Jeffrey Cheah Institute on Southeast Asia

Jeffrey Sachs Center on Sustainable Development
Sunway University, Malaysia

CONTAGION EFFECT IN ASEAN-5 EXCHANGE RATES DURING COVID-19

Nur Ain Shahrier
Chung Tin Fah

JCI-JSC Working Paper

JCI-JSC-WP-2021-02

ABSTRACT

The aim of this study is to examine the short and long run contagion effects in ASEAN-5 exchange rates during Covid-19 period using daily exchange rates from June 2019 to December 2020. We adopt VECM within the structural VAR framework and higher time-frequency wavelet analysis to identify the pure contagion that happens in the short run and fundamentals-based contagion in the long run. The VECM findings show that there exist a long run exchange rates equilibrium during Covid-19 and should there be any disequilibrium, daily rate of adjustments in the Indonesian rupiah, Malaysia ringgit and Singapore dollar are 6.58%, 1.47% and 2.45% respectively. The wavelet power spectrum provides evidence of short run pure contagion that leads to fundamentals-based contagion for Indonesia, Malaysia and Singapore. The Philippines only experience short run contagion while Thailand experiences more of a long run contagion. Furthermore, the wavelet coherence shows Indonesia rupiah that would react first during this pandemic while the Philippines peso is the last one to react. These findings are important as it gives insights into the nature of contagion among ASEAN-5 exchange rates due to global shock of Covid-19 and the need for timely intervention to prevent the short run contagion turning into the long run contagion.

Keywords: currency linkages, exchange rates, contagion, Covid-19, ASEAN, wavelet analysis, vector error correction model

JEL Classification: F41, F30 and C10.

Corresponding author: Dr Nur Ain Shahrier, Department of Economics and Finance, Sunway University Malaysia. (nurains@sunway.edu.my). Department of Regional Science and Planning, Cornell University, USA. (ns296@cornell.edu)

Dr Chung Tin Fah, ELM Graduate School, HELP University. (tinfah@yahoo.com)

CONTAGION EFFECT IN ASEAN-5 EXCHANGE RATES DURING COVID-19

JCI-JSC Working Paper
JCI-JSC-WP-2021-02

October 2021

The JCI-JSC Working Paper series is published to disseminate preliminary research findings and stimulate intellectual discourse on wide-ranging public policy issues, ranging from security to sustainability. The views expressed herein are those of the author(s) and do not necessarily reflect the views of the Jeffrey Cheah Institute on Southeast Asia and the Jeffrey Sachs Center on Sustainable Development.

Authors
Nur Ain Shahrier
Chung Tin Fah

Editors
Woo Wing Thye
Shandre Mugan Thangavelu

ISBN: to be confirmed

Published by Sunway University Sdn Bhd
No. 5 Jalan Universiti
Bandar Sunway 47500
Selangor Darul Ehsan.

In collaboration with Jeffrey Cheah Institute on Southeast Asia and Jeffrey Sachs Center on Sustainable Development.

J**effrey Cheah Institute on Southeast Asia (JCI)** is an independent public policy think-tank based at Sunway University on the outskirts of the Malaysian capital, Kuala Lumpur. The Institute's research programme is grouped around three core disciplines: economic development, governance, and social progress, including education. Its mission is to develop solutions to some of the region's most pressing development problems. JCI seeks to engage policymakers, scholars and ordinary citizens through regular public lectures and discussions, and to build lasting academic partnerships in the region and the wider Asia-Pacific.

Jeffrey Sachs Center on Sustainable Development (JSC) is a regional center of excellence that advances the achievement of the 17 Sustainable Development Goals (SDGs) in Malaysia and Southeast Asia, tackling the sustainability agenda through education, training, research and policy advisory. Launched in December 2016, the Center operates out of Sunway University and was borne out of a $10 million gift from the Jeffrey Cheah Foundation (JCF) to the UN Sustainable Development Solutions Network (SDSN).

CONTAGION EFFECT IN ASEAN-5 EXCHANGE RATES DURING COVID-19

1. Introduction

The ebb and flows of Covid-19 infections along with the frequency and severity of lockdowns have raised concerns among emerging market and developing economies on the vulnerability of their currencies as national debt surge and growth plunge down. Covid-19 is a global shock that has triggered adjustments in international financial markets. Using the concept of contagion which is the intensification or increase in the spill over of a particular shock from one asset price to another asset price (Apergis and Christou, 2016), this study attempts to identify empirically the existence of exchange rates contagion among ASEAN-5 during this pandemic and the type of contagion in terms of pure-contagion (short-run) or fundamentals-based contagion (long-run).

Kollias et al. (2011) and Baker et al. (2020) illustrate that any exogenous shocks (e.g. outbreak announcement) are deemed to be infiltrated in terms of return and volatility in the financial markets and the severity is pronounced as 'black swan event' (Nicola et al., 2020). Cheong et al. (2020) confirms that financial market radiates signs of reversal with regards to the COVID-19 events that protrudes negativity connotation.

According to Dewandaru et al. (2017), contagion effect can be classified into two broad categories: pure contagion or fundamentals-based contagion. Pure contagion is defined as an excessive transmission shocks that is beyond the idiosyncratic and fundamental risks, which affects the short-term volatility without any effects on long-term trend (Forbes and Rigobon, 2012; Eichengreen et al., 1996). This usually happen as a result of investors or financial agents' irrational behaviour such as financial panics, herd behaviour, loss of confidence and increased risk aversion. On the contrary, fundamentals-based contagion can be transmitted through common shocks and common creditors, trade linkages, regional patterns, macroeconomic similarities or financial market integration which tends to shift the long-term trend (Pesenti and Tille, 2000; Calvo and Reinhart, 1996). Instead of looking at these two views as opposing, Pesenti and Tille (2000) suggested that they should complement each other to create a comprehensive picture of contagion in exchange rate markets. According to them, a country's pre-existing fundamental weaknesses will adversely affect the market sentiment and lead to confidence crisis that will further deteriorate its economic conditions. These self-fulfilling expectations and investors panic along with weak economic fundamentals are the crux to the genesis and spread of a crisis (Pesenti and Tille, 2000). Furthermore, transmission of shocks not necessarily happen from one country to its regional neighbours, but can be seen as initial disturbances being replicated by several countries due to common shocks. For example, ASEAN-5 countries share common features of stable exchange rate against the U.S. dollar as the U.S. is one of the ASEAN's largest trading partner. Hence, any shocks to the U.S. dollar as the anchor currency to ASEAN-5 is deemed as common shocks that can increase the vulnerability of ASEAN-5 countries' exchange rates (Klyuez and Dao, 20016).

For ASEAN-5 countries, the exchange rate regimes vary. According to IMF (2015) classification, Indonesia, the Philippines and Thailand are floaters since these countries profess floating exchange rates. On the contrary, Malaysia and Singapore's exchange rate regimes are classified as managed floating since they monitor the value of their currencies against an undisclosed basket of currencies and intervene in the market to ensure the currencies move within an undisclosed target band (Kluev and Dao, 2016). However, the monetary authorities of these ASEAN-5 countries do acknowledge their intervention in foreign exchange markets is to smooth excess volatility and not targeting any specific level of the exchange rates.

There are two main contributions of this research to the existing literature. First, this research is timely as it is among the earliest to examine the contagion effect in ASEAN-5 exchange rate markets during the ongoing Covid-19 pandemic. ASEAN-5 region is chosen as it is the fifth largest region by GDP in the world amounting to USD 2.77 trillion in 2017 with growth rate of 5-6% per annum (Aprilianti, 2019). Its stellar performance for the past 30 years and its success in weathering the Asian Financial Crisis (AFC)in 1997, SARS in the 2000s, and the Global Financial Crisis (GFC) in 2007 have made it worthwhile to study. Unlike those previous crises, the successive and cascading effect of Covid-19 has caused perilous disruption in global value chain on both supply and demand side. The restrictions on cross border mobility motivated by health reason have heavy impact on international trade and investments (Saurav et al., 2020) which can potentially expose countries to foreign exchange risks. According to Kumar and Persaud (2002), reduced in trade competitiveness can cause devaluation of currency that can trigger speculative attacks in the exchange rate equilibrium. Hence, in the absence of global efforts and the dire need for governments to quickly act in containing the Covid-19 worldwide, the rising financial volatility can heighten the currency contagion formation and transfer of uncertainty from one economy to another. The presence of contagion effects have empirically shown to exist among ASEAN-5 countries during AFC and GFC (Hurley and Santos 2001, Lee and Azali, 2010), however, no consensus emerged on the type of contagion.

Second, this research combines econometric techniques of vector error correction model (VECM) in the structural VAR framework and multi scale wavelet analysis. These two econometric techniques complement our findings such that the former captures the short- and long run impacts of exchange rates co-movement while the latter provides the specific timing, frequency and the origin country of the contagion effect. The results of the paper indicate that in both periods of before and during the Covid-19, there exists a long run causal relationship among ASEAN-5 exchange rates and only a few statistically significant exchange rate pairs in the short run. The VECM also reveals that should there be any shocks to the exchange rates, Indonesian rupiah, Malaysia ringgit and Singapore dollar appear to be the important bearers of short run adjustments to a long run equilibrium in the region as shown by the error correction term (ECT) whereby the volatilities are dampen at rates of 6.58%, 1.47% and 2.45% of daily adjustment respectively. The BIC and transfer entropy ratios further show significant reduction in bilateral relationship from pre Covid-19 period to more of unilateral relationship and isolated states during Covid-19. The wavelet power spectrum highlights heightened short and long run volatilities in Indonesia, Malaysia and Singapore exchange rates during this pandemic while the Philippines only experience minimal short run volatility. We also observe that Thailand experiences minimal short run volatility but heightened long run volatility. This result implies the effect of pure contagion in all ASEAN-5 countries due to market sentiment but this pure contagion becomes fundamentals-based for Indonesia, Malaysia, Singapore and Thailand.

