terms of detecting the effect of the GFC. The reason for that is closely related to sample size. The results in Fig. 2 show that the volatility process of oil prices is very similar for the period of 1995–2010. Note that we use a more extended period than those employed by earlier studies that focus on structural breaks in the variance of oil prices. These results indicate that the modified ICSS procedure is very sensitive to sample size, and this finding also shows the importance of investigating time-varying relations between variables.

The empirical studies that examine the impacts of variance breaks on the GARCH model show that the presence of structural breaks leads to an upward bias in the estimation of the GARCH parameters. This finding is significant for the causality in variance test, because the testing procedure depends on the unbiased estimation of the GARCH parameters. We thus follow Lamoureux and Lastrapes (1990); Aggarwal et al. (1999); Arago-Manzana and Fernandez-Izquierdo (2007); Wang and Thi (2007), and Ewing and Malik (2010) and include the dummy variables according to the structural breaks dates in the variance equation of the GARCH model to account for the effects of structural breaks in the model estimation.

After confirming the presence of ARCH effects in the return series, we employ a GARCH model and find GARCH(1,1) to be the best. It should be noted that the AIC is considered to determine the lag length for the autoregressive–moving average structure in the mean equation. We present the GARCH model results in Table 3. We estimate three different GARCH models for each return series. Although we do not take structural breaks into account in the first model, we use dummy variables for the structural breaks in the variance equation in the second model. We follow Hammoudeh and Li (2008) and Wang and Moore (2009) and consider only statistically significant dummy variables in the last model. This allows us to examine more clearly the effects of structural breaks on the causality in variance test.

The results of the model estimations in Table 3 show that the GARCH parameters (α and β) are statistically significant at the 1% level, where the α and β parameters indicate the persistence of shocks and persistence in volatility clustering, respectively. In addition, when the sum of α and β is greater than unity, the effects of shocks on volatility never die out. The results in Table 3 indicate that the breaks in variance cause the overestimation of GARCH parameters. Specifically, when the structural breaks are taken into account in estimating the GARCH model, significant decreases are observed in the sum of the α and β parameters. Note that this finding is similar to the empirical result of Kang et al. (2011), because, when the authors take breaks in variance into account, the persistence in volatility is significantly reduced.

We present the causality in variance test results in Table 4. In addition to the GARCH model results, three different LM statistics are calculated for each pairwise causality relation. According to the results in Table 4, bidirectional volatility spillovers between WTI and Brent is determined at the 1% significance level when the breaks in variance are not taken into account. We find that the results

