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The Impact of Covid-19 on Oil Market Returns: Has Market Efficiency Being Violated?

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ABSTRACT

This study examines the effect of COVID-19 pandemic on the efficiency of oil markets from February 2nd, 2020 to August 4th, 2021. By relying on dynamic conditional correlation GARCH and Wavelet coherence techniques, we able to provide correlations between the variables across time and frequency domains. Our empirical findings point to significant yet weak correlations between COVID-19 recovery/death rates for the time period extending from early February to early May even though we observe strong correlations between WTI prices and COVID-19 health statistics in mid-April. Moreover, during this identified time period, the length of frequency cycles within the correlations decreases from 16 days to 8 days. Altogether, these findings imply that oil markets were inefficient between February and early May and have since turned market efficient for the remaining duration of the pandemic.

Keywords: DCC-GARCH, Wavelet Coherence, WTI, Brent, OPEC, Efficiency Market Hypothesis, COVID-19
JEL Classifications: C02, C22, G14, G15

1. INTRODUCTION

The role which oil markets play in ensuring overall global stability cannot be overemphasized and this has recently been demonstrated during the ongoing coronavirus pandemic. Take for instance, the US stock market crash experienced in mid-April 2020 which was a direct result of the historical collapse of WTI prices and expiring WTI futures contracts in the midst of a geopolitically-induced oil price war between Saudi Arabia and Russia (Jefferson, 2022; Hanieh, 2021; Ma et al., 2021). Initially, energy markets were the most affected sectors during the early stages of the pandemic with market prices declining by over 60% (Albulescu, 2020) and via contagion effects resulted in adverse spillovers into international equity and currency markets (Elgammal et al., 2021; Ghorbel and Jeribi, 2021; Jababli et al., 2021), which, in turn, led to heightened financial market panic and distorted global investor sentiments (Salisu et al., 2020; Chen et al., 2021; Shaikh, 2021). Since irrational behaviour by investors arising from financial market distress contradicts the efficient market hypothesis of Fama (1970), many academics have re-ignited the classical debate on information efficiency of financial markets in context of the COVID-19 pandemic (Al-Awadhi et al., 2020; Aslam et al., 2020; Dima et al., 2021; Kakinaka and Umeno, 2021; Navratil et al., 2021; Vasileiou, 2021; Wang and Wang, 2021) and yet it remains surprising that very little attention has been paid to examining the efficiency of oil markets during the periods of the pandemic.

Our study examines market efficiency in international oil markets during the COVID-19 pandemic and we consider this to be an important empirical exercise as it bears substantial implications for investors, portfolio managers, market regulators as well as global policymakers. From the perspective of risk management and optimal portfolio design, market participants such as investors and portfolio managers would be interested in knowing whether oil markets are informationally efficient since oil has been found to be an effective hedge in diversifying risk against equity markets (Ali et al., 2021; Batten et al., 2021; Mandaci and Kirkpinar, 2021; Abuzayed et al., 2022), precious metals and agricultural commodities (Hernandez et al., 2019; Naeem et al., 2022), conventional currencies (Olstad et al., 2020; Liu, 2022), cryptocurrencies (Okorie and Lin, 2020; Moussa et al., 2021) as well as political risk (Bouoiyour et al., 2019) particularly during periods of financial turmoil and distress. On the other hand, market regulators need to be assured that information is rapidly absorbed into oil prices and this is important for reducing the scope of speculative investment behaviour geared towards making abnormal profits as well as for preventing the build-up of market bubbles in oil markets (Gharib et al., 2021). Moreover, international policymakers should be concerned with state of efficiency of oil markets as the pandemic has intensified global efforts to shift from dirty energy use to cleaner renewable sources which could distort demand and supply factors in energy markets through declining demand, technological-led supply response, intense competition, and investor scepticism; all which pose a threat to the stability of oil markets (Masnadi et al., 2021; Halttunen et al., 2022). In this sense, ensuring informational efficiency within oil markets is important for navigating the world into a "greener earth" without compromising the stability of commodity markets.

Whilst we acknowledge the existence of many previous studies which have investigated market efficiency in oil markets, it is interesting to note that most of these studies exclusively focus on weak-form informational efficiency, that is, examining whether past historical information can be used to predict future oil returns by subjecting the time series to tests for random walk behaviour (Ghazani and Ebrahimi, 2019; Ghazani and Jafari, 2019; Shao, 2020; Arshad et al., 2021). Moreover, only the works of Gil-Alana and Monge (2020), Mensi et al., (2020) and Okoroafor and Leirvik (2022) have examined weak-form informational efficiency in oil markets for periods covering the COVID-19 pandemic. Notably, a handful of recent studies have further investigated semi-strong form market efficiency in financial markets during the pandemic by examining whether COVID-19 statistics help to predict international equity market returns at national level (Ashraf, 2020; He et al., 2020; Liu et al., 2020; Rakshit and Neog, 2021; Xu, 2021) or at industry/firm level (Alfaro et al., 2020; Mazur et al., 2021; Narayan et al., 2021). However, to the best of our knowledge, there are no previous studies which have examined semi-strong-form informational efficiency in oil markets by testing the predictability of COVID-19 statistics on oil returns.

Our study contributes to scientific literature by treating the coronavirus pandemic as a natural experiment to investigating semi-strong form market efficiency in oil markets, that is, we question whether publicly available COVID-19 health statistics (cases, recoveries, and deaths) can be used to predict oil returns in OPEC, Brent and WTI markets. To test this hypothesis, we examine dynamic correlations between the time series and make use of dynamic conditional correlation generalized autoregressive conditional heteroscedasticity (DCC-GARCH) and complex wavelet coherence as empirical frameworks.