The findings are important as it highlights the vulnerability in ASEAN-5 fundamentals that can turn short run market sentiment contagion into the long run contagion effect which will prolong the economic recovery post pandemic. Furthermore, the rate of exchange rate daily adjustments offer insights to investors and financial agents in their portfolio diversification decision. Realizing that ASEAN-5 central banks will intervene to dampen any excessive volatility in their exchange rates which can deplete their international forex reserve quickly, identifying the type of contagion can offer suggestions to policy makers on the appropriate intervention to adopt and the timing of the intervention. Too late intervention can cause short term contagion effect to spill over to a long one.

This paper is organized as follows. Section 2 discusses the literatures on pure contagion versus fundamentals-based contagion. Section 3 presents empirical methodologies of VECM and wavelet analysis. Section 4 discusses the results. Section 5 provides the policy conclusion.

2. Pure Contagion versus Fundamentals-Based Contagion in ASEAN

Many research studies have tried to show the cause and effect of contagion especially in currency and equity markets. Omrane & Savaşer, (2017) report that currency market has reacted strongly with news release during the financial crisis, reflecting a contagion effect. Mondria and Quntana-Domeque (2013) conclude the investors reaction to news as the presence of an attention reallocation structure of financial contagion. Kaminsky and Schmukler (1999) characterize this as herd instincts while Dewandaru et al. (2017) classify it as an over- reaction of investors to apparent substantial bad news from international organizations, credit ratings, and so on that cause market turbulence.

The most recent study on currency linkages by Qureshi and Aftab (2020) covering the period of GFC shows the existence of contagion for Indonesia that lag behind all other ASEAN countries during the crisis period. However, these ASEAN countries show significant greater interdependency at lower level frequency (long run) which reaffirm the evidence of financial interdependence rather than pure contagion effect. During the period of AFC, studies on ASEAN currency markets by Hurley and Santos (2010), Lee and Azali (2010) and Chung and Ariff (2005) conclude the existence of contagion originated from Thailand as a results of greater variance decomposition during the crisis and Granger causation from Thailand to other ASEAN countries. Candelon et al. (2008) finds a similar conclusion that there is a significant increase of cross-country correlations in five Asian stock markets (Singapore, Thailand, South Korea, Taiwan and Malaysia) during AFC. The rising co-movement was due to sudden nature reflecting pure contagion effects rather than gradual adjustments suggesting financial interdependence.

On the contrary, when Forbes and Rigobon (2002) remove heteroscedasticity bias from correlations, they find a small evidence of co-movement during AFC and conclude that this is merely interdependence rather than pure contagion. Meng and Huang (2019) also detect different degree of financial interdependence among ASEAN economies when they examine the variables at lower and higher frequencies. Park and Song (2002) also show evidence that AFC did not trigger the crisis in South Korea because the contagion effect is very minimal.

As an unclear debate pertaining to pure contagion versus fundamentals-based contagion progress, our study contributes to this pool of literatures in investigating the evolution of short-run and long-run exchange rates contagion pre and during the Covid-19 pandemic using daily data from June 2019 to December 2020 whereby WHO official announcements are used as the break point for crisis period. Instead of looking at pure contagion and fundamentals-based contagion as mutually exclusive event, our empirical results have shown that they are indeed complementary, a prolong short run that eventually turns into a long run contagion, supporting Pesenti and Tille (2000) argument.

In terms of the methodology used to analyse the exchange rate inter-dependency and contagion, many of the studies have used co-integration tests to find long run relationship among exchange rates (Kuhl 2010; Jeon and Lee 2002). The idea is that any short run deviations without shifting apart the long-term state is deemed as pure contagion effect. Other studies use Granger causality between exchange rates (Beirne & Gieck 2014; Nikkinen et al. 2011) to detect the presence of contagion during the period of calamities; principal component analysis that decomposed exchange rates into distinctive component and a common factor (Beckmann et al., 2012); generalized autoregressive conditional heteroskedasticity (GARCH) model to observe volatility spill over among different currencies (Zabiulla, 2015; Tamakoshi and Hamori, 2014) ; wavelet analysis that allows the investigation of financial interdependence and contagion across time and frequency (Qureshi and Aftab, 2020; Meng and Huang, 2019); spatial econometrics (Frexedas and Vaya, 2005) and panel probit model (Salgado et al., 2000) that identify common creditor and reserve adequacy as the main factors that propagate the contagion effect. Since some of these empirical techniques suffer from heteroscedasticity problem in their correlation estimate, the testing of contagion effect can be biased (Dewandaru et al., 2017; Forbes and Rigobon, 2002). In addition, the econometrics techniques only have standard time domain instruments that make it hard to distinguished fundamentals-based contagion versus other shocks transmission.

Due to this, our study supplements the econometrics technique of VECM with wavelet multi-scale analysis to examine the evidence of contagion among ASEAN-5 exchange rates that happen during Covid-19 at varying degree of severity and time period.

3. Data and Empirical Models

3.1 Data Description

The daily data for exchange rate (local currency per USD, end of the period) come primarily from E-Ikon DataStream and it spans from 3rd June 2019 to 25th December 2020. Data are Malaysia ringgit (MYR), Singapore dollar (SGD), Thai baht (THB), Indonesia rupiah (IDR), and Philippine peso (PHP). The cut-off dates for pre and during crisis periods vary across countries and were obtained from Oxford Covid-19 Government Response Tracker.

The pre-crisis period starts from 3rd June 2019 to the dates when lockdowns were announced. According to WHO, lockdowns are often referred to as large scale physical distancing and non-essential movement restrictions, including stay-at-home orders which is the strictest measures possible to contain the pandemic. The earliest imposition of lockdowns among ASEAN-5 countries was in Indonesia on 17th March, followed by Malaysia on 18th March and the Philippines on 21st March. Thailand imposition was on 26th March and finally Singapore on 7th April.

3.2 Volatility Measure

The volatility measure adopted in our study is constructed following Hurley and Santos (2001). The construction use moving average sample standard deviation of the growth rate of exchange rate to capture time varying movements of exchange rate fluctuations:

$$\left[\frac{1}{12}\sum_{i=1}^{12}(Z_{t+i-1} - Z_{t+i-2})^2\right]^{\frac{1}{2}}$$

where Z_t is the log of exchange rate. This measure is widely employed in the international trade and exchange rate volatility literature (Hurley and Santos, 2001).

As shown in Table 1, the average exchange rate volatilities have increased for Indonesia, Malaysia and Thailand during the Covid-19 but decreased for the Philippines and Singapore. Indonesia experienced the highest average and variations in volatility pre and during Covid-19, similar to the findings of Hurley and Santos (2001) during AFC while Singapore's exchange rate volatility has always been the lowest reflecting the country's strong economic fundamentals. In spite of Singapore having the lowest mean average volatility among the ASEAN countries, its exchange rate variation has increased during Covid-19 taking the second spot behind Indonesia. Moreover, the increased in kurtosis of Indonesia and Malaysia indicates the volatility of exchange rates have shifted to fatter tail distribution, whereas the significant decline in kurtosis (less than 3) of remaining nations imply lighter tail distributions in which their exchange rates volatility are more concentrated around the peak.

Country	Mean	Standard Deviation	Min/Max	Kurtosis
2019:06-2020:03 (Pre)				
Indonesia	0.2870 (1)	0.1784 (1)	0.0475/ 0.9645	4.6435
Malaysia	0.2019 (4)	0.0787 (5)	0.0904/ 0.4811	2.8886
Philippines	0.2847 (2)	0.0971 (3)	0.1387/ 0.5843	0.5695
Singapore	0.1717 (5)	0.0912 (4)	0.0477/ 0.6017	8.4331
Thailand	0.2349 (3)	0.1126 (2)	0.0636/ 0.6708	2.5452
2020:03-2020:12 (During)				
Indonesia	0.4341(1)	0.2534 (1)	0.0552/ 1.6351	6.5747
Malaysia	0.2441 (3)	0.1379 (3)	0.0992/ 0.0810	6.5468
Philippines	0.2010 (4)	0.0704 (5)	0.0831/ 0.3945	-0.0700
Singapore	0.1453 (5)	0.1879 (2)	0.0016/ 0.7789	1.6856
Thailand	0.2575 (2)	0.0741 (4)	0.1144/ 0.4717	0.2142

Table 1: Mean and Standard Deviation of Pre and During Covid-19 Exchange Rate Volatility Indices: Daily Observations from 2019:6-2020:12

Notes: Number in parentheses are ranks. Source: E-IKON Datastream

We also examine the exchange rate volatility correlations across the ASEAN-5 countries with the results in Table 2 show almost all the correlations across these nations volatility in exchange rates decline during Covid-19 from the period before. The above diagonal values refer to correlation of these countries exchange rate volatilities during crisis period, and the below diagonal values refer to pre-crisis period volatilities. There are high volatility correlations before the period of Covid-19 in March 2020 and for some, they are cut by more than half during Covid-19. For example, the correlation of Malaysia ringgit and Singapore dollar exchange rates volatility is 0.6950 (pre) and has declined to 0.1909 (during Covid-19). The results are in contrast to the experience during the AFC whereby ASEAN-5 correlation in exchange rate volatilities had heightened.