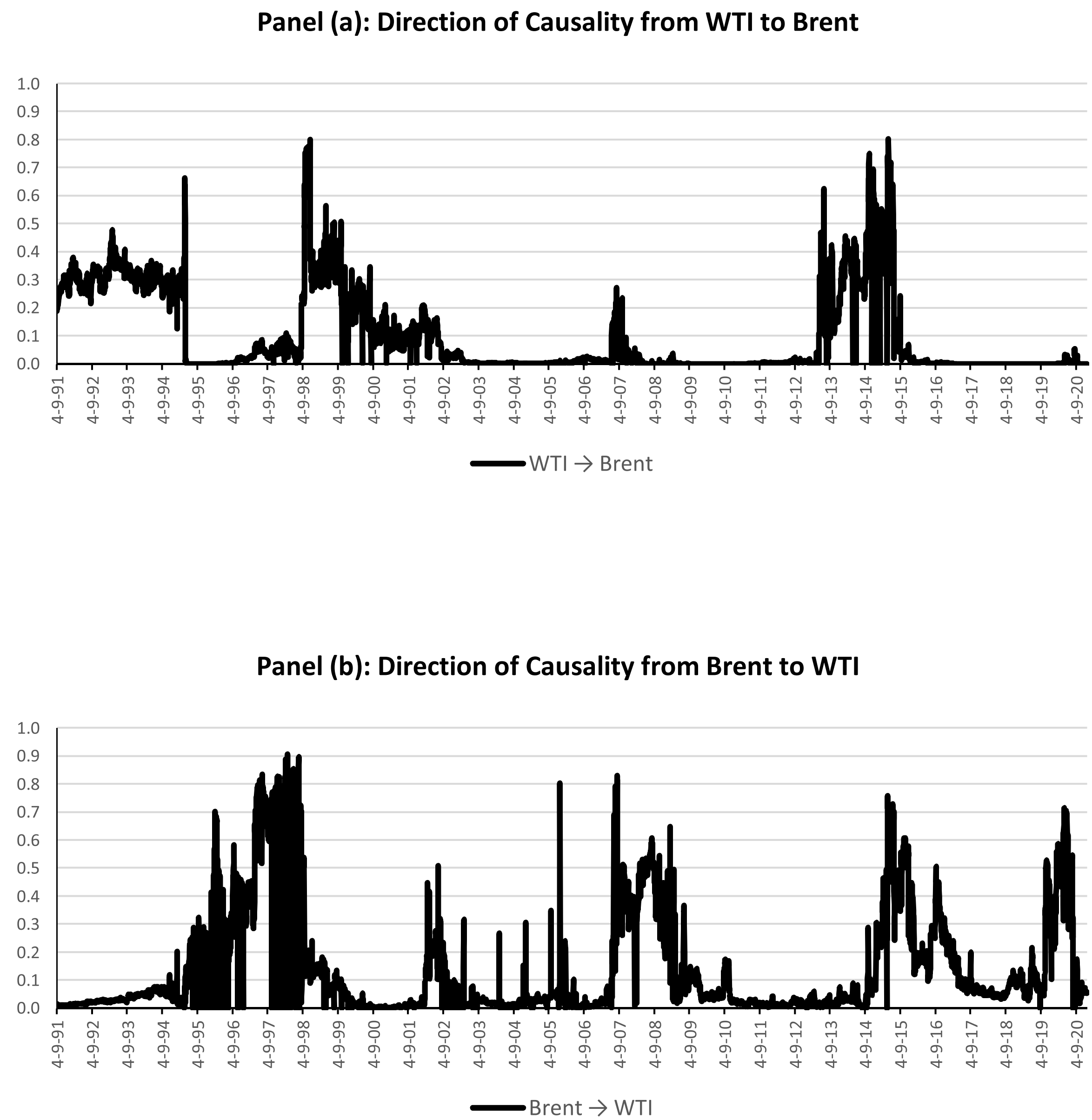

Fig. 3. Time-Varying Causality in Variance Test Results.
Panel (a): Direction of Causality from WTI to Brent
Notes: → indicates the direction of causality relation. The vertical axis shows the *p*-value of rejecting the null hypothesis that the WTI price volatility does not Granger-cause Brent price volatility.
Panel (b): Direction of Causality from Brent to WTI
Notes: → indicates the direction of causality relation. The vertical axis shows the *p*-value of rejecting the null hypothesis that the Brent price volatility does not Granger-cause WTI price volatility

favoring a bidirectional causal link between Brent and WTI are consistent with the literature. Coronado et al. (2017) find bidirectional causality in mean between Brent and WTI. In addition, Lu et al. (2008) and Lu et al. (2014) determine bidirectional information spillovers between Brent and WTI. Moreover, Lu et al. (2014) argue that Brent and WTI are the leading commodities, compared to the other crude oils, and that neither WTI nor Brent can dominate the other.[3]

[3] We use Rossi and Wang's (2019) time-varying Granger causality in mean test, which is invariant to instabilities, and monthly data. The trimming parameter is selected as 15% in performing the time-varying causality test. The results indicate bidirectional Granger causality between Brent and WTI oil prices throughout the sample, in line with earlier findings in the literature. The test results and graphics are shown in the Appendix (Table A1, Fig. A1, and Fig. A2).

