Chapter

COVID-19 Outbreak and Co-Movement of Global Markets: Insight from Dynamic Wavelet Correlation Analysis

Maurice Omane-Adjepong, Imhotep Paul Alagidede and John Bosco Dramani

Abstract

The COVID-19 pandemic has in its short existence caused economic downturn and affected global markets. As would be expected, the occurrences of global crises or shocks often heighten uncertainties in international markets and increase correlations among them. Yet, not much is known of the actual impacts of COVID-19 on the behavior of global markets. This piece attempts to investigate whether the COVID-19 crisis has had any impact on the interrelationship structure of international markets using the cross-wavelet squared coherence and a dynamic wavelet correlation technique. It emerges that co-movements of the pairwise series become stronger (0.70–0.89) during the heightened periods labeled as epidemic and pandemic phases of COVID-19, than that of the periods that mark the pre-COVID-19 era (−0.49–0.36), hence announcing the influence of the crisis and eroding prospect of benefiting from a hedge instrument and/or a diversifier. Again, we observe that stock market-Global REITs have been the most influenced pair, showing significantly peaked co-movements (0.63–0.87) during the distinct phases of COVID-19. We attribute these developments to the loose monetary and financial measures implemented by central banks of the world. The findings hold important implications for economic and financial actors regarding diversification, hedging, and investment risk management.

Keywords: global markets, COVID-19 outbreak, co-movement, RWWC, portfolio diversification

JEL classification: C22, G15

1. Introduction

The COVID-19 pandemic has triggered untold uncertainties in most global financial and commodity markets. In March 2020, stock price fell intensely, mortgage-backed securities and yield spread of corporate bonds surged significantly, and U.S. Treasury bonds which usually serve as a safe-haven, plunged [1, 2]. Specifically, the behavior of global stock market appears illogical in presence of the

pandemic to many investors. For instance, S&P500, one of the mega-size stock markets experienced three phases of changes as the rate of COVID-19 infection worsens. In phase one, it recorded a high value on 19th February 2020, prior to the declaration of the outbreak as a pandemic by the World Health Organization (WHO). However, a surge in the spread of the virus, exacerbated by soaring death rates, caused panic and created a colossal urgency to accumulate cash balances, sparking a concurrent selloff in stocks [3]. Thus, in phase two, the S&P500 plummeted by 34% reaching its low on March 23, 2020. In the third phase, S&P500 rose by 30% on April 30, 2020, despite the lockdown orders initiated by many countries to curb the spread of the virus. In hindsight, stock markets have performed well, generally, because on the eve of the COVID-19 outbreak been pronounced a pandemic, the ratio of market capitalization to GDP was higher compared to its level in 2007, and a little higher than the maximum value during the dot-com bubble [4]. Analysts attribute the rebound of the stock market partly to various loose monetary policy and other interventions pursued by central banks [4], which instilled confidence into shareholders, lightening fears of the health crisis. Besides, country-specific characteristics such as structural economic fragility and "at-risk" population, also seem to have had little effect on stock market reactions to the pandemic [5].

As the pandemic intensifies, bond trading has also encountered challenges, regardless of the asset's significance and essential role in the financial market system. In the face of the pandemic, the observed behavior of the bond market is similar to that of the global stock market. For instance, the U.S. Treasury bond and Canadian government bond markets, in phase one, witnessed an increase in demand for liquidity as investors embarked on a significant selloff [2]. In phase two, dealers curtailed the supply of liquidity, which deteriorated trading conditions. In the third phase, demand gradually reduced, due to some interventions introduced by the respective central banks of these giant economies.

In another development, commodity markets such as crude oil and the real estate markets equally experienced volatilities as the COVID-19 pandemic unfolds. On 20th April 2020, a barrel of West Texas Intermediate crude oil to be delivered in May recorded a negative price, implying sellers had to pay buyers [6]. Though the price for June also fell over a quarter on 27th April, it however remained a little above $12 a barrel. Crude oil market analysts attribute these fluctuations to a price-war between Russia and Saudi Arabia, which they claimed flooded the international market with crude oil and a slump in demand due to traveling and aviation restrictions imposed by countries following the pandemic [7].

A convergence of the uncertainties in the above global markets triggered an immediate deterioration of business environment with unintended negative consequences on commercial real estate markets. Demand for lease space slumped and continue to deteriorate as the pandemic unfolds due to the effects of social distancing and business closures across the globe. However, the impact appears to vary extensively across the real estate sectors. Whiles some sectors are severely and directly affected by the pandemic, others are less and indirectly affected. The performance of the stock market for Real Estate and Investment Trusts (REITs) reflects the differences in the degree of the uncertainties across different types of properties [8].