	MYR	IDR	PHP	THB	SGD
MYR	1	0.7498*	**0.2970**	0.3328*	0.1909
IDR	0.847*	1	**0.3909***	0.3728*	0.2282
PHP	**0.2473**	**0.3497***	1	**-0.2227**	0.2889
THB	0.7286*	0.7413*	**0.3302***	1	-0.1670
SGD	0.6950*	0.6752*	0.4763*	0.8029*	1

Table 2: Pairwise Correlation between Countries' Volatility Exchange Rates

Note: The above diagonal values refer to correlation of these countries during crisis period; below diagonal values refer to correlation of these countries' pre-crisis period. The bold numbers show the decreased in correlation from pre to during Covid-19.

3.3 Empirical Model I: Vector Error Correction (VECM)

The In order to evaluate the dynamic linkages of exchange rates among these currencies both in short and long run, we adopt cointegration and vector error correction model (VECM) within the vector auto regression (VAR) framework. The initial step is to examine the stationarity or integration properties for the log of exchange rates using augmented Dickey Fuller (ADF) and Philips-Perron (PP) unit root tests for both period of pre and during Covid-19. In addition to the standard interpretation of unit root tests, the stationarity of ASEAN-5 exchange rates suggests these series are moving together against the third currency, in this case their anchor currency, U.S. dollar. Furthermore, to use the VECM model, all our variables need to be I(1).

Next, in order to avoid arbitrary ordering of the variables in the triangular identification schemes used in VAR-VECM, we use variable-lag Granger causality and variable-lag Transfer Entropy that was recently developed (Amornbunchornvej et al., 2020). The typical Granger causality makes a strong assumption that the effect of time series at every time point is influenced by a combination of other time series with a fixed time delay (Amornbunchornvej et al. 2020). However, this assumption of fixed time delay may not be accurate when these variables move in a non-linear manner. To address this potential problem, we attempt to use variable-lag Granger causality and variable-lag Transfer Entropy that is a non-linear structural equations of Granger causality. The ordering of the ASEAN-5 countries are based on the degree of strength define by Bayesian Information Criterion (BIC) difference ratio in variable-lag Granger causality and Transfer Entropy ratio in variable-lag Transfer Entropy to determine whether X causes Y. The assumption is that the larger the strength of causation, the greater the susceptibility of that exchange rate to another exchange rate. The analysis is needed since the cointegration tests are sensitive to the inclusion or exclusion of a country's exchange rate (Majid and Kassim, 2009). The results from these tests are used in the ordering of our

VAR multivariate framework and as robustness checks to our conclusion. An alternative approach in VAR ordering is using variance decomposition of each of this time series (Hurley and Santos, 2001).

From here, we construct a structure to be used as a basis in our VAR (structural VAR) pre and during the Covid-19. The structure is important when we analyse the innovation shocks and its transmission from one exchange rate to the other in order to avoid specification of relationship that are weak or may not exist. The following are estimates of VAR model:

$$AY_t = \mu + \sum_i \Gamma_i Y_{t-i} + B\varepsilon_t \quad \text{(structural VAR)} \qquad (2)$$

$$Y_t = \alpha + \sum_i Z_i Y_{t-i} + Q\varepsilon_t \quad \text{(reduced form VAR)} \qquad (3)$$

Where Y_t is a (n*1) vector of I(1) variables; β_1 are (n x n) matrices of parameters; α is a (n x 1) vector of constants; ε_t is a vector of error terms; and k is the maximum number of lag to obtain white noise process. The appropriate lag used is identified using Schwarz information criteria (SC) and error autocorrelation (correlogram).

To investigate the existence of a long run equilibrium relationship, we employ the Johansen and Julius maximum-likelihood test procedure.[1] This test is based on maximum likelihood estimation (MLE) of the VAR model. This means that each variable is treated as an endogenous variable that depends on its own lags and the lags of other variables, including the exogenous variable. Specifically, Y_t is a vector of n stochastic variables, then there exists a k-lag vector autoregression with Gaussian errors of the following form:

$$\Delta Y_t = a + \Gamma_1 \Delta Y_{t-1} + \ldots + \Gamma_{k-1} \Delta Y_{t-k-1} + \Pi Y_{t-1} + z_t \qquad (4)$$

where Γ are coefficient matrices and z_t is a vector of white noise process.

In addition to optimal lag length test within the VAR framework, we also conduct a cointegration test to provide complementary support to the unit root conclusion. The cointegration procedure yields two likelihood ratio test statistics, referred to as the trace test and the maximum eigenvalue (λ-max) test. Engle and Granger (1987) observe that although economic time series (log of exchange rates) may not have the stationary characteristics at level, meaning that the time series can wander through time, however, the linear combination of these series can converge to a long run relationship over time. In other words, system's short-run dynamic is determined, among others, by its steady state, and hence the latter should be incorporated into the model exogenously. In the context of present analysis, a finding of cointegration would simply mean that linear combination of ASEAN-5 exchange rates move together against their anchor currency, U.S. dollar. So, the transmission mechanism underlying these exchange rates dynamic movement hypothesis is stable and thus more predictable over long periods. Furthermore, shocks that are unique to one time series will quickly dissipate as the variables adjust back to their common trend.

Using 3-lagged variable model, the VECM's specification is as follows:

$$\Delta Y_t = \alpha + \Pi Y_{t-1} - \Pi_1 \Delta Y_{t-1} - \Pi_2 \Delta Y_{t-2} + \varepsilon_t \qquad (5)$$

---

[1] This approach is especially appealing since it provides a unified framework for estimating and testing cointegrating relations in the context of a VECM model. Thus, by treating all the variables as endogenous, this approach avoids the arbitrary choice of the dependent variable in the cointegrating equations, as in the Engle-Granger methodology. They have also been shown to have good large- and finite-sample properties (see Phillips, 1991, Cheung and Lai, 1993, and Gonzala, 1994).

Generalization of the above result yields the following expression for ΔY_t:

$$\Delta Y_t = \alpha + (\sum_i^n Z_i - I)Y_{t-1} - \sum_i^{n-1}(\sum_{j=i+1}^n Z_j)\Delta Y_{t-i} + \varepsilon_t \quad , \tag{6}$$

where $\Pi = \sum_i^n Z_i - I = \eta\beta^T$, $\Pi_i = \sum_i^{n-1}(\sum_{j=i+1}^n Z_j)$, (η, β are adjustment and cointegration matrices respectively[2]). From equation (6), we can summarize the conventional Error Correction Model (ECM) for cointegrated series as:

$$\Delta Y_t = \alpha_0 + \gamma Z_{t-1} + \sum_i^{n-1} \delta_i \, \Delta Y_{t-i} + \sum_i^{n-1} \theta_i \, \Delta X_{t-i} + \varepsilon_t \tag{7}$$

Z is the Error Correction Term (ECT) and is obtained from the OLS residuals from the following long-run cointegrating regression:

$$Y_t = \alpha_0 + \alpha_1 X_t + \mu_t, \tag{8}$$

$$Z_{t-1} = \text{ECT} = Y_{t-i} - \alpha_0 + \alpha_1 X_{t-1} \tag{9}$$

The ECT shows how the last period deviation from the long run equilibrium (the error) influences the short run dynamics of the dependent variable. Thus, the coefficient γ measures the speed at which Y returns to equilibrium after a change in Z.

While VECM methodology provides evidence to our hypothesis that contagion effect exists in ASEAN-5 exchange rate markets through the existence of cointegration during the pandemic, it doesn't answer the type of contagion that each country is facing and which country responds first to the Covid-19 shocks and which comes in later. In other words, we need more specific time and frequency scale variables to dissect what actually happen to these exchange rates on daily basis that lead to long run effect. The latter part is proved using wavelet analysis. The wavelet approach offers time and frequency decomposition on currencies co-movement among these ASEAN-5 markets. The multi scale relationship is important as dynamics of co-movement of currencies can potentially be different at different time horizon (Meng and Huang, 2019). Therefore, we use wavelet power spectrum (WPS) to estimate the variation of each exchange rates movement and wavelet coherency (WC) to capture the covariance between two time series at different time and frequency domains.

3.4 Empirical Model II: Wavelet Analysis

The wavelet transform is a powerful tool for analyzing nonstationary time series in both time and frequency domains. It can overcome issues related to current techniques in econometrics on: (1) how these markets move together and (2) find the strength of cointegration in the Johanson cointegration method, which provide the number of co-integrating relationship. As mentioned by Dewandaru et al. (2017) and Forbes and Rigobon, (2002), the standard correlation in econometrics fail to correct for heteroscedasticity problem that may cause over estimation of the contagion effect. Since wavelet analysis is flexible and does not require strong assumption about the data generating process and its stationarity, such problems will not arise here.