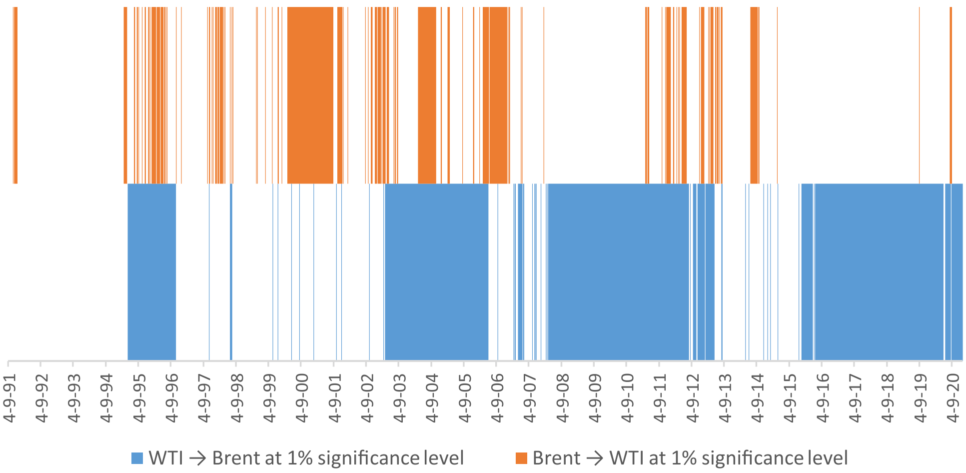

Fig. 4. Granger Causality in Variance over Time between WTI and Brent Spot Oil Prices at the 1% Level of Significance.
Note: The lower part of the figure shows instances of WTI price volatility Granger-causing Brent price volatility. The upper part shows instances of Brent price volatility Granger-causing WTI price volatility.

However, when we consider structural breaks, although WTI Granger-causes Brent in variance at the 1% significance level, we cannot reject the null hypothesis of no causal link from Brent to WTI at any conventional significance level. The causality test results imply the presence of unidirectional volatility spillovers from WTI to Brent, where WTI has an edge over Brent, consistent with the empirical findings of Lu et al. (2008). It should be noted that the effect of structural breaks on volatility spillovers has been argued by Kang et al. (2011), who determine the presence of bidirectional volatility spillovers between WTI and Brent when they do not take into account structural breaks in variance. However, when structural breaks in variance are considered in the GARCH model estimation, only the volatility spillover from WTI to Brent is found to be statistically significant. As argued by Kang et al. (2011), structural breaks in variance lead to a spurious volatility spillover effect.

Given the potential regime changes in the crude oil markets, a time-varying analysis is warranted. Furthermore, as indicated above, the modified ICSS procedure is very sensitive to sample size, which demonstrates the importance of investigating time-varying relations between the variables. Therefore, we also employ time-varying causality in variance tests to investigate the dynamic relation between the crude oil return series by using rolling subsamples. It can be said that time-varying causality in variance test results are robust when there is instability in the data. Note that we present the probability (*p*-values) of rejecting the null hypothesis on the vertical axes in Fig. 3, in Panels (a) and (b).[4]

Although, according to the results in Table 4, the presence of unidirectional causality relation is determined, Panels (a) and (b) of Fig. 2 provide evidence that the dynamic relations in the crude oil market vary over the subsamples, consistent with the empirical findings of Lu et al. (2014). For instance, the null hypothesis of no causality in variance from WTI to Brent cannot be rejected until 1995. On the other hand, we determine a causal link from WTI to Brent in 1995. After that, the causality relation becomes insignificant, and the null hypothesis cannot be strongly rejected for 1996–2002. After 2002, we determine that WTI is the Granger cause of Brent until 2013. Although the estimated probabilities to reject the null hypothesis are significantly increased for 2013–2015, the presence of a volatility spillover effect from WTI to Brent is determined after 2015.

In Panels (a) and (b) of Fig. 3, the vertical axis indicates the statistical significance level of the Granger causality test results in the rolling samples. Hence, when the line is closer to zero, it shows the presence of Granger causality in variance for the period in question. For instance, from April 1991 till about April 1995, there is no volatility spillover from WTI to Brent at conventional (1 % and 5 %) statistical significance levels. Nevertheless, Fig. 3, Panel (b), shows that, for the same period, there exists volatility spillover from Brent oil prices to WTI oil prices, at least at the 10 % level of statistical significance. The qualitative conclusion is, then, the detection of unidirectional Granger-causal volatility spillover from Brent oil prices to WTI oil prices from April 1991 to April 1995. The remainder of the results depicted in Fig. 3 (Panels (a) and (b)) can be interpreted using similar logic. For instance, the results for the most recent period since about mid-2015 until now indicate that it is rather the WTI price volatility that Granger-causes Brent price volatility. A unidirectional Granger-causal relation from the volatility in WTI oil prices to the volatility in Brent oil prices has been detected mostly in the last four years.