Though the individual global markets' responses to the COVID-19 pandemic may seem somehow similar, albeit yet to be determined actual worldwide impact quantification, there is a strong likelihood of a potential lead–lag co-movement among the markets, which may be induced or heightened by major news of the health crisis. There is an astronomical increasing number of empirical studies towards the reactions of individual global markets to the COVID-19 crisis. In a short

epistle, Krugman [4] disclosed that the "*stock market is not the economy*", and that "*connection between stock growth and the expansion of the real sector of the economy lies within loose and nonexistence*". Capelle-Blancard and Desroziers [5] confirmed various interventions by governments, as well as the believe that loose monetary policy and lockdown initiatives stimulated the rebound of stocks, they further agreed with Krugman [4] that there exists a loose relationship between market fundamentals and stock market uncertainties. Jefferson [7] on the other hand established that projections of future crude oil prices are uncertain, however, in the absence of supply-side shocks, oil prices are likely to rebound by the end of the third quarter of 2020. Goodell and Goutte [9] investigate co-movement of Bitcoin with levels of COVID-19 fatalities and show that the levels of COVID-19 deaths cause a rise in Bitcoin prices. However, the analyses from the previous studies have failed to examine coherences and lead–lag behavior among conventional global markets as they react to the COVID-19 crisis. Again, to the best of our knowledge, the existing studies have not analyzed the interrelationship structure and reactions of global markets to distinctive stages of the COVID-19 outbreak.

In response to the identified gaps, this study attempts to offer fresh insights as to whether major news items of COVID-19 influence the interdependence structure of international markets. We contribute to the existing literature in two-fold. First, we explore the degree of co-movement and lead–lag relationship among aggregate global stock index, commodities, and the REITs market using the cross-wavelet squared coherence and a rolling-window wavelet correlation (RWWC) technique. In addition to its ability to address issues of nonlinearity, (non-) economic shocks, regime shifts, and non-stationarities, the RWWC approach possesses time-varying attributes that makes it possible to measure the temporal variations of cross-market correlations over time and frequency domains [10], with implications for heterogeneous market actors. Second, we examine the influence of the COVID-19's epidemic and pandemic stages on global market interrelatedness and determine whether international investors can hold positions in the markets to offset short-run investment losses during the crisis.

The remaining structure of the study is set as follows. Section 2 provides a review of the extant literature. Section 3 discusses the econometric techniques employed. Section 4 presents the results, while Section 5 provides conclusion and policy recommendations.

2. Literature review

Ramelli and Wagner [11] found a significant effect of world trade and global value chain on the value of corporations. Corporate bodies appeared profitable depending on the location of the epicenter of the pandemic. For instance, stocks of corporate bodies in China initially appeared risky as the pandemic unfolded while those in Europe were considered profitable. However, as the epicenter moved to Europe and America, investors perceived stocks of these regions to be unfavorable, causing the markets to behave feverishly. Investors were equally alarmed about the possibility of corporate bodies incurring high debts as well as the survival potentials of businesses with insufficient cash balances. Though the opportunity cost of holding cash balances appeared high, there was an increasing need to hold precautionary cash to soar the value of firms. Capelle-Blancard and Desroziers [5] revealed that investors in the stock markets were quick to respond to soaring cases of COVID-19, with advanced economies being highly affected. The authors also unearth that loose monetary and fiscal policies introduced by central banks and governments caused interest rates to fall, which moderated the fall in stock prices, making the market

less responsive to the crisis. Baker et al. [12] argued that the stock market responded to the pandemic in a way that has never happened in history. The authors attributed this behavior to a host of factors such as governments' restraints on economic activity and the introduction of social distancing measures in the presence of a service dominated economy. Ehrmann and Jansen [13] revealed the presence of significant co-movement between stock returns and national stock markets. Investors placed a high value on global news and the effects were moderated by large oscillations in global stock markets. However, investors turned to place less value on firm-specific news, which caused stock returns and national stocks market to move together. The authors observed that, this relationship was significant for stocks that are characterized by low co-movement with national market, resulting in a convergence of beta across stocks.

Haddad et al. [14] in studying the disruptions in debt markets as the pandemic unfolded made interesting revelations. The authors revealed that bonds that are usually regarded as safe havens recorded weighty losses which analysts found difficult to explain applying risk premium channel or standard default. Corporate bonds traded at a huge discount to their equivalent credit default swaps and this became worse for many safer bonds. Similarly, liquid bond exchange-traded funds witnessed a huge discount to their corresponding net asset value. These findings imply traders attempted to sell safer and high liquid securities to increase cash balances. However, these disruptions did not see the light of day as the market recovered in a matter of weeks. The authors attributed the fast recovery of the bonds market to the unparalleled measures the Fed introduced by purchasing corporate bonds instead of extending credit. Fontaine et al. [2] and Kargar et al. [15] found that the market for bonds evolved in three phases as the pandemic worsens, using two-year benchmark bonds for Canada. The first phase witnessed a sharp rise in the demand for cash balances, which traders did well to accommodate but at a higher cost. The second phase experienced a massive decrease in the supply of cash balances by dealers, leading to a huge deficit as demand for cash kept soaring. The third and final phase saw trading activity and price of cash balance stabilizing due to the interventions by central banks to assist the financial sector.

Regarding the crude oil market, the Arezki et al. [16] pointed out that net oil-exporting economies face a dual shock emanating from the health crisis and a fall in prices of crude oil. However, the shock from the pandemic turned to lead and influence the collapse in oil prices. This manifested itself through the traveling restrictions placed on the aviation industry, self-isolation, and social distancing and complete lockdowns measures introduced by governments around the globe [7]. Elsewhere, Barbosa et al. [17] revealed that the dual shock on net exporting countries negatively affected the financial and structural health of the oil sector in an unprecedented manner. Since the intensity and length of the health crisis are uncertain, the authors suggested net exporting countries should introduce fundamental intervention to reverse the trend to make the industry profitable again.