[2] Number of long-run equilibria is exactly the rank of matrix Π

In this study, we apply wavelet power spectrum (WPS) and wavelet coherency (WC) in the form of continuous wavelet transform, following Dewandaru et al. (2017). WPS and WC capture the variation in exchange rate movement for each country and covariation across countries exchange rates movement pre and during Covid-19 period respectively.

The continuous wavelet transforms of a time series W_x with respect to t is a function of the following convolution:

$$W_x(\tau, s) = \int_{-\infty}^{+\infty} X(t)\overline{\varphi}_{t,s}(t)dt = \frac{1}{\sqrt{s}}\int_{-\infty}^{+\infty}\left[x(t)\overline{\varphi}\left(\frac{t-\tau}{s}\right)\right]dt \quad (10)$$

where the bar denotes the complex conjugate, τ is the time position/parameter controlling its location, s is the scale or dilation parameter that controls width of the wavelet, and is a normalization factor to make sure that wavelet transforms are comparable across frequency bands and time series. The chosen mother wavelet is Morlet wavelet given by:

$$\varphi_{\omega_0} = \pi^{-\frac{1}{4}} \mathrm{j}\omega_0 \tau e^{-\frac{t^2}{2}} \quad (11)$$

The Morlet wavelet is a complex sine wave within a Gaussian envelope and ω_0 is the wave number. In this study, we choose ω_0 equals to 6 since it provides a good balance between time and frequency localization (Dewandaru et. al., 2017). According to Aguiar-Conraria and Soares (2015), Morlet wavelet has extra properties such as its ability to convert wavelet scales into equal frequencies; optimal joint time-frequency concentration; equal time and frequency radius and more importantly, it is an analytical wavelet. WPS is defined as:

$$(WPS)_x(\tau, s) = |W_x(\tau, s)|^2 \quad (12)$$

WPS measures the relative variance contribution at different time and frequency for each time series. The hypothesis is the statistically significant of wavelet power against the null hypothesis of a stationary process. In its output, the thick black contour estimated using Monte Carlo simulations phase randomized surrogate series defines the region that is significant at 5% statistical level against the red noise. The cone of influence (COI) signals the edge effects is displayed using grey line and any areas outside this grey line (or COI) should be neglected as there is no statistical confidence. The power of variation ranges from blue (low power) to red (high power). WC is given by two times series $x(t)$ and $y(t)$ as follows:

$$R^2_{x,y}(\tau, s) = \frac{|s\left(s^{-1}W_{x_i x_j}(\tau,s)\right)|^2}{\left(s\left(s^{-1}|W_{x_i}(\tau,s)|^2\right).s(s^{-1}|W_{x_j}(\tau,s)|^2\right)}, R^2 \in [0,1] \quad (13)$$

where S is a smoothing operator in time and frequency bands. The WC measures co-movement of two time series over time and frequencies. High (low) value of wavelet coherency indicates a strong (weak) co-movement and this is displayed using contour plot. The horizontal axis represents time component and the vertical axis represents frequency component. The degree of co-movement is measured through the coherency ranging from blue (low coherency) to red (high coherency) and regions that have high coherency shows strong local correlation. Similar to WPS, we only read the values within the cone of influence as it shows a 5% significance level estimated from a Monte Carlo simulation. In addition to the colour ranges, the appearance of arrows shows a phase-difference, meaning the co-movement of these time series at the specified frequency.

If $\emptyset_{xy} \in \left[0, \frac{\pi}{2}\right]$, then the two series x and y are said to move in-phase with x leads y; if $\emptyset_{xy} \in \left[-\frac{\pi}{2}, 0\right]$, then y leads x. The two series move anti-phase when $\emptyset_{xy} \in \left[\frac{\pi}{2}, \pi\right]$with y leading, or $\emptyset_{xy} \in$

$\left[-\frac{\pi}{2}, -\pi\right]$ with x leading. Therefore, the WC has the power to not only show exchange rate co-movements during the pandemic at different time and frequency but offers the leading market that can has spill over effect to other market.

In this study, we define a short-term horizon as less than 3 months (or higher frequency band up to 2^5=64 working days) to reflect the trading behaviour of short-term investors while beyond this period is considered as long term or lower frequency bands. The 3 months period is also in line with most duration on currency swap and production line contracts. Hence, pure contagion effect that falls in short term period are associated with market sentiment, liquidity preferences, cross-border asset listing, financial panics, herd behaviour, loss of confidence and increased risk aversion (Dewandaru et al., 2015). In contrast, the lower frequency of more than 64 working days (3 months) reflects the fundamental linkages that are related to real economy and long run equilibrium among ASEAN-5 exchange rates.

4. Results and Analysis

The ADF and PP tests show that all series are stationary after first differencing, implying that they are integrated of order one, I(1)[3] . Since the first differencing represents the growth in ASEAN-5 exchange rates, this implies that the growth in exchange rates move in synchronisation against their anchor currency, U.S. dollar. The unit root tests are not satisfactory at level implying that the level exchange rates can wander off from its long run trajectory and do not have any specific level targeting towards the U.S. dollar[4].

Next, from the variable-lag Granger Causality and variable-lag Transfer Entropy results, we conclude that the number of bidirectional causations decrease from pre-pandemic period to during Covid-19 period. In other words, we have more unidirectional effects among ASEAN-5 countries during the pandemic that results in absorbing or isolated states in which such effect remains in that particular state and doesn't spill over to its neighbouring countries. According to Pesenti and Tille (2000), the international transmission of a currency crisis can occur even if country A and country B do no trade with each other but the exports are competing in the same foreign markets. Since the causation between these countries are reduced during the pandemic, it is more likely that the synchronised movement in their exchange rates are due to the third currency, U.S. dollar. Based on BIC and Transfer Entropy ratios, the ordering of variables in our structured VAR model during both periods starting with the most susceptible exchange rate to outside influence are as follow:

Indonesia -> Thailand -> Singapore -> Malaysia -> Philippines. *(Pre and During)*

Next, the trace test and the maximum eigenvalue (λ-max) test for cointegration postulate the existence of one cointegrating vector (r=1) in each period. This means there is a common factor or permanent component i.e. the U.S. dollar driving the entire system of exchange rate movements in ASEAN-5. These variables are connected in the long run and their eccentricities from the long run equilibrium have been rectified.

Given the cointegration results, the next stage in our model building process requires the construction of a multivariate VECM for Indonesia, Malaysia, the Philippines, Singapore and Thailand where the time series are found to be cointegrated. Looking at the long run results in Equation (14) and (15) below, there seem to be a positive relationship between Indonesia rupiah and Singapore dollar and negative relationship between Indonesia rupiah and Malaysia ringgit and Thai baht in

[3] The results for Augmented Dickey Fuller (ADF) and Philips Perron (PP) unit root tests, variable-lag Granger Causality and variable lag Transfer Entropy, trace test and maximum eigen value test are available upon request.
[4] The ADF and PP tests results are available upon request.

both periods. The positive relationship between Indonesia rupiah and the Philippines peso before the pandemic turns into negative relationship during the pandemic.

The positive relationship here implies that the two exchange rates reaction to the common shocks move up and down in a broadly synchronous fashion but a negative relationship implies the asynchronous movements in the two exchange rates. If we take an example of Singapore dollar and Indonesia rupiah, this implies that a 1% change in Singapore dollar moves with 1.03% change in Indonesia Rupiah (pre-pandemic) while the effect is 8.75% during the pandemic[5]. For exchange rates of Singapore, the Philippines and Thailand, the long run impact with Indonesia exchange rate amplifies during this Covid-19. In contrast, the elasticity of Indonesia rupiah and Malaysia ringgit becomes insignificant and decline during the pandemic.

Pre Covid-19 Results:

$$IDR_{t-1} = (1.03^{***}) * SGD_{t-1} - (2.73^{***}) * MYR_{t-1} + (0.04) * PHP_{t-1} - (0.64^{***}) * THB_{t-1} - 3.93$$

[2.85] [-8.16] [0.18] [-3.43] (14)

LM (2) = 17.45 (0.8648***) LM (4) = 29.58 (0.2401***)

During Covid-19 Results:

$$IDR_{t-1} = (8.75^{***}) * SGD_{t-1} - (1.16) * MYR_{t-1} - (4.93^{***}) * PHP_{t-1} - (3.72^{***}) * THB_{t-1} - 21.29$$

[1.88] [1.18] [1.07] [0.52] (15)

LM (2) = 28.75 (0.2744***) LM (4) = 35.05 (0.0874)

, ** and * denote significance at 1%, 5% and 10% respectively. The values in square parentheses are t-statistics.*

Next, we analyse the magnitude and speed of adjustments among these countries exchange rates from their long run equilibrium pre and during Covid-19 through the ECTs in Table 3. First, the magnitude of ECTs pre COVID-19 are almost negligible across ASEAN-5 and should there be any shocks to the equilibrium, only Indonesia rupiah that is statistically significant in bringing the exchange rate back to its long run path by 8.42% adjustment daily. The speed of adjustments back to this long run equilibrium is about 20 trading days (8.42/100*254days=21 trading days).