On one hand, we use DCC-GARCH model to capture time-varying relationship between COVID-19 statistics and oil returns and this allows us to examine whether oil markets switch between being efficient and inefficient at different time periods as speculated by the adaptive market hypothesis (AMH) of Lo (2004). Recent evidence of time-varying informational efficiency in oil markets is provided in the studies of Ghazani and Ebrahimi (2019), Ghazani and Jafari (2019), Shao (2020), Arshad et al., (2021) and Okoroafor and Leirvik (2022) albeit these previous works strictly focus on weak-form market efficiency and establish time-variation for periods prior to the COVID-19 pandemic.

On the other hand, we make use of complex wavelet coherence techniques which allows us to decompose the time series along a time-frequency space and thereafter yield localized time-frequency information on the series. This differs from econometrical tools such as the DCC-GARCH in which the framework is strictly localized in time and therefore provides little to no information on the frequency components. Distinguishing between the different cyclical components in oil market efficiency is important for capturing for the heterogenous activity of different market participants who base their decisions across different frequency horizons. For instance, speculative traders and myopic investors would be interested in obtaining public information related to shorter time horizons where the time series data is characterized by higher frequency oscillations. Conversely, long-term, or safer investors would be more concerned with long-term or lower frequency variations between COVID-19 information and oil returns.

All-in-all, our study enriches the current knowledge of time-varying and cyclical varying informational efficiency in oil markets using more recent data covering the COVID-19 pandemic. Interestingly, both DCC-GARCH and Wavelet coherence analysis mutually show that the oil markets has been generally market inefficient with respect absorbing information from COVID-19 cases and deaths, and less so for recoveries. Moreover, both analyses provide similar evidence of time-variation in oil market (in) efficiency which can be summarized in two points. Firstly, we mutually find that semi-weak market efficiency was most compromised during the periods of the initial announcement of the pandemic by the WHO in early March, during the oil and stock market crashes in mid-April as well as during the emergence of the Delta variant which marks the beginning of the second wave of the pandemic. Secondly, we find that during periods corresponding to intervention of global policymakers in financial markets; the US diplomatic intervention into the oil price-war in mid-April; as well as during the start of the vaccines, market efficiency is improved. Altogether these findings bear important implications for different stakeholder in oil markets.

The remainder of our study is structured as follows. Section 2 presents a review of the associated literature. Section 3 outlines the DCC-GARCH, and wavelet coherence methods used in our empirical analysis. Section 4 presents the empirical findings whereas section 5 concludes the study in the form of policy implications.

2. LITERATURE REVIEW

Theoretically, efficient market hypothesis (EMH) developed by Fama (1970) stipulates that asset prices reflect all the available information and therefore precludes any likelihood of investors earning abnormal returns. In this context, assets prices adjust with the arrival of new information to reflect the real value of the asset. This theory categorises market efficiency into three forms based on the type of information incorporated in the asset price namely the weak, semi-strong and strong form efficiency. The weak form efficiency holds that future price of an asset cannot be predicted based on the past and current price movements. This implies that future price changes are independent of past and current price changes, and it assumes that future price movements follow a random walk process. The semi-strong efficiency holds that an asset price should reflect all publicly available information and that investors cannot earn abnormal returns by relying on any publicly available information. In term of strong form efficiency, the theory holds that private information in addition to historical and public information are reflected in the market price of an asset.

Earlier criticism of the EMH in literature is taken from Grossman and Stiglitz (1980), LeRoy and Porter (1981) and Shiller (1981). Grossman and Stiglitz (1981) point to the cost of obtaining information in their rejection of the EMH. LeRoy and Porter (1981) and Shiller (1981) argue that excess volatility of stock prices provide enough information to invalidate the EMH. Furthermore, as alluded to by Lo (2004), the EMH has be criticised by authors in fields such as Behavioural Economics, Psychology and Sociology who outline departures from the standard assumptions in Mainstream Economics with regards to preferences and behaviour of market participants. Specifically, critics argue that there is behavioural bias (irrational behaviour) among market participants in the event of uncertainty, which invalidates the EMH. Lo (2004) advocates for the Adaptive Market Hypothesis (AMH) as an alternative to the efficient market hypothesis, which suggests the co-existence of both market efficiency and inefficiency.

Empirically, a number of studies have investigated whether the EMH applies to the crude oil market by focusing on weak-form efficiency. Studies by Charles and Darné (2009), Chen et al., (2020), Mensi et al., (2012), Lin et al. (2014), Mensi et al. (2014) as well as Arshad et al., (2021) found evidence that support the EMH. Charles and Darné (2009) investigated the weak-form efficient market hypothesis for the UK Brent and US WTI and found that brent crude oil is characterised by weak-form efficiency while the WTI oil market was found to be inefficient during the period 1994-2008. Chen et al. (2020) assessed the efficiency of the newly developed crude oil futures market in China and found support for weak-form efficiency in the Shanghai International Exchange (INE) crude oil futures. Mensi et al., (2012) found evidence of weak-form market efficiency for crude oil (WTI and Europe brent) between the period May 1987 and March 2012. Lin et al. (2014) found evidence of market efficiency in 13 energy markets thus supporting the efficient market hypothesis. Furthermore, technical analysis was thus found to be ineffective in improving the prospects of making higher profits. Mensi et al., (2014) found evidence of weak-form efficiency in both WTI and brent crude markets. Arshad et al., (2021) found that the benchmark crude oil prices follow the weak-form efficiency for the period 1996-2018. Furthermore, the authors reported improvements in the efficiency of the oil market in the short-term compared to the long-term.