In the Real Estate and Investment Trusts market, Schnure [8] observed that the social distancing and lockdown measures caused almost all businesses in the global economy to shut down. There is a high probability that most of these businesses may find it very difficult to honor their rent in the near future, which will affect negatively on cash flow of property owners. Again, the authors explained that hikes in unemployment would cause unspeakably high rent default by households. Coibion et al. [18] found persistence in low inflation, heightened uncertainty, and lower mortgage rates as the pandemic worsened. The authors attributed this low consumer spending and collapse in demand for office space as employees work from home.

It is important to mention that the existing literature is yet to explain whether COVID-19 has influenced the interdependence structure of global markets. Besides, the influence of the crisis at the onset stage and its transition into a pandemic has rarely been explored. Thus, applying time-frequency estimation methods, this paper augments the literature by assessing the extent of co-movement and the direction of linkages (lead–lag relationship) among selected major global market, amid COVID-19 major news. Our study provides international investors with further insight as they seek to diversify their investment portfolios by purchasing securities that do not or less co-move to minimize losses under the heightened market periods of COVID-19.

3. Data and methods

The data for the empirical analysis and the econometric approach for the multidimensional dynamic correlation measure is explained in this section. As preliminary to the main analysis, static descriptive measures, and a correlation matrix based on a global measure, computed under different time samples are provided.

3.1 Data

Daily price levels of MSCI All Country World Index (MSCI ACWI), S&P GSCI Energy Index, S&P GSCI Non-Energy Index, and S&P Global Real Estate and Investment Trusts (SREITGUP), which spans from January 01, 2016, to August 17, 2020 (giving us 1165 realizations after cleaning and synchronization the timestamps) are considered and used as proxy for global markets[1]. The US dollar denominated price level datasets are sourced from the Bloomberg database terminal. The daily prices are converted to percentage log changes: $r_{i,t} = In(P_{i,t}/P_{i,t-1}) \times 100$, for $i = 1, \ldots, 4$ and $t = 2, \ldots, 1165$, where $P_{i,t}$ and $P_{i,t-1}$ denote the close of day prices for global market i at day t and $t - 1$ respectively. The time sample is foremost divided into pre-COVID-19 crisis (January 01, 2016, to December 07, 2020) and periods marking the onset and duration of COVID-19 (December 08, 2019, to August 17, 2020).

To establish the dynamic impact of the COVID-19 outbreak on the interrelationship structure of international markets and its implication thereon, the crisis period is further separated into epidemic (December 08, 2020, to March 10, 2020) and pandemic (March 11, 2020, to August 17, 2020) stages. The dating of these distinct periods is based on the announcements or timelines of the first patient who was reported to have developed symptoms of the Wuhan coronavirus (on December 08, 2019) and the subsequent declaration of the outbreak by WHO as a pandemic (on March 11, 2020)[2].

Table 1 shows summary moment measures for the global markets during the crisis and non-crisis periods. Compared to the non-crisis, the average daily returns fairly decrease under the crisis period, with all markets recording low negative skewness values, indicative of a high tendency of reaping non-positive investment returns. Noticeably, the markets appear to be more volatile as we transition from

[1] International bonds, bills, and the currency markets are beyond our scope, perhaps, they could be considered in future studies.

[2] For the applicable COVID-19 timelines, refer to: https://www.weforum.org/agenda/2020/04/coronavirus-spread-covid19-pandemic-timeline-milestones/ (Accessed on July 29, 2020).

	Period I: Pre-COVID-19 crisis				Period II: COVID-19 crisis			
	Mean	**Std Dev**	**Skew**	**Kurt**	**Mean**	**Std Dev**	**Skew**	**Kurt**
MSCI ACWI	0.0359	0.6733	−0.7606	4.6379	0.0131	2.0655	−1.1728	7.2169
GSCI Energy	0.0486	1.8979	0.1638	3.2746	−0.2060	5.1673	−1.3398	9.8393
GSCI Non-Enr	0.0123	0.5844	−0.1489	0.7892	0.0019	0.7723	−0.7365	2.2106
SREITGUP	0.0137	0.6934	−0.4641	1.8341	−0.1105	2.7274	−1.6971	9.5034

Table 1.
Descriptive measures.

	Period I: Pre-COVID-19 crisis				Period II: COVID-19 crisis			
	(a)	**(b)**	**(c)**	**(d)**	**(a)**	**(b)**	**(c)**	**(d)**
(a) MSCI ACWI	1				1			
(b) GSCI Energy	0.3668	1			0.4671	1		
(c) GSCI Non-Enr	0.2921	0.2511	1		0.5813	0.4340	1	
(d) SREITGUP	0.5598	0.1608	0.1450	1	0.8962	0.3764	0.5599	1

Table 2.
Pearson correlation matrix.

the pre-crisis to the crisis period. For instance, the volatility measures for MSCI ACWI, S&P GSCI Energy, and the Global REITs (SREITGUP) increased almost three-fold between the two periods. Meaning, the COVID-19 crisis has ushered in periods of heightened uncertainty and created a high financial risk environment. Besides, the return distributions of the markets exhibit relatively more leptokurtic features under the crisis, hence giving rise to extreme return realizations.