In contrast, during the Covid-19 period, Indonesia, Malaysia and Singapore ECTs are all significant in bringing their exchange rates back to their long run equilibrium. In other words, when there is any disequilibrium during this pandemic period, 6.58%, 1.47% and 2.45% of short run adjustments to a long run equilibrium respectively come from Indonesia rupiah, Malaysia ringgit and Singapore dollar. These adjustments to long run convergence take up to 20 days for Indonesia rupiah, 68 days for Malaysia ringgit and 40 days for Singapore dollar. The central banks of these three countries would intervene in the market to stabilise any excessive fluctuations in their exchange rates at the mentioned ECTs to avoid prolonged contagion effect.

In the short run, there are no obvious causation among these exchange rates (Appendix 1) both pre and during Covid-19. This implies that in the short run, there is no high likelihood of spill over shocks between different exchange rates except for a few significant pairs. For example, pre Covid-19

[5] The coefficient represents the elasticity since we have log-log regression.

shows statistically significant relationship between Malaysia ringgit and Singapore dollar but during Covid-19, this relationship is no longer significant.

Dependent Variable	Pre-Crisis Period (ECT)	During Crisis (ECT)
IDR	-0.0842***	-0.0658***
MYR	0.0039	-0.0147***
PHP	0.0177	-0.0051
SGD	0.0170	-0.0245***
THB	0.0013	0.0139

Table 3: Error Correction Term (ECT) for ASEAN-5 Currencies

Although the VECM results are useful in proving to us the existence of a long run contagion effect and the daily adjustments when there is disequilibrium, the short run results between these exchange rates are inconclusive. The WPS in wavelet analysis offers greater empirical evidence at more granular frequency and time domains that can identify when contagion happen and the timely reaction of reaction of exchange rates between these countries.

The WPS results (Appendix 2) show heightened volatility (red colour) during the Covid-19 period (at x-axis=200) that exists for both short (less than 64 days) and long-term period in Indonesia, Malaysia and Singapore. This implies that pure contagion that happen in the short run due to market sentiments has become fundamentals-based contagion. According to Pesenti and Tille (2000), self-fulfilling prophecy can shift market participants' expectations in the short run to one that plays a prominent role in the determination of a crisis in the long run. Combining with the results from VECM (Table 4), we know that should there be any disequilibrium, the central banks of these three exchange rates will intervene to stabilize the volatilities in order to prevent any contagion effect in the short run and disruption to long run equilibrium. The exchange rate volatility effect in the Philippines is very minimal in the short run and doesn't prolong to long run (orange patch that appears at lower frequency band). This implies that the Philippines only experience pure contagion during the Covid-19. For Thailand, the short run volatility is minimal but more pronounced in the long run.

To determine the lead and lag currency, we use wavelet coherency (Appendix 3) that provides evaluation on market integration. The WC shows a country that first response to the shocks follow by another country. In this study, the shock referred to is the common shock of Covid-19 that affects the countries anchor currency, U.S. Dollar. Indonesia rupiah reacts first to the shocks in the short run followed by the remaining four countries (Table 4). This pure contagion due to market sentiments will spill over to fundamentals-based contagion in the long run for Indonesia rupiah-Thai baht and Indonesia rupiah-Malaysia ringgit pairs. It is also interesting to note on the co-movement of Malaysia ringgit and Singapore dollar that seems to affect each other in the short run but in the long run, Malaysia ringgit will react first followed by Singapore dollar. It is to be noted that Malaysia is Singapore third largest trading partner and both countries main exports are the U.S. and China. In the case of Malaysia and Thailand, the immediate contagion effect to Thai baht comes from Malaysia ringgit performance. For Thai baht and Singapore dollar, the lead in the short run comes from Thai baht performance but in the long run it depends on Singapore dollar. For the Philippines peso, its volatility in the short run during the pandemic (at x-axis =200) is highly affected by the co-movement in the other four countries as shown by the wavelet coherency results with arrows pointing in various direction (Appendix 3).

Covariance of Countries during Covid-19:	Short Run (leads)	Long Run (leads)
Indonesia and Malaysia	Indonesia	Indonesia
Indonesia and Philippines	Indonesia	-
Indonesia and Thailand	Indonesia	Indonesia
Indonesia and Singapore	Indonesia	-
Malaysia and Philippines	Malaysia	-
Malaysia and Thailand	Malaysia (up to 16 days) Thailand (32 days to 64 days)	-
Malaysia and Singapore	Malaysia Singapore	Malaysia
Philippines and Thailand	Thailand	-
Philippines and Singapore	Singapore	
Thailand and Singapore	Thailand (8 to 16 days)	Singapore

Table 4: Wavelet Coherency for ASEAN-5 Currencies

5. Policy Conclusion

We started this paper with two main objectives: (1) to investigate into the existence of contagion effect in ASEAN-5 exchange rates during Covid-19, (2) the nature of contagion whether it is a pure-contagion (short run) or fundamentals-based contagion (long run) or both are complementary in nature. Since this paper investigates the impact on exchange rates due to common global shock of Covid-19, we believe the disequilibrium that arise is due to the anchor currency of these exchange rates, that is the U.S. dollar. In other words, it is unlikely for example Malaysia ringgit to react solely because the movement in Indonesia rupiah, but the reaction is more plausible due to the movement in the U.S. dollar.

To begin with, the ADF and PP unit root tests show nonstationarity at log level of exchange rates. This implies that ASEAN-5 exchange rates do not have specific target of U.S. dollar to maintain which is consistent with the free floating of Indonesia rupiah, the Philippines peso and Thai baht while Malaysia ringgit and Singapore dollar are classified as managed floating. However, the unit root tests are stationary at first differencing, which implies that the fluctuations in the exchange rates growth are monitored and central banks will intervene to dampen any excessive variation. The cointegration in the VECM results demonstrate the existence of a long run equilibrium among these ASEAN-5 exchange rates and that there are a few statistically significant currencies pairs in the short run. Hence, any disequilibrium from the long run trajectory during this pandemic period will cause Indonesia rupiah, Malaysia ringgit and Singapore dollar to adjust on daily basis by 6.58%, 1.47% and 2.45% respectively to bring the exchange rates back to the long run equilibrium. These daily adjustments can take up to 20 days for Indonesian rupiah, 68 days for Malaysia ringgit and 40 days for Singapore dollar to converge back to its long run equilibrium.

Next, the findings from wavelet power spectrum imply that ASEAN-5 countries experience different degrees of exchange rates volatility throughout the pandemic period. We define short run as period that is less than 3 months (64 working days) and long run is the time period beyond that. Pure and fundamentals-based contagion happen to Indonesia rupiah, Malaysia ringgit and Singapore dollar. This shows the prolonged pure contagion can turn into fundamentals-based contagion for these three exchange rates. The Philippines peso has only experienced pure contagion and no spill over to fundamentals-based contagion. The Thai baht also experiences minimal pure contagion in the short run but heightened fundamentals-based contagion in the long run.

The wavelet coherency shows a country that first response to the shocks follow by another country's reaction. Indonesian rupiah reacts first to the shocks in the short run followed by the remaining four countries. However, this pure contagion shock due to market sentiments will spill over to fundamentals-based contagion in the long run to exchange rate pairs of Indonesian rupiah-Thai baht and Indonesian rupiah-Malaysia ringgit. Malaysia ringgit and Singapore dollar seem to affect each other in the short run but in the long run, the Malaysia ringgit will react first followed by Singapore dollar. In the case of Malaysia and Thailand, the immediate contagion effect to Thai baht comes from Malaysia ringgit performance. For Thai baht and Singapore dollar, the lead in the short run comes from Thai baht performance but in the long run it depends on Singapore dollar. For the Philippines peso, its volatility in the short run is highly affected by the co-movement in the other four countries.

Our findings show that ASEAN-5 central banks do intervene in their forex market to dampen excessive variation of the growth in exchange rates fluctuations from its anchor currency, U.S. dollar due to adverse impact of Covid-19. This costly intervention could mean a substantial depletion of their international reserves at a very quick rate. Hence, in the short run, it is important to manage market sentiments since prolonged negative market expectations can spill over to long run and threaten the economic fundamentals of a country. Financial integration either through multilateral or bilateral currency swap can be arranged among these countries to hedge against exchange rate risk and potential short selling from speculators.

In the long run, the fundamental-based contagion requires these countries to diversify their trading partners and reform the structure of country's fundamentals including its current account balance, fiscal deficit, technological growth, labour market, human development capacity and physical infrastructure. The short run contagion should not be undermined as self-fulfilling prophecy could mean that it complements the long run contagion. Further research is needed to identify the cause of this contagion to provide a more comprehensive narrative to these findings and to tests if other major currencies do play their roles in ASEAN's exchange rate movements.