Some studies reported that efficiency in the oil market is dependent on financial stability. Ortiz-Cruz et al. (2012) investigated the efficiency of crude oil markets during the period January 1986 to March 2011 and found that the crude oil market is efficient over the selected sample period. However, efficiency decreased during the late 1990s and late 2000 s due to the financial crises. Zhang (2013) investigated weak-form efficiency in crude oil markets. The author concluded that crude oil markets exhibit week-form efficiency in the long-term. However, the degree of efficiency is dependent on the time period. Ftiti et al. (2021) investigated the weak-form efficiency in oil and gas prices during stable and crisis periods using multifractal approach. The study found that oil and gas markets are inefficient for horizon less than two weeks but become efficient after two weeks. In addition, the oil and gas markets displayed increased multifractal behaviour during the post-crisis period.

Also, Jiang et al. (2014) investigated the weak-form efficiency of the WTI crude oil futures market for the period 1983-2012 and reported that the crude oil market is efficient when the entire sample is considered. However, the market was inefficient during periods of instability such as the Gulf war, Iran war and the oil price crash of 2008. Zhang et al. (2014) investigated the weak-form efficiency of crude oil spot markets in Europe, US, UAE and China during the period December 2001 to August 2013 and found evidence of efficiency in all the four markets despite brief periods of inefficiency especially the 2008/2009 global financial crisis.

However, studies by Górsha and Krawiec (2016), Ghazani and Ebrahim (2019), Shao (2020), Ghazani and Jafari (2021) and Okoroafor and Leirvik (2022) found evidence which refutes the EMH. Górsha and Krawiec (2016) investigated the weak-form efficiency hypothesis in the crude oil market during the period 2000-2015 and failed to find evidence to support the hypothesis. Ghazani and Ebrahimi (2019) employed the automatic portmanteau and generalised spectral test to investigate the presence of the adaptive market hypothesis (AMH) in crude oil prices. The authors found evidence of the AMH, an alternative to the efficient market hypothesis, which suggests the co-existence of both market efficiency and inefficiency in a consistent manner. Ghazani and Jafari (2021) also confirmed that the oil market is best explained by the AMH. Shao (2020) found evidence of improvements in the oil market after the lifting of the ban on US oil exports. Furthermore, crude oil market is characterised inefficiency in the short-term, although the weak-form hypothesis holds in the long-run. Okoroafor and Leirvik (2022) found evidence of time-varying efficiency in crude oil markets which supports the AMH. Furthermore, the efficiency of the brent crude market has improved compared to that of the WTI market during the period May 1987 till September 2020.

A number of studies investigated the effect of the COVID-19 pandemic on the efficiency of the oil market. Narayan (2020) found that the COVID-19 pandemic contributed 30% towards oil price clustering behaviour which is an indication of market inefficiency. Furthermore, clustering during the COVID-19 period is 8% more compared to the pre-pandemic period Mensi et al., (2020) found that before the COVID-19 pandemic the oil market was inefficient during periods of upward trends in the price. However, during the period of the COVID-19 pandemic the oil market was inefficient during the downward trends in the price. Overall, the COVID-19 pandemic had a negative impact on oil market efficiency. Gil-Alana and Monge (2020) reported evidence of market efficiency in its weak-form for crude oil prices before the COVID-19 pandemic. However, there is evidence of some inefficiency during the period of the pandemic which is expected to be transitory.

Tudor and Anghel (2021) examined the efficiency of the crude oil market by investigating the predictive performance of technical analysis trading rules (TTR) for the period 1999-2021. The authors found that weak-form efficiency is applicable to the WTI crude oil market as TTRs have no effect on the oil market. However, there is evidence of temporal inefficiency in the oil market during the 1st year and quarter period of the COVID-19 pandemic. Usman and Akadiri (2021) confirmed the presence of weak-form efficient market hypothesis in oil markets for the period 1st January 2015 to 24th December 2020. However, it should be noted that the COVID-19 pandemic caused a significant increase in persistence of oil returns. Wang et al. (2022) investigated the effect of the COVID-19 pandemic on the energy market (WTI crude and coal). The authors found that market efficiency reduced significantly in the first quarter of 2020. Market efficiency improved in the second half of 2020 after the implementation of quantitative easing. Furthermore, in the early part of 2021 market efficiency deteriorated due to increased market risk.

Most studies in the literature examine the effect on the COVID-19 pandemic on oil markets, investigate the weak-form market hypothesis. Our study contributes to scientific literature by treating the coronavirus pandemic as a natural experiment to investigating semi-strong form market efficiency in oil markets for a longer time period. The study employs the DCC-GARCH and Wavelet coherence analysis as empirical frameworks and these are discussed in detail in the next section.

3. METHODOLOGY

The empirical approach employed in this paper composed of two frameworks, the DCC-GARCH model and wavelet coherence analysis. These two methodological approaches are discussed below.