Results of the Pearson's unconditional correlations for the market pairs are presented in **Table 2**. Except for MSCI ACWI-Global REITs (with correlation measure of 0.5598), low positive correlations (ranging from 0.1450 to 0.3668) characterizes the pairs before the coming into being of the crisis. However, all the pairwise correlations increased in magnitude from low positive to moderately low positive values (0.3764 to 0.5813), with a peaked measure of 0.8962 for MSCI ACWI-Global REITs. These static-based measures signal the influence of the COVID-19 crisis on cross-market relationship, which seems to be in line with the literature that suggests that financial markets tend to move closely together (i.e., increased correlation or co-movement intensity) during turmoil or crisis. Yet, estimations that are more robust are undertaken to validate these early detections.

3.2 RWWC methodology

To examine the interrelationship structure between the daily percentage log changes of MSCI ACWI, S&P GSCI Energy Index, S&P GSCI Non-Energy Index, and S&P Global REITs Index across time and frequency, we employed a dynamic correlation version of the wavelet correlation approach by Gençay et al. [19]. The rolling-window wavelet correlation (RWWC) method, which was introduced by Ranta [20, 21] has recently gained traction in the economics and financial literature, perhaps due to its ability to unearth the temporal variations of the wavelet correlation for distinct time series, by incorporating a dynamic measure under a multidimensional setting. Using the Maximal Overlap Discrete Wavelet

Transformation (simply, MODWT) methodology (see, [22–24]; etc.) and following Gençay et al. [19], we express the MODWT-based unbiased estimator of the wavelet correlation for pairs of the market series, X_t and Y_t for scale λ_j as:

$$\tilde{\rho}_{XY} = \frac{\operatorname{cov}\left(\tilde{W}_{X,j,t},\ \tilde{W}_{Y,j,t}\right)}{\left(\operatorname{var}\left(\tilde{W}_{X,j,t}\right)\operatorname{var}\left(\tilde{W}_{Y,j,t}\right)\right)^{1/2}} = \frac{\tilde{\gamma}_{XY}(\lambda_j)}{\tilde{\sigma}_X(\lambda_j)\,\tilde{\sigma}_Y(\lambda_j)} \tag{1}$$

where, $\tilde{\gamma}_{XY}(\lambda_j)$ represent the unbiased estimator of the wavelet covariance for the wavelet constituents $\tilde{W}_{X,j,t}$ and $\tilde{W}_{Y,j,t}$ involving the pair of distinct series, and $\sigma_X^2\tilde{(}\lambda_j)$ and $\sigma_Y^2\tilde{(}\lambda_j)$ denote unbiased measures of the wavelet variances for X and Y at scale λ_j.

We specify the MODWT-based unbiased estimator of the wavelet variance as:

$$\tilde{\sigma}_X^2\left(\lambda_j\right) = \frac{1}{\tilde{N}_j}\sum_{t=L_j-1}^{N-1}\tilde{W}_{j,t}^2 \tag{2}$$

where, $\tilde{w}_{j,t}$ represent the j^{th}-level MODWT wavelet constituents for market variable X, $L_j = \left(2^j - 1\right)(L-1) + 1$ give the length of the scale λ_j wavelet filter, and $\tilde{N}_j = N - L_j + 1$ present the number of wavelet constituents unaffected by the boundary. Next, an expression for the computation of a random interval that captures non-spurious wavelet correlations [21] and offers an approximate $100(1-2p)\%$ confidence interval is deduced from the extended work of Whitcher et al. [25]:

$$\left[\tanh\left\{h\left[\tilde{\rho}_{XY}(\lambda_j)\right] - \frac{\Phi^{-1}(1-p)}{\left(\tilde{N}_j - 3\right)^{1/2}}\right\},\ \tanh\left\{h\left[\tilde{\rho}_{XY}(\lambda_j)\right] + \frac{\Phi^{-1}(1-p)}{\left(\tilde{N}_j - 3\right)^{1/2}}\right\}\right] \tag{3}$$

where, $h(\tilde{\rho}_{XY}) = \tanh^{-1}(\tilde{\rho}_{XY})$ describes Fisher's z-transformation and $\tilde{N}_j$ remains the number of wavelet constituents that correspond to a particular scale.

To provide short-term investment solutions for traders during the ongoing COVID-19 crisis, we considered to perform our analysis at the lower frequency bands or investment horizons, thus, the $2 \sim 4$ day band (D1: intraweek), $4 \sim 8$ day band (D2: weekly), and the $8 \sim 16$ day band (D3: fortnight), which are associated respectively with scales λ_j of the MODWT time-scale decomposition, where $j = 1, \ldots, 3$. We computed the RWWC using a 100-day window size, which we rolled forward one day (or datapoint) at a time, and centred around time t. With a sample size of 1165, we obtained a total of (1165 minus 100 = 1065) windows. We later varied the window size to 120 (or half-year) to verify the sensitivity of the results to the choice of window length. The two window sizes, $w = 100$ and $w = 120$ truncated on June 04, 2020, and May 20, 2020, respectively, giving us relatively less information losses compared to using higher window sizes. On the other hand, selecting very low window lengths plays down on the power of the test, therefore our choices are not misplaced.