APPENDIX 1

Short Run Causation in Multivariate VECM (Pre COVID-19)

	Lags=2 Independent Variables				
Dependent Variables	ΔSGD	ΔPHP	ΔIDR	ΔTHB	ΔMYR
ΔSGD_{t-1}	0.1267	-0.0071	0.2484	0.1377	0.1798
	(0.1010)	(0.1624)	(0.1813)	(0.1314)	(0.1187)
ΔPHP_{t-1}	-0.1085*	-0.0506	0.1246	-0.0376	0.0537
	(0.0584)	(0.0939)	(0.1048)	(0.0759)	(0.0687)
ΔIDR_{t-1}	-0.0394	-0.1072	-0.0810	-0.1428**	0.0163
	(0.0492)	(0.0792)	(0.0884)	(0.0640)	(0.0578)
ΔTHB_{t-1}	-0.0490	-0.0823	0.0024	0.0728	-0.0232
	(0.0610)	(0.0982)	(0.1095)	(0.0794)	(0.0717)
ΔMYR_{t-1}	0.2228**	0.1641	-0.2139	0.0778	0.0239
	(0.0834)	(0.1341)	(0.1496)	(0.1085)	(0.0980)
ΔSGD_{t-2}	0.1786*	0.1113	0.2231	0.3114**	0.0776
	(0.0996)	(0.1601)	(0.1786)	(0.1295)	(0.1170)
ΔPHP_{t-2}	-0.0682	-0.0659	0.0065	0.0152	0.0155
	(0.0587)	(0.0944)	(0.1054)	(0.0764)	(0.0690)
ΔIDR_{t-2}	-0.0210	-0.0172	0.0481	0.0290	-0.0148
	(0.0497)	(0.0799)	(0.0892)	(0.0646)	(0.0584)
ΔTHB_{t-2}	-0.0079	0.1053	0.1829*	-0.0394	0.1409**
	(0.0603)	(0.0969)	(0.1081)	(0.0784)	(0.0708)
ΔMYR_{t-2}	0.1062	0.0830	-0.2036	-0.0602	0.0679
	(0.0826)	(0.1328)	(0.1482)	(0.1074)	(0.0970)
Adj. R^2	0.1252	0.01702	0.2757	0.1624	0.3643

*Significance at the 10 percent level, **Significance at the 5 percent level, ***Significance at the 1 percent level.ECT_{t-1} is the Error Correction Term derived from the residuals of long run estimation. Figures in parentheses are standard errors.

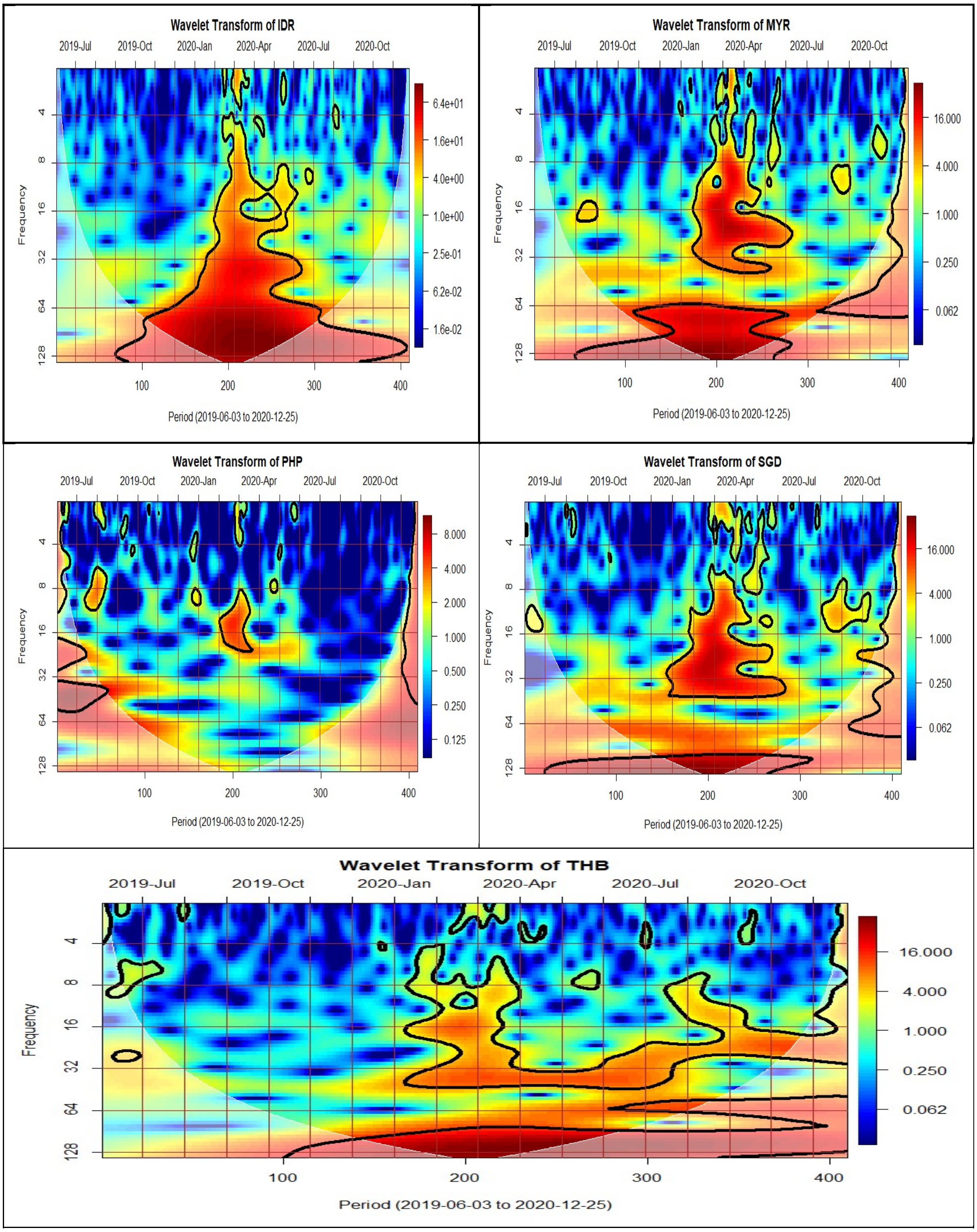
Short Run Causation in Multivariate VECM (During COVID-19)

	Lags=2 Independent Variables				
Dependent Variables	ΔSGD	ΔPHP	ΔIDR	ΔTHB	ΔMYR
ΔSGD_{t-1}	0.2235	0.1257	0.3328	-0.1073	0.1153
	(0.2375)	(0.226)	(0.4437)	(0.1799)	(0.2285)
ΔPHP_{t-1}	-0.2751	-0.1483	-0.1135	-0.0289	-0.1261
	(0.2266)	(0.2165)	(0.4233)	(0.1716)	(0.2180)
ΔIDR_{t-1}	0.1240	0.0324	0.0666	0.0221	-0.1058
	(0.1014)	(0.0969)	(0.1895)	(0.0768)	(0.0976)
ΔTHB_{t-1}	0.0111	0.0542	0.4543	0.1057	0.1348
	(0.2888)	(0.2756)	(0.5388)	(0.2185)	(0.2775)
ΔMYR_{t-1}	0.0532	0.0723	0.2686	-0.0281	0.4351***
	(0.2004)	(0.1915)	(0.3744)	(0.1518)	(0.1929)
ΔSGD_{t-2}	0.3405	0.1866	0.5956	0.0692	0.2991
	(0.2261)	(0.2161)	(0.4225)	(0.1713)	(0.2176)
ΔPHP_{t-2}	-0.1649	0.0732	0.4752	0.01906	0.4215**
	(0.2196)	(0.2098)	(0.4102)	(0.1663)	(0.2113)
ΔIDR_{t-2}	0.0156	-0.0882	0.0274	0.0549	-0.1229
	(0.1047)	(0.1000)	(0.1956)	(0.0793)	(0.1007)
ΔTHB_{t-2}	-0.7837***	-0.2241	-0.8596	-0.3350	-0.2772
	(0.2714)	(0.2593)	(0.5070)	(0.2056)	(0.2612)
ΔMYR_{t-2}	-0.1167	-0.1004	-0.1893	-0.1619	-0.0806**
	(0.2148)	(0.2052)	(0.4012)	(0.1627)	(0.2067)
Adj. R^2	0.1252	0.01702	0.2757	0.1624	0.3643

*Significance at the 10 percent level, **Significance at the 5 percent level, ***Significance at the 1 percent level.ECT_{t-1} is the Error Correction Term derived from the residuals of long run estimation. Figures in parentheses are standard errors.