3.1. DCC-GARCH Model

To analyze the time evolution of correlation between the global crude oil prices and COVID-19, this paper relies on a bivariate AR (1)-GJR-GARCH-DCC. As a first step, it is assumed that each series (r_t) follows an autoregression of order one, AR (1). This can be expressed as:

$$r_t = \mu + \theta r_{t-1} + \varepsilon_t \;\; \varepsilon_t \,|\Omega_{t-1} \sim N(0, H_t) \tag{1}$$

Where r_t denotes a vector of returns of the crude oil or change in COVID indicators. □ is constant vector. $r_{t\text{-}1}$ is the vector of past returns and $\square_t$ is a vector of error term conditional on past information Ω_{t-1} at time t–1. The conditional variance h_t follows the univariate GARCH mode proposed by Glosten et al. (1993) and it is expressed as:

$$h_{it} = \omega_i + \beta_i h_{i,t-1} + \alpha_i \varepsilon_{i,t-1}^2 + \gamma_i I_{t-1} \varepsilon_{i,t-1}^2 \text{ for } i = 1, \ldots n \tag{2}$$

Where h_t captures the conditional variance of each series. The parameters α and β are the ARCH and GARCH coefficients respectively. I_t is a dummy variable that takes the value of 1 if $\varepsilon_{it} < 0$ but 0 if otherwise, indicating the evidence of asymmetry in returns.

In the second step, the DCC model proposed by Engle (2002) is applied to provide time-varying correlation between crude oil and COVID-19 indicators. In DCC, the variance -covariance matrix (H_t) is define as:

$$H_t = D_t R_t D_t \tag{3}$$

Where $D_t = diag\left(h_{1t}^{1/2}, \ldots.., h_{2t}^{1/2}\right)$ is a diagonal matrix of time-varying conditional standard deviation derived from equation (2) R_t is the conditional correlation matrix which is given as:

$$R_t = [diag(Q_t)^{-1/2}] Q_t [diag(Q_t)^{-1/2}] \tag{4}$$

Where, $Q_t = \sqrt{q_{ij,t}}$ is the conditional covariance matrix of the standardised residuals, ε_t. The DCC model is given as:

$$Q_t = (1 - \alpha - b)\bar{Q} + \alpha \varepsilon_{t-1} \varepsilon_{t-1}^{'} + b Q_{t-1} \tag{5}$$

Where α and b are positive scalar parameters satisfying $\alpha + b < 1$ condition. The conditional correlation is expressed as:

$$\rho_{ij,t} = \frac{(1 - \alpha - b)\bar{q}_{ij} + \alpha \varepsilon_{it-1} \varepsilon'_{jt-1} + b q_{ijt-1}}{\sqrt{[(1 - \alpha - b)\bar{q}_{ii} + \alpha \varepsilon_{it-1}^2 + b q_{iit-1}] [(1 - \alpha - b)\bar{q}_{jj} + \alpha \varepsilon_{jt-1}^2 + b q_{jjt-1}]}} \tag{6}$$

The coefficient $\rho_{ij,t}$ indicates the strength and direction of correlation between crude oil returns series and COVID-19 at time t. Following Engle (2002), the estimation of this model is done by using two-step quasi-maximum likelihood estimation method.

3.2. Wavelet Coherence Analysis

The second approach used in this paper is the wavelet analysis which enables simultaneous analysis of co-movement between stock markets and COVID-19 infections. This approach offers a way of analysing localised variations of power within time series. As such, it provides a framework to determine the level of interdependencies between two time series variables in both frequency and time spaces (Aguiar-Conraria and Soares, 2011). In addition, the model captures the possible dynamic changes in the relationship by accounting for both short-run and long-run movements. Specifically, this paper employed the wavelet coherence (WTC) and cross-wavelet phase angle (phase difference) to analyse the dependencies between stock market and COVID-19 infections. This framework is briefly presented below.

We begin the discussion of our methodology by defining a continuous wavelet transform (CWT) for a wavelet ψthrough the following function:

$$W_x(s,) = \int_{-\infty}^{\infty} x(t)\frac{1}{\sqrt{s}}\psi^*(\frac{t-}{s})dt \tag{7}$$

Where * denotes a complex conjugation, τ is the translation parameter which dictates where the wavelet is centred, and s is the scaling parameter controlling the length of the wavelet which is compressed if |s| < 1 and stretched if |s| > 1. Since the wavelet coefficients contain combined information on both x(t) and ψ(t), Aguiar-Conraria et al. (2008) and Aguiar-Conraria and Soares (2011, 2014) propose the use of a complex-valued wavelet function since its corresponding transform will also be complex and can be separated into an amplitude and a phase. The following Morlet wavelet is employed as the continuous 'mother' wavelet and is defined as:

$$\psi(t) = {}^{-\frac{1}{4}} \exp(i\omega_0 t)\exp(-\frac{1}{2}t^2) \tag{8}$$

To ensure that the parameterization of the Morlet wavelet depicts an inverse relation between wavelet scales and the frequencies, $f \approx s^{-1}$, Aguiar-Conraria et al. (2008) and Aguiar-Conraria and Soares (2014) propose that the Morlet be set to approximately 6 (i.e. $\omega_0 = 2\pi$) in order for the wavelet scale, s, to be almost equal to the Fourier period. Within the continuous mother wavelet domain, the wavelet power spectrum (WPS) can be extracted, which measures the variance of a time series across a two-dimension plane i.e. time and scale (Aguiar-Conraria et al., 2008, Aguiar-Conraria and Soares, 2011, 2014). Formally, the WPS for a discrete time series, x_n, can be expressed as:

$$W_m^s(s) = \frac{\delta t}{\sqrt{s}}\sum_{n=0}^{N-1} x_n\psi^*((n-m)\frac{t}{s} \quad n = 0, \ldots., N-1, \quad m = 0, \ldots., N-1 \tag{9}$$