4. Empirical results

We begin the main analysis with results from the cross-wavelet squared coherence method of Grinsted et al. [26]. Under this well-known technique, the estimator

of interdependence is rooted on a continuous wavelet transform (see, [9, 21, 27]; etc., for detailed explanation) rather than the discrete wavelet transform. Besides, unlike the RWWC, the wavelet coherence does not incorporate a dynamic measure in its computation. Therefore, taken as a precursor to the RWWC analysis, we initially gleaned the direction and nature of the interdependence structure that emerges for the market pairs using the wavelet coherence plots shown in *Appendix B*. A general observation of *Appendix B* reveals that the arrows are mostly pointing to the right, implying the series are positively correlated, with patches of varying significant coherences predating the year 2020. Observably, the post-2020 period recorded a high degree of coherences for pairs involving stock market-Global REITs and stock market-energy commodities, which witnessed long stretches of white contours over the frequency bands. These detected peaks in coherences conform to the contagion effect literature that projects high co-movements (or increased correlation intensity) for financial markets during and/or after the occurrences of turmoils or major crises. This finding is in line with the findings of Polanco-Martínez et al. [24] who reported strong correlation (0.56–0.87) among global financial markets during episodes of heightened economic crises, particularly during the 2008 financial meltdown.

Specifically, in *Appendix B*, we first focus on the behavior of the global stock market and energy commodity pair. As noted, a significantly strong positive correlation could be gleaned between the 16 and 128 trading day bands, with purloins of co-movement within the intraweek to fortnight trading frequencies. The strongest level of coherences falls within March and May 2020, where the equity market clearly leads energy commodity. This post-2020 co-movement pattern could perhaps be attributed to the lockdown measures, which brought global transportation to a temporary halt, hence the lagging of global energy commodity in its interrelationship with stock market. This finding confirms those of Nguyen et al. [28] who established strong evidence of co-movement (ranging from 0.62–0.89) between stock and energy markets at the peak of the global financial crisis 2007–2009. Similar visibly strong coherences, which intensifies at the beginning of 2020 and beyond, conspicuously grows from the intraweek to half-year trading day bands for the stock market and Global REITs pair. It is also important to stress that the coherences between stock market-Global REITs stretch over longer periods than what could be witnessed for the other global market pairs. These zones of strong correlations are suggestive of contagion impact resulting from the imposition of measures, implemented by world governments and their central banks to avert meltdown of the global financial markets.

With respect to stock market and non-energy commodity in *Appendix B*, we notice isles of significantly segmented zones of coherences, which mark periods, before, during, and after the outbreak of COVID-19. Coherences between energy and non-energy commodities appear generally weak, with few moderately low correlations concentrated between frequency bands of 8–32, and fairly distributed across time. Similarly, besides the 32–128 trading day bands of the opening months of 2020, coherences between energy commodity and global REITs are equally weak. Finally, we observe patches of moderately low significant co-movements between non-energy commodity and Global REITs, which appears mounded within the medium-to-long-run frequencies (16–128) with weak coherences below the fortnight band, coupled with a nonhomogeneous lead–lag relationship.

Our RWWC analysis in **Figure 1**, drawn from a dynamic version of the discrete wavelet transform is initially estimated using a 100-day window length using Eq. (3). The estimations from the dynamic approach reveal thought-provoking findings that may be hardly discernible with static or global measures. The