The time-varying results show that the interconnectedness between the two major crude oil markets broke down when global imbalance rose (e.g., for the periods 1996–2002, 2007–2009, and 2013–2015). The null hypothesis of no volatility spillover can seldom be rejected in these periods. On the other hand, we find that WTI oil prices had the edge over Brent oil prices during the GFC, because we find volatility spillovers only from WTI to Brent during that period.

[4] We also consider that the rolling sample size is 1,500 days in the estimation of the rolling GARCH model and obtain almost similar results. The results are available upon request.

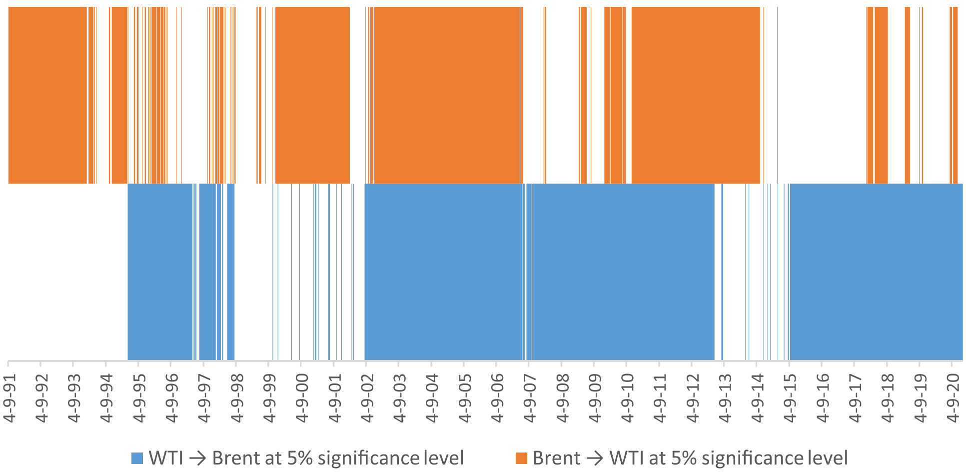

Fig. 5. Granger Causality in Variance over Time between WTI and Brent Spot Oil Prices at the 5% Level of Significance.
Note: The lower part of the figure shows instances of WTI price volatility Granger-causing Brent price volatility. The upper part shows instances of Brent price volatility Granger-causing WTI price volatility.

Although it is possible to gain a general understanding of the volatility spillover relations between WTI and Brent oil prices through a visual examination of Fig. 3, a more precise depiction of the findings at the 1% and 5% statistical significance levels necessitates the construction of additional graphs. In Figs. 4 and 5, we indicate the periods when WTI oil price volatility Granger-causes Brent oil price volatility separately in the upper and lower graphs. Fig. 4 shows the results at the 1% level of statistical significance and Fig. 5 shows the results at the 5% level of statistical significance.

According to Fig. 4, between 1991 and mid-2002, except for a brief period in 2005, any Granger causality in volatility spillovers between WTI and Brent was from the Brent to the WTI prices. Nevertheless, no Granger-causal relation is detected between late 1991 and the end of 1994, and there is mostly no Granger causality between WTI and Brent price volatility between 1996 and 1999 at the 1% level of statistical significance.

From 2002 until the beginning of 2007, there is mostly a feedback relation between WTI and Brent crude oil price volatility, with WTI price volatility having more effect on Brent price volatility than the Brent price volatility's effect on WTI volatility. During this period, oil prices greatly increased, from about $20 per barrel to about $150 per barrel. The feedback relation appears to break down during the GFC. We find unidirectional volatility spillovers from WTI to Brent during and after the GFC. As the world economy starts to recover from the deep recession, we again observe volatility spillover effects from Brent oil prices to WTI oil prices. Still, the main volatility spillover effects are from WTI oil prices to Brent oil prices since 2015 until the end of our sample period (August 3, 2020).