Where δ_t is a uniformed time step. The Cross-Wavelet Power Spectrum (CWPS) is then introduced to measure the covariance between two time series variables, x(t) and y(t). By defining the WPS of x(t) and y(t) as $W_{xx} = |W_x|^2$ and $W_{yy} = |W_y|^2$, respectively, the CWPS between x(t) and y(t) is computed as:

$$(WPS)_{xy} = W_{xy} = |W_{xy}| \tag{10}$$

We finally compute the wavelet coherence, which is analogous to the correlation between x(t) and y(t) across time and frequency, as the ratio of the cross spectrum to the product of the product of the spectrum of the individual series i.e.

$$R_n(s) = \frac{|S(W_{xy})|}{[(S|W_x|^2)(S|W_y|^2)]^{\frac{1}{2}}} \tag{11}$$

Where S is a smoothing operator in both time and scale. Aguiar-Conraria et al. (2008) and Aguiar-Conraria and Soares (2011, 2014) further propose the use the phase-difference to describe the relative positions of the pair of time series. Aguiar-Conraria and Soares (2014) note that "phase differences" are important since the wavelet coherence cannot distinguish between negative and positive correlation between two time series as well as identifying causal relationships between the variables. The phase-difference can be defined as:

$$\phi_{x,y} = tan^{-1}(\frac{I\{W_x\}}{\Re\{W_x\}})) \tag{12}$$

Where $\varphi_{x,y}$ is parametrized in radians, bound between π and −π. If $\varphi_{x,y} \in (0, \frac{\pi}{2})$ and $\varphi_{x,y} \in (0, -\frac{\pi}{2})$, then the series are said to be in-phase (positive correlation) with *y* leading *x* in the former and *x* leading *y* in the latter. Conversely, If $\varphi_{x,y} \in (\frac{\pi}{2}, \pi)$ and $\varphi_{x,y} \in (-\frac{\pi}{2} -\pi)$, then the series are said to be in an anti-phase (negative correlation) with *x* leading *y* in the former and *y* leading *x* in the latter. A phase-difference of zero implies co-movement between the pair of series at the specified frequency.

4. DATA AND EMPIRICAL RESULTS

4.1. Data Description

Our study makes use of 4 time series variables, namely, the COVID-19 recovery rates which are sourced from the "Worldometers" online statistics; the WTI oil prices, Brent oil prices and OPEC oil prices which are all sourced from "inveting com" database. All data is collected in daily frequencies over the period 2nd February 2020 to 4th August 2021, given us a sample size of 550 observations to work with. Table 1 summarises the statistical properties of the variables. More specifically, the table shows that the average global cases and death associated with COVID-19 infection per thousand population was growing at a rate of 1.8% per day while recovery rate was growing at a fast pace of 2.4% daily. The daily global oil price returns ranges between 0.01% for OPEC and 0.06% for WTI. However, the skewness coefficients shows that the distribution of return series for Brent and OPEC crude were negatively skewed, suggesting high probability of realising negative returns than positive returns. Also, the oil returns series have leptokurtic distribution, indicating that oil returns were highly concentrated around the mean values. Consequently, the Jarque bera test shows deviation of the oil return series from normality. Further analysis shows that the variables are first difference stationary series as shown by the results of the augmented Dickey-Fuller (ADF) and Phillips and Perron (PP) tests. Lastly, the analysis also shows evidence of ARCH effect in the residuals up to ten lags as indicated by the ARCH test and Ljung-Box (LB) tests. This finding confirms that the use of the DCC-GARCH model is appropriate for this study.

Table 2 shows the unconditional correlation between the oil returns and COVID-19 indicators. The analysis of the unconditional correlation shows that oil returns were negatively correlated with the changes in the number of coronavirus cases, death, and recovery. In other words, the global oil returns fall as the number of coronavirus cases, death and recovery increased. This suggests that the global oil market investors may be very cautious about investing in the global oil market as the virus spreads. However, some studies have cautioned against the use of the unconditional correlation method as a decision-making tool (Hemche et al., 2016 and Pukthuanthong and Roll, 2009). Hence, this study utilises more advance tools namely the DCC-GARCH and Wavelet techniques.

Table 1: Summary statistics

	Cases	Recovery	Death	Brent	OPEC	WTI
Panel A: Descriptive statistics						
Mean	1.763	2.399	1.770	0.038	0.015	0.061
Median	0.958	0.907	0.623	0.121	0.077	0.108
Maximum	33.500	36.683	22.630	8.285	9.932	13.882
Minimum	0.167	−12.656	0.155	−12.150	−14.382	−12.276
Std Dev.	2.899	4.597	3.240	1.536	1.865	1.971
Skewness	4.803	4.482	3.044	−1.383	−0.841	0.030
Kurtosis	36.749	27.564	12.212	19.704	20.323	18.581
Jarque Bera	28165.6***	15641.4***	2788.9***	6569.7***	6941.6***	5563.7***
ADF level	0.920	10.463	0.859	−0.581	−0.393	−0.817
ADF 1st Diff	−1.608	−3.879***	−2.343	−17.708***	−9.348***	−18.413***
PP level	5.766	7.576	6.184	−0.618	−0.471	−1.334
PP 1st Diff	−4.129***	−22.164***	−7.712***	−17.967***	−19.537***	−18.553***
LB (10)	3788.100***	51.104***	2433.000***	14.900	67.800***	25.080***
LB2 (10)	306.450***	0.828	1504.300***	174.840***	200.130***	208.070***
ARCH (10)	121.460***	0.807	415.060***	113.470**	92.550***	111.220***