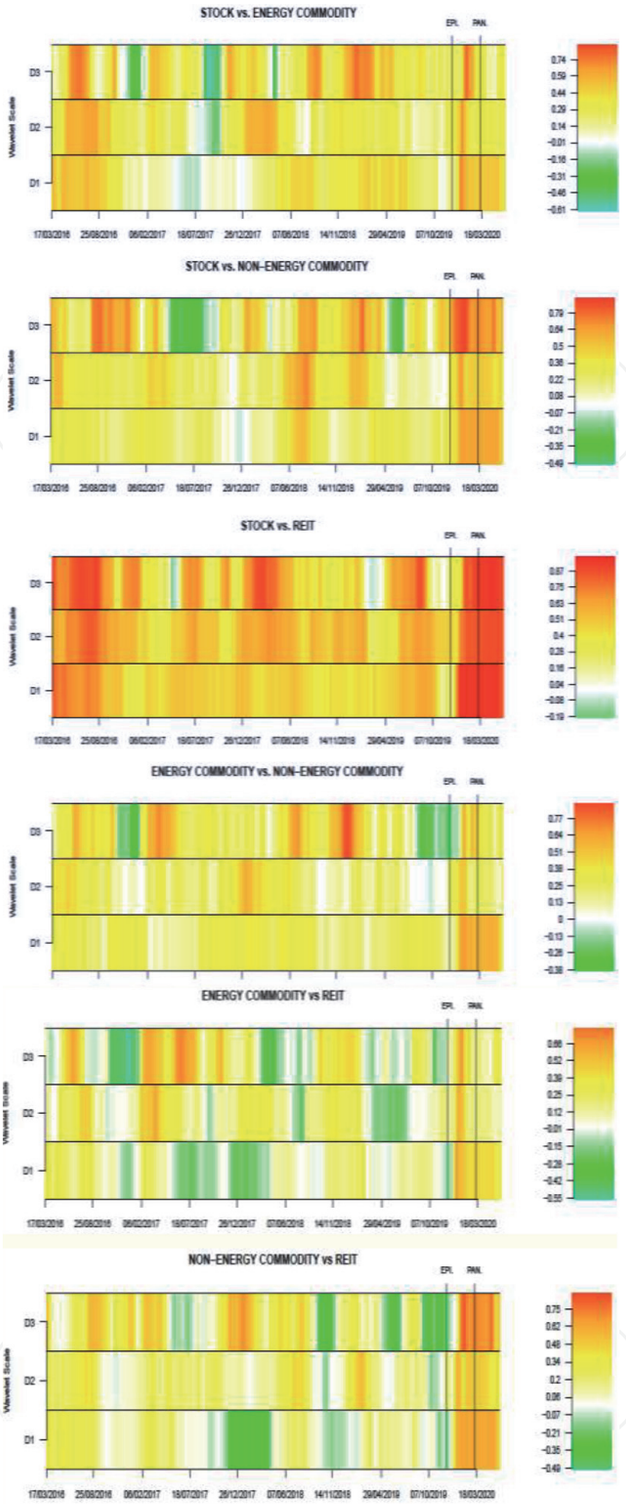

Figure 1.
A 100-day RWWC for pairs of selected global markets. Note: the strength of the dynamic wavelet correlation for the pairs is displayed by the heat map colors, which ranges from weak to high (thus, from blue, cyan, green, white, yellow, orange, to red respectively), where red (blue) denotes highest (lowest) wavelet correlation coefficients within a 95% confidence interval (refer to the web version of the article for color representation).

horizontal axis of **Figure 1** depicts timelines (or time intervals) and the vertical axis represents frequency bands or investment horizons categorized into D1 (intraweek), D2 (weekly), and D3 (fortnight)[3]. A glance from the RWWC results in **Figure 1** shows that the market pairs are predominantly characterized by weak to

[3] For recent applications, readers may refer the works by Polanco-Martíneza et al., (2018); Omane-Adjepong and Alagidede [10]; Nguyen et al., (2020); etc.

moderately low positive correlations, with few abrupt zones of inverse correlations that completely disappear during the uncertain periods ushered in by the global outbreak of COVID-19. This latter finding signals a negligible or unlikely opportunity of benefiting from any of the market assets as a safety net tool or instrument to hedge against short-term losses of an international investment portfolio. Generally, except for stock market and the Global REITs pair, we observe fairly low but steadily increasing correlations for the markets over the frequency bands before the onset of COVID-19.

Particularly in **Figure 1**, we notice vast yellow to less warm orange regions with scores of white and green patches before the dating of the COVID-19 crisis for markets pairs of non-energy and Global REITs on one side, and energy versus Global REITs at the other side. Similar colors from the correlation heatmap could also be somehow advance to describe interrelationship behavior for the pairs involving energy and non-energy commodities, as well as stock market and (non-) energy commodity. These pre-COVID-19 co-movement patterns mark an era that is generally dominated by moderately fewer interactive markets, except for the stock market and Global REITs pair, which exhibited moderately high interactions. Besides, the latter market pair witnessed strong co-movement across the trading frequencies in the second to the third quarter of 2016, a period which coincides with the UK's referendum on June 23, 2016, to leave European Union. Perhaps, the uncertainties induced by the referendum accounted for such high cross-market interactions[4].

As viewed from **Figure 1**, the onset and the distinct phases of COVID-19 has had cause to alter the correlation patterns of the market pairs. For instance, the RWWC measure becomes strong (warm orange to reddish heatmap colors) during the epidemic phase of COVID-19 for stock market-energy commodity and energy commodity-Global REITs, only to reverse to moderately low correlations, as observed under the pre-COVID-19 period, thereby signaling a temporal effect of the crisis on the market pairs. The remaining markets recorded increasing co-movements in the early period of the epidemic, however, these intensifies and peaks in the latter part of the epidemic, and subsequently overflows into the pandemic period. Our finding confirms that of Samadi et al. [29] who provided strong evidence to the effect that energy market exhibited low co-movement (0.36) during the pre-Ccovid-19 episode, which later heightened (0.88) during the pandemic era. The results presuppose that COVID-19 has exerted varying influences on the relatedness of global markets, and as a result decreased, to a large extent, the tendency of reaping diversification gains. These strong co-movements could be a consequence of looming heightened financial instabilities, compelling central banks to implement loose monetary and financial measures to curtail the effect of the crisis.

From the above context, it would be non-advantageous to hold a position in pairs of these global markets during the ongoing crisis, more importantly, for the stock market and Global REITs. As the evidence suggests, the latter pair react more to global shocks or crises, perhaps, owing to the reason that both markets are subjected to similar circumstances, hence, in periods where stock prices plummet, REITs are not overly immune to the perils of falling stock prices.