In Fig. 5, we examine the timeline of the Granger-causal volatility spillovers between WTI and Brent crude oil prices at the 5% significance level. The findings are qualitatively similar to those found at the 1% significance level, but we see greater feedback effects from Brent to WTI oil price volatility at the 5% significance level. The results from the more recent period, from 2015 till February 2019, however, do not change the finding that the volatility in WTI oil prices Granger-causes volatility in Brent oil prices.

Fig. 1 previously showed a significant increase in the WTI–Brent spot crude oil price spreads during and after the GFC. The results in Tables 1 and 2 showed that the volatility in oil prices and price spreads increased substantially during and after the GFC as well. Combining the results from Figs. 1,4, and 5, it can be said that, when the WTI–Brent price differential was highest, in 2012–2014, the volatility increase in Brent prices Granger-caused the volatility increase in WTI prices. As the price differentials started to drop, the Granger causality from Brent prices to WTI prices also disappeared. The presence of a Granger-causal link from Brent price volatility to WTI price volatility is also suggested in earlier periods, such as in 1991–1992, the early-2000s, and during the GFC. Hence, it could be said that, when volatility in oil prices is low or returning to normal levels, the volatility spillovers (if any) run from WTI to Brent oil prices; however, during episodes of higher oil price volatility, Granger causality also exists from Brent price volatility to WTI price volatility.

5. Conclusions

This paper investigates the Granger-causality patterns in volatility (Granger causality in variance) between WTI and Brent crude oil prices. WTI and Brent crude oil have similar chemical compositions, both being classified as sweet crude oil, and they are considered to be close substitutes. Hence, from the financial and commodity markets' perspective, there should not be large differences between the prices per barrel of these two sweet crudes, except for transportation costs or other factors that influence the immediacy of their regional demand and supply. Nevertheless, the history of price differentials between WTI and Brent show various periods where substantial price differences between WTI and Brent are observed. A large increase in the volatility of oil prices also occurred during and after the GFC. The literature on price differentials between Brent and WTI crude oil prices has mostly focused on the levels of the crude oil price series. Only a handful of papers have investigated the causal relations between the volatility of Brent and WTI crude oil

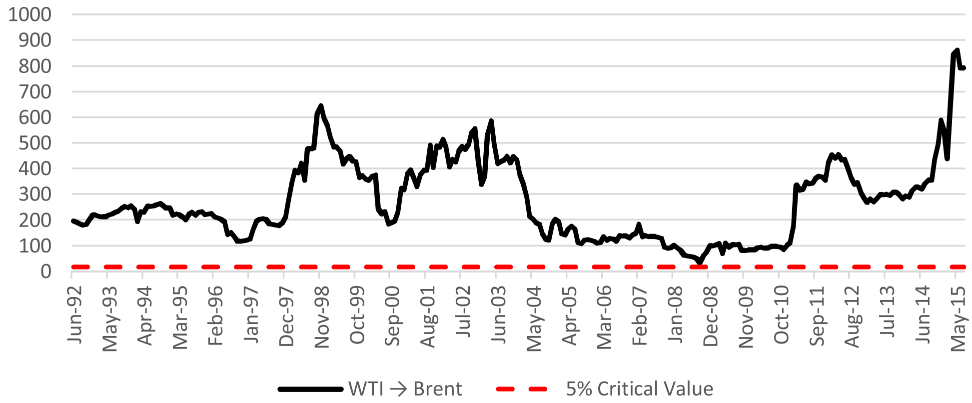

Fig. A1. Time-Varying Wald Statistics: Granger Causality in Mean from Brent to WTI.

prices.