***, ** and * indicate 1%, 5% and 10% levels of significant respectively

Table 2: Correlation matrix

	Cases	Recovery	Death	Brent	OPEC	WTI
Cases	1.000					
Recovery	0.696	1.000				
Death	0.932	0.743	1.000			
Brent	−0.085	−0.046	−0.096	1.000		
OPEC	−0.070	−0.029	−0.076	0.518	1.000	
WTI	−0.101	−0.037	−0.120	0.805	0.428	1.000

4.2. DCC-GARCH Results

We firstly make use of a DCC-GARCH (1,1) specification in examining the time-varying conditional volatility and correlations between the COVID-19 indicators and oil prices. Table 3 present the estimation result from DCC-GJRGARCH and the results show that oil returns volatility is mostly influenced by shocks to the conditional variance as indicated by the significant GARCH parameters. This further indicate evidence of persistence of volatility in the oil returns given that the GARCH coefficients ranges from 0.85 to 0.89, suggesting that it takes time for a shock to the conditional variance to die out. Moreover, the second moment condition $\alpha+\beta+(\frac{1}{2})\gamma<1$ is satisfied by each oil return series, indicating long memory and weak form efficiency of oil market. It is also shown that OPEC oil return is more volatile compared to others with a GARCH coefficient of 0.89. In addition, the analysis in the table shows evidence of significant asymmetry in the oil returns volatility as indicated by the coefficient γ. This finding indicates that negative shocks have significant impact on oil returns compared to positive shocks of equal magnitude. Also, it suggests that bad news associated with the number of coronavirus cases and death is likely to cause more volatility than good new as a result of number individuals who had recovered from the virus infection.

The analysis of the residual diagnostic tests shows that the estimated DCC-GJR-GARCH model was adequately specified and that the model is robust in capturing all the data generating process. Specifically, the diagnostic tests show there is no further serial correlation and ARCH effect in the oil returns series as indicated by the LB and ARCH tests. Furthermore, the DCC parameters (a and b) are statistically significant, and the sum of the parameters is less than unity, indicating shock to model die out after some time. Hence, this finding emphasises the stability of the estimated DCC model.

To analyse the dynamic correlation between COVID-19 and oil returns, Figure 1 provides the visual plots of the dynamic volatility co-movement across time. The figures shows that dynamic co-movement of oil returns is more volatile in relation to the number of COVID-19 cases and deaths compared to recoveries. In other words, oil returns exhibited more correlation with the number of cases and death, this can be inferred from the number of spikes. Another important evidence emerging from the figure is that the oil returns exhibited high correlation with the COVID-19 during the early period of the pandemic, from February to July 2020. In addition, there is evidence of more negative co-movement during this early phase. It is also, shown that the co-movement intensified during the period September 2020-January 2021, which coincides with the second wave of the pandemic. However, following the rollout of mass vaccinations by governments around the in January 2021, we observe les significant co-movements between health statistics and oil returns.

4.3. Wavelet Coherence Results

In this section of the paper we present the findings from our wavelet coherence analysis of the time series variables. Figure 2 presents the wavelet coherence plots between COVID-19 recoveries and oil prices (Top panel) and COVID-19 death rate and oil prices (Bottom panel). The coherence plots provide a 3-dimensional analysis of the dynamic correlations between the pairs of time series, with the time-varying domain being measured across the horizontal axis between February 2nd, 2020 and August 4th, 2021, the frequency domain being measured along the vertical axis which captures cycles from 1 to 512 days and the strength of the correlations being measured by the colour contours which range from blue (weak correlation), to green (moderate correlations) to red (strong correlations). The 5% significance levels of the correlations across different time and frequency components represented by the faint white lines whilst the phase difference dynamics are captured by the arrows within the diagrams. Note that arrows pointing to the right (left) indicate the phase-in (phase-out) or positive (negative) correlations between the series whereas arrows facing north-east,