To ensure the robustness of our results we conduct a sensitivity test by increasing the rolling-window size to 120-days and report the results in *Appendix A,* estimated using Eq. (3). Conspicuously, we observe similar trends for the market pairs, and therefore conclude that our results are invariant with the size of the rolling-window.

[4] It is imperative knowing that the weight composition of MSCI ACWI and SREITGUP captures several developed markets in Europe.

5. Conclusions

This study investigates the behavior of global markets amid the onset and the different stages of COVID-19. We represent the first period as pre-COVID-19 (January 1, 2016, to December 07, 2019) – this period is characterized by high financial market growth and stability; the second period as an epidemic (December 07, 2020, to March 10, 2020), which is considered as relatively high volatility in a specific country (China) or region; and the last as a pandemic stage (March 11, 2020, to August 17, 2020), branded as a period of heightened global markets instability. Four selected international markets, namely MSCI AWCI, S&P GSCI Energy, S&P GSCI Non-energy, and S&P Global REITs are used for the analysis. We accomplished the goal of the study by applying both static and dynamic measures to ascertain the extent to which COVID-19 has influence the interrelationship structure of global markets.

Overall, we detect that COVID-19, through its different stages has generally affected the relatedness patterns of global markets. Thus, co-movements of the markets become stronger during the heightened periods of COVID-19's epidemic and pandemic, and as a result, erodes, to a greater extent, the likelihood of diversification benefits. These increases in co-movement are attributed to the loose monetary and financial measures as well as stringent interventions imposed central banks and government, worldwide, as panic remediations to curtail global economic meltdown.

In conclusion, hitherto the general observation that global markets comove during episodes of heightened crisis, our study provides a strong evidence that these correlations are not just strong during the entire period but stronger at the peak of the crisis or pandemic stage (March 11, 2020, to August 17, 2020, in the case of COVID-19). This situation is likely to vary from country to country due to the degree of aggressive interventions and restrictions introduced by respective central banks and governments. The findings of this study indicate that health crisis (COVID-19) can have important implications for global markets through some transmission channels. It is thus important that policy-makers, through research, begin to identify these important channels and fashion both institutional and regulatory policies to address them. Future research can widen the scope to cover relevant aspects of this study by asking the following questions; what accounts for the differences in global markets or countries with dissimilar reactions to COVID-19 pandemic? Can these differences in reaction across global markets and countries be attributed to different approaches to the conduct of monetary policy or institutional characteristics? Can the differences in responses of global markets be due to approaches adopted by various countries in handling the pandemic? Even though COVID-19 health crisis has been pronounced a global pandemic, its negative impact has not been equally distributed, leading to dissimilar responses across countries. By asking and addressing the above questions using different techniques, researchers will produce findings with a strong heterogeneity.

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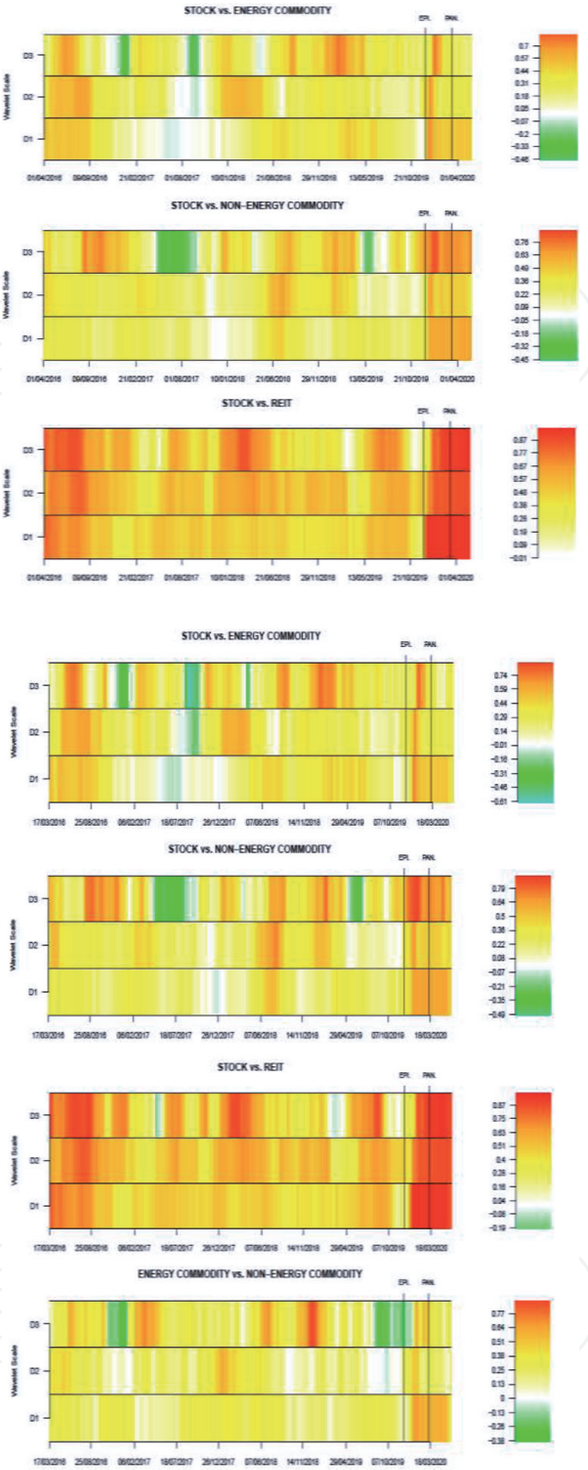
Conflict of interest

The authors declare no conflict of interest.