In this paper, we aim to contribute to the literature by analyzing the Granger-causal relations in the variance of the WTI and Brent crude oil price series using Hafner and Herwartz (2006) test for Granger causality in variance, which is known to be rather robust to the selection of lags and leads in the model specification. We use daily data from May 20, 1987, to August 3, 2020. We also use a 1000-day rolling-sample approach to examine the changes in the dynamics of Granger-causal volatility spillovers between WTI and Brent oil prices.

Our test results indicate that unidirectional volatility spillovers from WTI to Brent oil prices are found to occur more frequently, especially at the 1% level of statistical significance. We also find that volatility spillover from Brent to WTI prices is more pronounced at the beginning of the analysis period and during and in the aftermath of the GFC. Between 2015 and 2019, the direction of volatility spillovers runs unidirectionally from WTI to Brent oil prices. Nevertheless, the COVID-19 shock in 2020 has led to the reappearance of a Granger-causal feedback relation in the volatility spillovers of WTI and Brent crude oil prices. This is due to the uncertainty surrounding the magnitude and duration of the COVID-19 environment in which market participants react to signals on both crude oil types.

In-depth understanding of the Granger-causal relations involving the volatility of oil price series can have important consequences from economic, financial market, and pricing perspectives. On the financial market side, commodity traders and option pricing models can integrate this information into their calculations. Since we use daily data, the findings of this paper could be especially useful for commodity traders. As shown by recent studies, the use of social media and Google searches can influence the behavior of actors in the financial markets. In our case, for instance, if traders or other financial markets players become concerned about crude oil prices in general, the increased volatility will reflect itself in both WTI prices and Brent prices without clear causal precedence. This situation is in contrast to the period after 2015 but before the start of the COVID-19 pandemic in early 2020. We find a structural break in oil prices in March 2020. Our findings from rolling causality in variance tests indicate that this structural break also led to a change in the nature of the Granger-causal volatility spillovers between WTI and Brent crude oil prices. Further research is needed to understand the instability in Granger causality patterns. Determining the thresholds for different levels of extreme volatility movements and their causal effects on other economic and financial variables is important for financial market participants and policymakers in oil-importing countries, as well as policymakers in oil-exporting countries.

Authorship contributions

All authors have equally contributed to the paper.

Appendix A

Notes: → indicates the direction of causality relation. The dashed line is the critical value at the 5% significance level. The vertical axis shows the time-varying test statistics.

Notes: → indicates the direction of causality relation. The dashed line is the critical value at the 5% significance level. The vertical axis shows the time-varying test statistics.

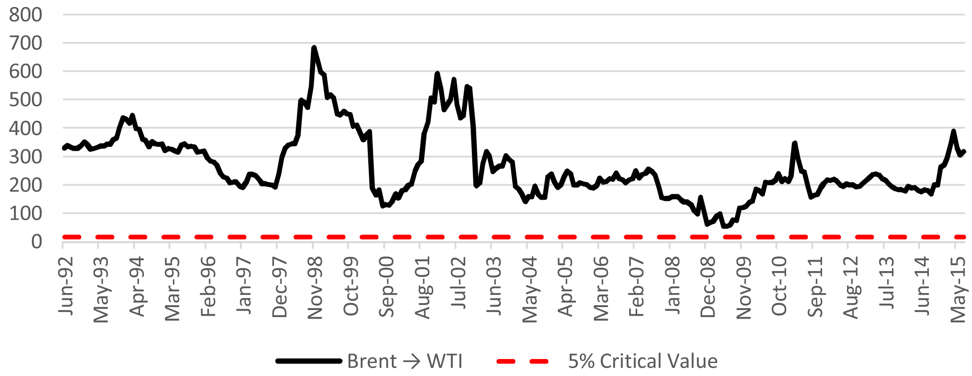

Fig. A2. Time-Varying Wald Statistics: Granger Causality in Mean from Brent to WTI.

Table A1
Wang and Rossi's (2019) Time-Varying Granger Causality-in-Mean Test Results.

	ExpW	MeanW	Nyblom	SupLR
WTI → Brent	425.764 [0.000]	273.989 [0.000]	6430.966 [0.000]	862.735 [0.000]
Brent → WTI	336.212 [0.000]	268.385 [0.000]	24954.644 [0.000]	683.669 [0.000]

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