APPENDIX 2

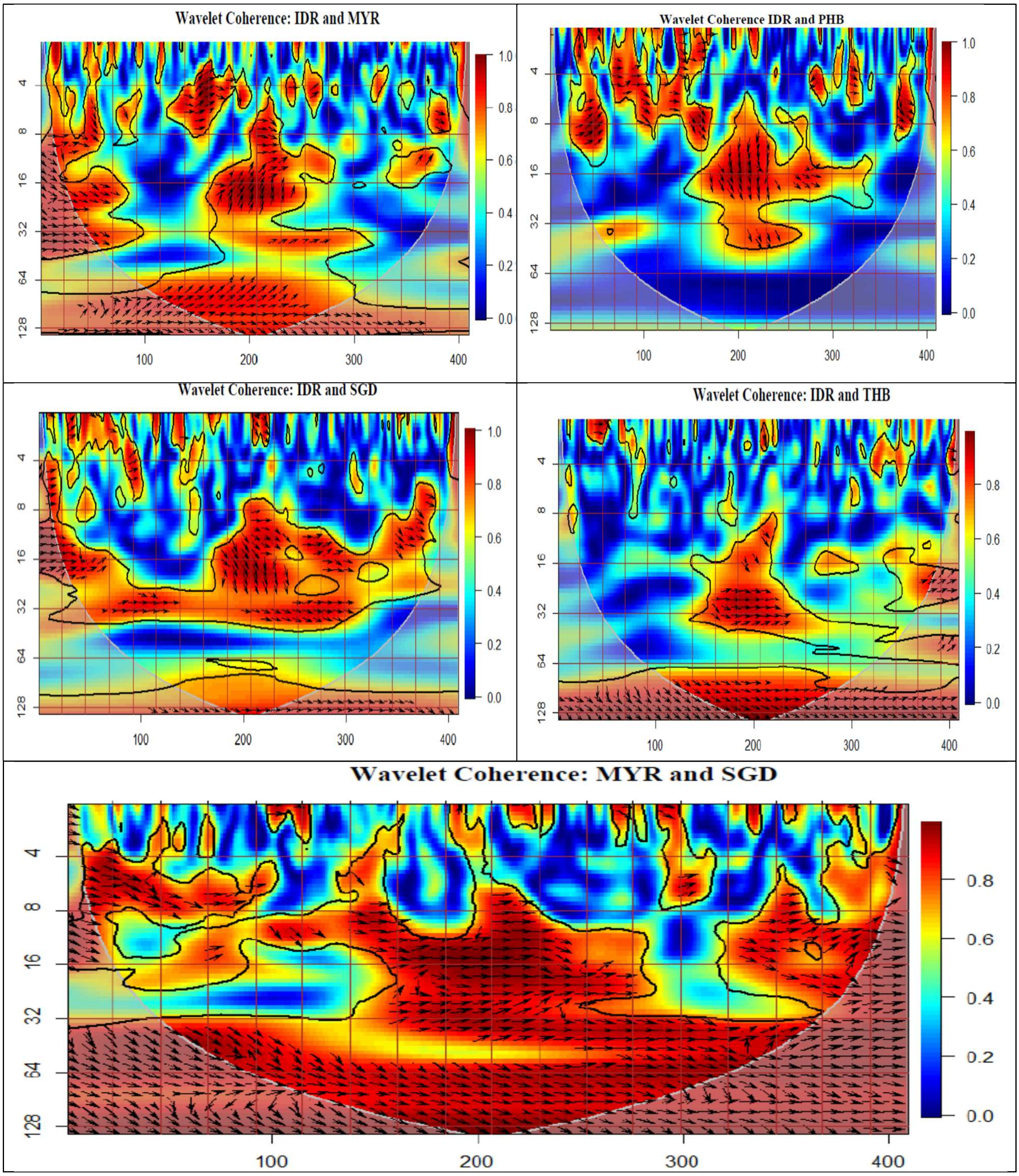
Wavelet Power Spectrum (Variance) for ASEAN-5 across Time and Frequency Domain



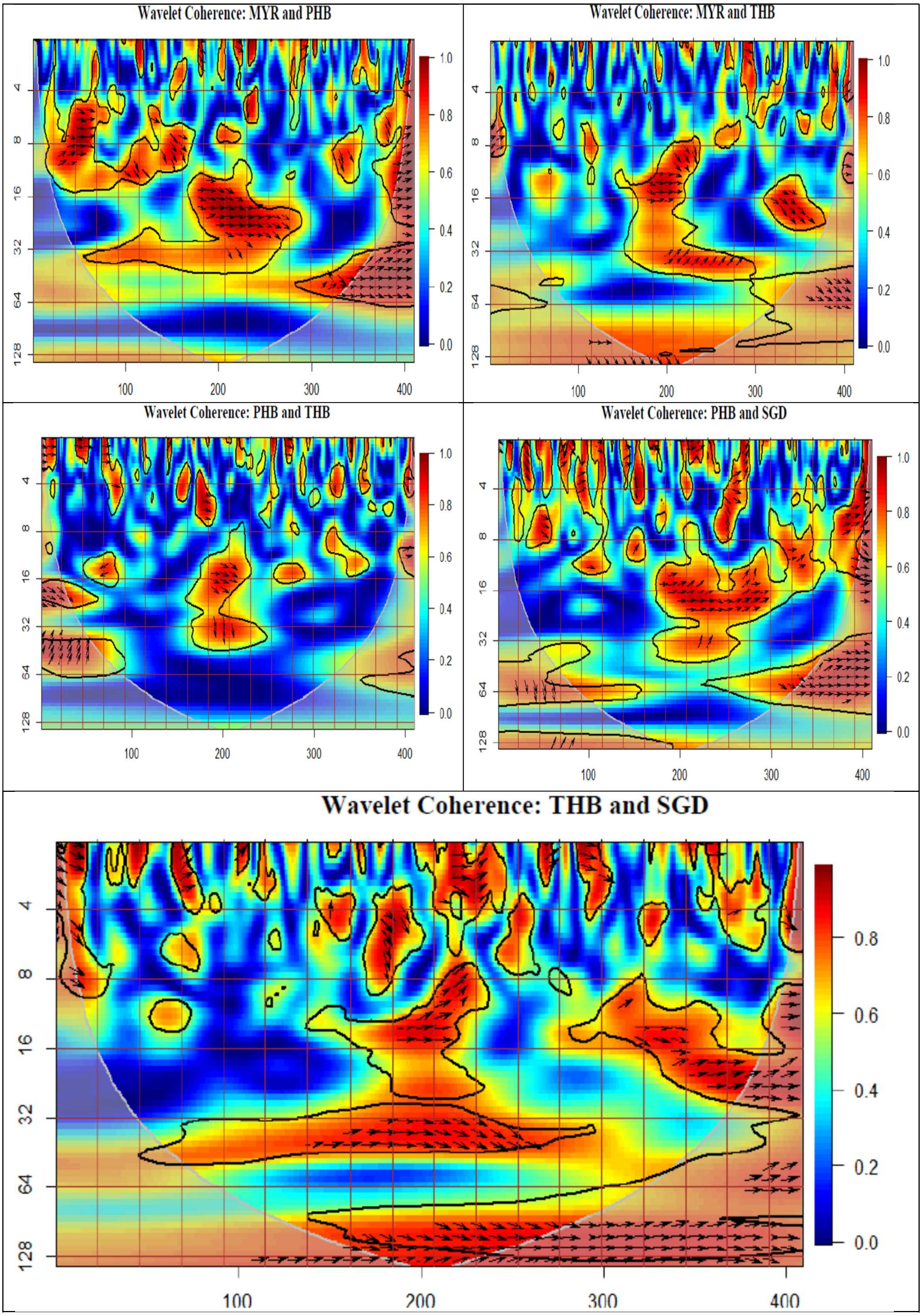
These images show heightened exchange rate volatility (red colour) during the Covid-19 period (at x-axis=200) that exists for both short (less than 64 days) and long run period in Indonesia, Malaysia and Singapore. In contrast, the exchange rate volatility effect in the Philippines is very minimal in the short run and doesn't prolong to long run (orange patch that appears at lower frequency band). For Thailand, it also experiences minimal volatility effect in the short run but heightened volatility in the long run.

APPENDIX 3

Wavelet Coherence (Covariance) for ASEAN-5 across Time and Frequency Domain



Wavelet coherence shows the covariance of the two exchange rates across different time and frequency. The degree of co-movement is measured through the coherency ranging from blue (low coherency) to red (high coherency) and regions that have high coherency shows strong local correlation. In addition to the colour ranges, the appearance of arrows shows a phase-difference, meaning the co-movement of these time series at the specified frequency. If $\emptyset_{xy} \in \left[0, \frac{\pi}{2}\right]$, then the two series x and y are said to move in-phase with x leads y; if $\emptyset_{xy} \in \left[-\frac{\pi}{2}, 0\right]$, then y leads x. The two series move anti-phase when $\emptyset_{xy} \in \left[\frac{\pi}{2}, \pi\right]$with y leading, or $\emptyset_{xy} \in \left[-\frac{\pi}{2}, -\pi\right]$ with x leading.



REFERENCES

Aguiar-Conraria, L., Soares, M.J. (2011). Business cycle synchronization and the Euro: a wavelet analysis. *Journal of Macroeconomics,* vol. 33, 477–489.

Amornbunchornvej, C., Zheleva E., and Berger-Wolf, T. (2019). Variable-lag Granger Causality for Time Series Analysis in: 2019 IEEE International Conference on Data Science and Advanced Analytics (DSAA). IEEE. 2019, pp. 21–30

Aprilianti, I. (2019). ASEAN Intra-Trade Integrations: do they really work? *SSRN Electronic Journal*. doi: 10.13140/RG.2.2.12732.18561

Baker, S. R., Bloom, N., Davis, S. J., Kost, K., Sammon, M., & Viratyosin, T. (2020). The Unprecedented Stock Market Reaction to COVID-19. *The Review of Asset Pricing Studies*. doi:10.1093/rapstu/raaa008

Beckmann, J., Belke, A., & Dobnik, F. (2012). Cross-section dependence and the monetary exchange rate model–A panel analysis. *The North American Journal of Economics and Finance*, 23(1), 38–53.

Beirne, J., Caporale, G.M., Schulze-Ghattas, M., & Spagnolo, N. (2010). Global and regional spillovers in emerging stock markets: a multivariate GARCH-in-mean analysis. *Emerging Market Review*, vol. 11, 250–260.

Candelon, B., & Tokpavi, S. (2016). A nonparametric test for granger causality in distribution with application to financial contagion. *Journal of Business & Economic Statistics*, 34(2), 240-253.