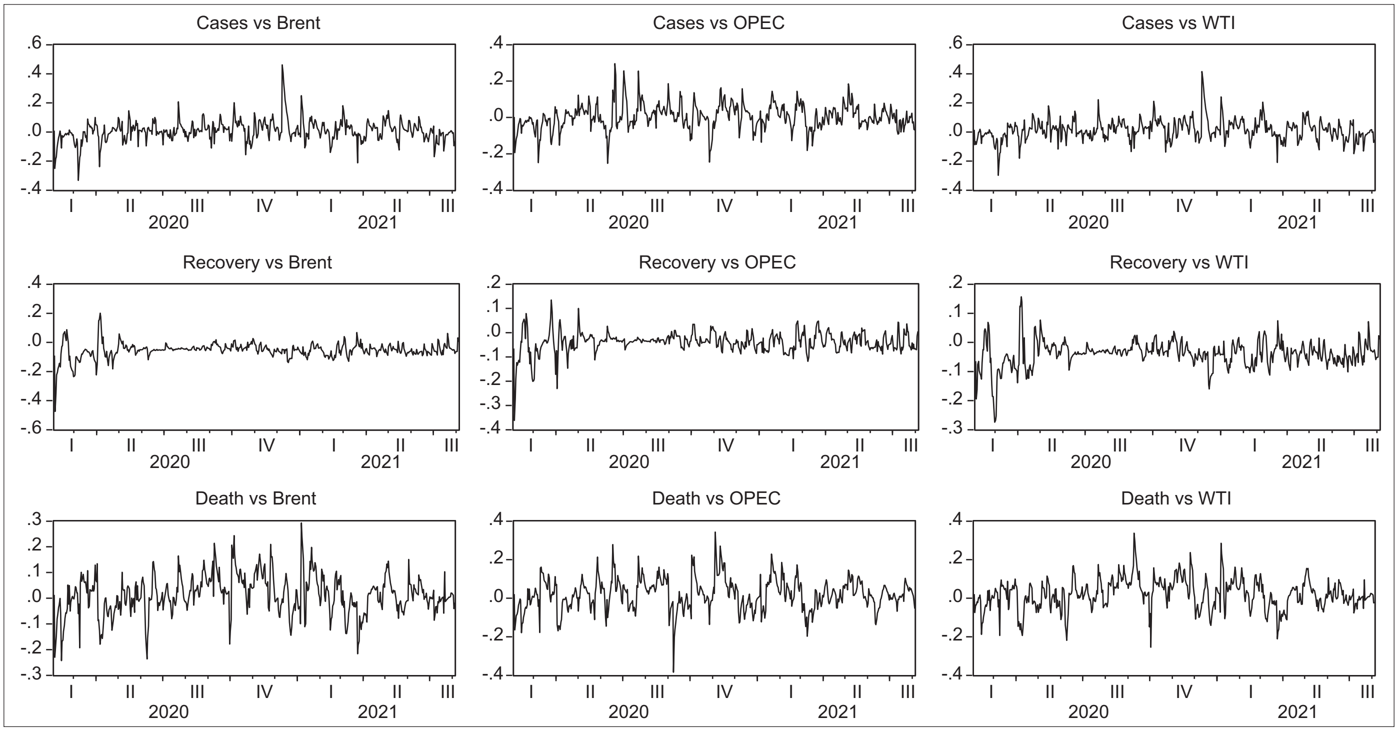
Table 3: DCC-GJR-GARCH (1,1)

Countries	Mean equation		Variance equation				Diagnostic tests		
	μ	r_{t-1}	ω	α	β	γ	LQ (10)	LQ^2 (10)	ARCH (10)
Cases	0.146	0.965***	0.000	0.715**	0.554***	0.412	194.17***	1.837	1.888
Recovery	2.232	0.091	10.008	0.153	0.540	-0.252	2004.1***	62.290***	130.220***
Death	−0.134	0.987***	0.001	0.063	0.707***	0.638**	267.27***	20.433***	23.865**
Brent	0.041	0.250***	0.028**	0.033	0.852***	0.200**	5.361	6.103	6.639
OPEC	0.008	0.284***	0.018**	−0.012	0.887***	0.244**	13.273	3.721	3.808
WTI	0.044	0.178***	0.027**	0.039	0.857***	0.196**	10.068	11.177	11.429

DCC parameters	A	b	a + b
Cases/Brent/OPEC/WTI	0.068*** (0.012) [5.835]	0.684*** (0.053) [12.818]	0.752
Recovery/Brent/OPEC/WTI	0.072*** (0.012) [5.787]	0.669*** (0.055) [12.119]	0.741
Death/Brent/OPEC/WTI	0.065*** (0.012) [5.897]	0.703*** (0.052) [13.471]	0.768

***, ** and * indicate 1%, 5% and 10% levels of significant respectively. The number in the normal brackets are the standard errors while number in the squared brackets are z-statistics

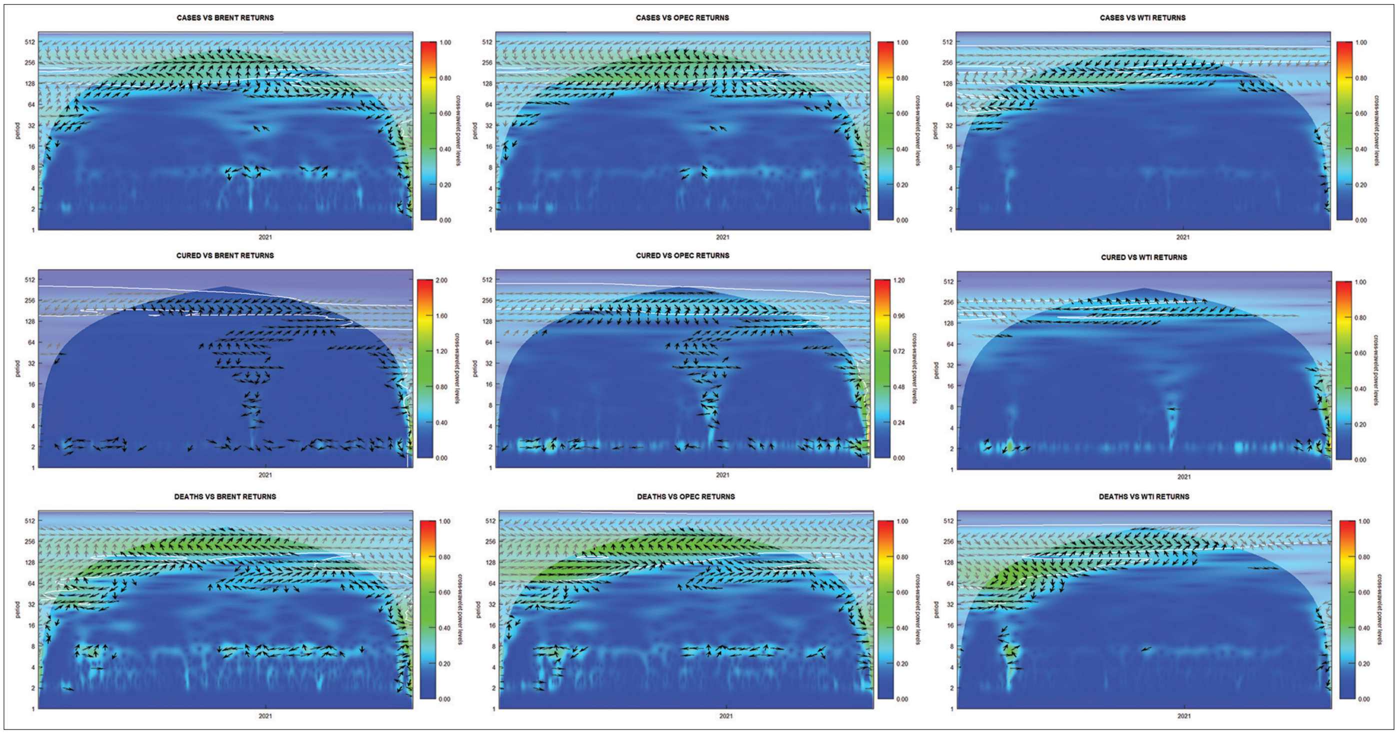
Figure 1: Dynamic conditional correlation