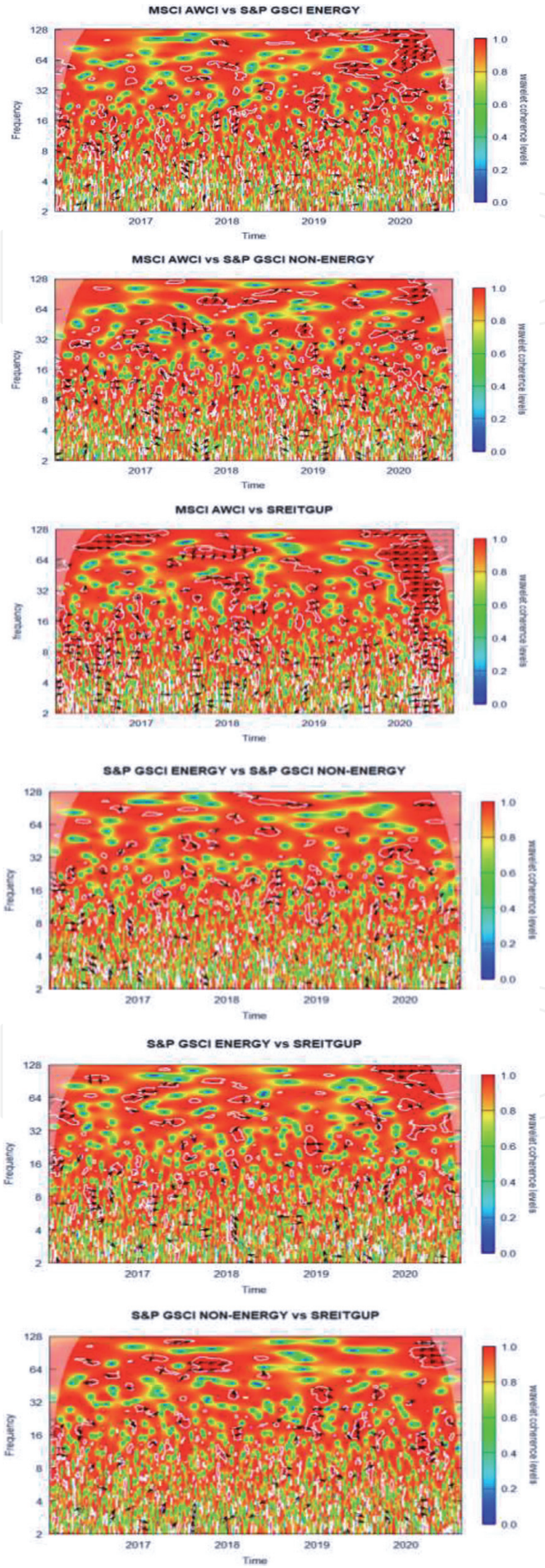
A. Appendix A



Appendix A: A 120-day RWWC for pairs of selected global markets.

Note: the strength of the dynamic wavelet correlation for the pairs is displayed by the heat map colors, which ranges from weak to high (thus, from blue, cyan, green, white, yellow, orange, to red respectively), where red (blue) denotes highest (lowest) wavelet correlation coefficients within a 95% confidence interval (refer to the web version of the article for color representation).

B. Appendix B


MSCI AWCI vs S&P GSCI ENERGY
MSCI AWCI vs S&P GSCI NON-ENERGY
MSCI AWCI vs SREITGUP
S&P GSCI ENERGY vs S&P GSCI NON-ENERGY
S&P GSCI ENERGY vs SREITGUP
S&P GSCI NON-ENERGY vs SREITGUP
Frequency
Time
2017
2018
2019
2020
wavelet coherence levels

Appendix B: Cross-wavelet squared coherence with phase difference for selected pairs of global markets.

Note: In the wavelet coherence plots, the time interval (01.04.2016–2017.08.2020) is represented by the horizontal axis, while the vertical axis gives the frequencies (ranging from a 2-day to 128-day or half-year band). The degree of coherence is described by the heatmap, where warmer greenish to reddish colors denote medium-to-high interrelationship, and the light to deep blue indicates weak to uncorrelated markets. The 5% statistically significant coherence is displayed within the zones bounded by the white contours, and also confined to the "cone of influence" (the bell-shaped region), beyond that, coherence estimates become spurious. The direction of coherence is detected through the phase arrows, where the left and right black arrows denote that the two market series are out-of-phase (negative correlation or opposite movement) and in-phase (positive correlation or same direction of movement) respectively. Down pointing arrows put the first series as a leader; upward arrows mean the second is leading; right and down means the first series is leading; right and up suggest the first is lagging; the first series lags when the arrows point left and down, and leads the second series when the directional arrows point left and up. In all our plots, the first and second series correspond to the positions of the figure caption.

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