Calvo, S., & Reinhart, C. (1996). Capital flows to Latin America: Is there evidence of contagion effects? In Private Capital Flows to Emerging Markets After the Mexican Crisis. *Institute for International Economics*, Washington, DC.

Cheung, Y., & Lai, K. S. (1993). A Fractional Cointegration Analysis of Purchasing Power Parity. *Journal of Business & Economic Statistics, 11*(1), 103. doi:10.2307/1391310

Chung, T., & Ariff, M. (2015). ASEAN Financial Market Integration -- A Rainbow on the Horizon? *SSRN Electronic Journal*. doi:10.2139/ssrn.2711294

Dewandaru,G., Masih, R., & Masih, M. (2017). Regional spillovers across transitioning emerging and frontier equity markets: A multi-time scale wavelet analysis, *Economic Modelling,* Vol. 65, 30-40, https://doi.org/10.1016/j.econmod.2017.04.026.

Eichengreen, B., Rose, A.K., & Wyplosz, C. (1996). Contagious currency crises: first tests. Scand. *Journal of Economics*. 98, 463–484.

Engle, R. F., & Granger, C. W. (1987). Co-Integration and Error Correction: Representation, Estimation, and Testing. *Econometrica, 55*(2), 251. doi:10.2307/1913236

Forbes, K.J., & Rigobon, R. (2002). No contagion, only interdependence: measuring stock market comovements. *Journal of Finance*, 57, 2223–2261

Frexedas, O. V., & Vayá, E. (2005). Financial contagion between economies: an exploratory spatial analysis. *Estudios De economia aplicada*, 23(1), 151-165.

Hurley, D.T., & Santos, R.A. (2001). Exchange rate volatility and the role of regional currency linkages: the ASEAN case, *Applied Economics*, 33:15, 1991-1999, doi: 10.1080/00036840010023779

Jeon, B. N., & Lee, E. (2002). Foreign exchange market efficiency, cointegration, and policy coordination. *Applied Economics Letters*, 9(1), 61–68.

Kaminsky, G.L., Schmukler, S.L. (1999). What triggers market jitters? A chronicle of the Asian crisis. *Journal of International Money Finance*. 18 (4), 537–560.

Klyueve, K. & Dao, T.N. (2016). Evolution of Exchange Rate Behavior in the ASEAN-5 Countries. *IMF Working Paper.* WP/16/165.

Kollias, C., Manou, E., Papadamou, S., & Stagiannis, A. (2011). Stock markets and terrorist attacks: Comparative evidence from a large and a small capitalization market. *European Journal of Political Economy, 27*. doi:10.1016/j.ejpoleco.2011.05.002

Kühl, M. (2010). Bivariate cointegration of major exchange rates, cross-market efficiency and the introduction of the Euro. *Journal of Economics and Business*, 62(1), 1–19.

Kumar, M. S., & Persaud, A. (2002). Pure contagion and investors' shifting risk appetite: analytical issues and empirical evidence. *International Finance*, 5(3), 401-436.

Lee, C., & Azali, M. (2010). Currency Linkages Among Asean. *The Singapore Economic Review, 55*(03), 459-470. doi:10.1142/s0217590810003845

Majid, M.S.A. & Kassim, S.H. 2009. Impact of the 2007 US financial crisis on the emerging equity markets. *International Journal of Emerging Markets* 4(4): 341–357.

Mondria, J., & Quintana-Domeque, C. (2013). Financial contagion and attention allocation. *The Economic Journal*, 123(568), 429-454.

Nikkinen, J., Pynnönen, S., Ranta, M., & Vähämaa, S. (2011). Cross–dynamics of exchange rate expectations: A wavelet analysis. *International Journal of Finance & Economics*, 16(3), 205–217.

Nicola, M., Alsafi, Z., Sohrabi, C., Kerwan, A., Al-Jabir, A., Iosifidis, C., & Agha, R. (2020). The socio-economic implications of the coronavirus pandemic (COVID-19): A review. *International Journal of Surgery, 78*, 185-193. doi:10.1016/j.ijsu.2020.04.018

Omrane, W. B., & Savaşer, T. (2017). Exchange rate volatility response to macroeconomic news during the global financial crisis. *International Review of Financial Analysis, 52*, 130-143. doi:10.1016/j.irfa.2017.05.006

Ong, S. L., & Sato, K. (2018). Regional or global shock? A global VAR analysis of Asian economic and financial integration. *The North American Journal of Economics and Finance, 46*, 232-248. doi:10.1016/j.najef.2018.04.009

Park, Y. C., & Song, C. Y. (2001). Financial contagion in the East Asian crisis: With special reference to the Republic of Korea in *International financial contagion* (pp. 241-265). Springer, Boston, MA.

Pesenti, P. & Tille, C. (2000). The Economics of Currency Crises and Contagion: An Introduction. *Federal Reserve Bank of New York (FRBNY) Economic Policy Review.,*

Phillips, P.C.B., 1991. Optimal Inference in Cointegrated Systems. *Econometrica* 59: 283-306.

Qureshi, S., & Aftab, M. (2020). Exchange Rate Interdependence in ASEAN Markets: A Wavelet Analysis. *Global Business Review,* 097215092091937. doi:10.1177/0972150920919371

Salgado, M. R., Ricci, M. L. A., & Caramazza, M. F. (2000). Trade and financial contagion in currency crises (No. 0-55). *International Monetary Fund*.

Saurav, A., Kusek, P., Kuo, R. & Viney, B. (2020, Oct. 6). The impact of Covid-19 on foreign investors: Evidence from the second round of a global pulse survey. https://blogs.worldbank.org/psd/impact-covid-19-foreign-investors-evidence-second-round-global-pulse-survey

Tamakoshi, G., & Hamori, S. (2014). Co-movements among major European exchange rates: A multivariate time varying asymmetric approach*. International Review of Economics & Finance*, 31, 105–113.

WHO (2020), available at: www.euro.who.int/en/health-topics/health-ergencies/coronavirus-covid19/news/news/2020/3/who-announces-covid-19-outbreak-a-pandemic (accessed 23 September 2020).

Xiangcai M. & Chia-Hsing, H. (2019). The time-frequency co-movement of Asian effective exchange rates: A wavelet approach with daily data, *The North American Journal of Economics and Finance*, Volume 48, 2019, Pages 131-148. https://doi.org/10.1016/j.najef.2019.01.009.

AUTHORS

Dr Nur Ain Shahrier is Senior Lecturer at Sunway University Business School's Department of Economics and Finance. Prior to joining academia, she was an economist at the Central Bank of Malaysia (BNM) and a consultant for the Asian Development Bank and Malaysia's Ministry of Human Resource. Dr Nur Ain holds a PhD in Regional Science (concentration in macroeconomics and economic development), Master of Science in Regional Science and Master of Engineering in Financial Engineering from Cornell University, and a Bachelor of Science (Honors) in Actuarial Science, Economics and Mathematics from University of Iowa. Her research focuses on regional macroeconomics policies, monetary policies, growth and poverty using various empirical methodology including Econometrics and Computable Financial General Equilibrium (FCGE) Method.

Dr Chung Tin Fah is Associate Professor at the ELM Graduate School of HELP University. He specialises in quantitative finance and economics. His industry experience of over 30 years covered regulatory, corporate and consulting aspects in institutions like Bank Negara Malaysia, Securities Commission, SOCSO and investment banks. His writings on finance and economics have appeared in scholarly journals and as book chapters. He has also provided commentary to the national press. He is an independent member of the Market Participants Committee of the Malaysian Stock Exchange, and past member of the RAM Rating Committee. He has undertaken consultancies for the Malaysia Tax Foundation, Rating Agency Malaysia, Securities Commission, World Bank and the government of Malaysia. Dr Chung was a Malaysian Institute of Certified Public Accountants (MICPA) examiner. He is a reviewer for the Journal of Economic Studies and Journal of the International Academy for Case Studies, and a member of the editorial board of Issues in Economics and Business.

Comments on the working paper can be directed to Dr Nur Ain Shahrier, Department of Economics and Finance, Sunway University Malaysia. (nurains@sunway.edu.my).

The Jeffrey Cheah Institute on Southeast Asia is an independent public policy think tank, based at Sunway University on the outskirts of the Malaysian capital, Kuala Lumpur. The Institute's research programme is grouped around three core disciplines: economic development, governance and social progress, including education. Its mission is to develop solutions to some of the region's most pressing development problems. JCI seeks to engage policymakers, scholars and ordinary citizens through regular public lectures and discussions, and to build lasting academic partnerships in the region and the wider Asia-Pacific.

jci@sunway.edu.my | jeffreycheahinstitute
www.jci.edu.my | jeffreycheahinst

The Jeffrey Sachs Center on Sustainable Development is a regional center of excellence that advances the achievement of the 17 Sustainable Development Goals (SDGs) in Malaysia and Southeast Asia, tackling the sustainability agenda through education, training, research and policy advisory. Launched in December 2016, the Center operates out of Sunway University and was borne out of a $10 million gift from the Jeffrey Cheah Foundation (JCF) to the UN Sustainable Development Solutions Network (SDSN).

jsc@sunway.edu.my | jeffreysachscenter
www.jeffreysachs.center | jeffreysachscenter