or south-west (north-west or south-east) indicate causality running from COVID-19 to oil prices (oil prices to COVID-19).

From Figure 2, it is clear to observe that the dynamic correlations between COVID-19 health outcomes and oil prices do not differ much amongst the three markets which is not surprising considering the observed interconnectedness of oil markets (Bhanja et al., 2021). Secondly, in all markets, we observe significant co-movements between health statistics and COVID-19 across the entire time window which implying correlation between the series throughout the entire pandemic. Secondly, judging from the colour contours in the wavelet plots, we observe stronger correlations between COVID-19 cases/deaths and oil market returns and weaker correlations for recovery data which shows that cases and death statistics are more efficient at predicting oil market returns. Thirdly, whilst co-movements are dominated by low frequency synchronizations at cycles of between 125 and 512 days, we observe some short-run frequency components of 8 to 64 days which are clustered (i) during the March 2020-April 2020 period which corresponds to the "Black Swan" period in turmoil in financial markets which encompasses the oil market crash event (ii) during the 2020 October-2020 December periods, particularly for recovery statistics, which coincides with the announcement of the Alpha and Beta variants as well as the peak of the second wave (iii) during the post-April 2020 period which corresponds to period when the delta variant was announced. Lastly, from the

Figure 2: Wavelet coherence plots



phase difference dynamics within the wavelet coherence the plots, we find that the cases and deaths series are predominantly anti-phase (negative) at lower frequency and more in-phase (positive) at high frequency oscillations.

Altogether the findings from our wavelet coherence analysis compliments those obtained from the DCC-GARCH model, and the findings can be collectively summarized in three points. Firstly, we find evidence against the semi-weak form market efficiency since we find that COVID-19 statistics are correlated with oil returns during the entire pandemic. Secondly, we our findings mutually show evidence of time-variation in the synchronization between the time series which we treat as evidence in favour of the AMH and these findings compliment previous literature which found similar time-variation in oil market efficiency in the weak-form sense (Mensi et al., 2020; Gil-Alana and Monge, 2020; Usman and Akadiri, 2021; Okoroafor and Leirvik, 2022). Lastly, indicate that market efficiency is has been most compromised during the periods corresponding to the oil-price war as well as during the announcements of different variants of the COVID disease, whereas market efficiency has been generally improving after the mas rollout of vaccines in January 2021 as observed by Rouatbi et al. (2021) for the case of stock markets.

5. CONCLUSION

The ongoing COVID-19 pandemic is the deadliest wave of viral infection our current generation has faced and there has increasing evidence that information contained within public available COVID-19 health statistics are influencing movements in financial markets. In our study, we examine the co-movement between COVID-19 and global oil prices for WTI, Brent and OPEC markets between 02 February 2020 and 04 August 2021 using the DCC-GARCH model and wavelet coherence analysis in our empirical analysis. On one hand, the DCC-GARCH estimates capture the time-varying co-movement between the variables whereas, on the other hand, the wavelet coherence analysis captures both the time-varying and frequency-varying co-movements between the time series.

Mutually, both the DCC-GARCH and the Wavelet coherence estimates reveal time-varying co-movements between COVID-19 health statistics and oil market prices throughout our entire study sample which is evidence in support of the AMH. Moreover, the wavelet coherence analysis further shows that synchronizations between the time series are dominated by low frequency components whereas short frequency components are dominant during (i) periods of financial turmoil and geopolitical instability (ii) periods around the announcements of the various COVID-19 variants. However, both DCC-GARCH and wavelet analysis inform us that the co-movement between health statistics and oil returns is weaker after the roll out of mass vaccinations around the world.

Altogether, our has important implications for investors, market regulators, policymakers and academics. For investors, our evidence demonstrates that the market returns can be predicted using publicly available information on health statistics particularly those for cases and death statistics. For market regulators and policymakers, our study provides evidence that the oil market has been most vulnerable during periods of geopolitical instability as well as when newer variants of the disease have been discovered and yet improves after the rollout of vaccines. In turn, this emphasizes the importance which a vaccinated population plays towards oil market stability during the pandemic and highlights the threat of the recent Russian-Ukraine tensions, as a more recent geopolitical event, on the informational efficiency of oil markets. Lastly, our study demonstrates the importance of using more updated time series and empirical techniques to draw novel information on the efficiency of oil markets and encourages future studies to keep monitoring the evolving nature of the pandemic on oil markets as more data becomes available.

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