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Edson Zambon Monte and Lucas Barbosa Defanti

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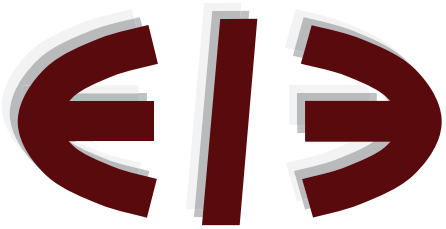

EERI
Economics and Econometrics Research Institute
Avenue Louise
1050 Brussels
Belgium

Tel: +32 2271 9482
Fax: +32 2271 9480
www.eeri.eu

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Edson Zambon Monte (corresponding author)
Department of Economics, Research Group in Econometrics (GPE), Federal University of Espírito Santo (UFES), Avenue Fernando Ferrari, 514, Goiabeiras, Vitória, Espírito Santo, Brazil, Code: 29075-910, edsonzambon@yahoo.com.br

Lucas Barbosa Defanti
Federal University of Espírito Santo (UFES)

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Abstract: the main aim of this paper is to verify the dynamic interdependence and transmission of volatility from the American (SP500) to the Brazilian stock market (IBOVESPA and sectoral indexes). Estimates were performed by GARCH/BEKK methodology, considering the period from January 2007 to December 2019. In the periods considered as "critical events" there was a significant increase in the conditional covariance between SP500 and Brazilian stock indexes (IBOVESPA and sector indices), which suggests for the hypothesis of financial contagion. The covariance increased more intensely and persistently during the so-called subprime crisis, one that had a major impact on the Brazilian economy, especially for the financial and industrial indexes. Furthermore, conditional variance estimates for Brazilian indexes revealed that that internal turmoil, whether economic or political, regardless of the international scenario ("critical events"), affected the volatility of the Brazilian stock market. These results have important implications regarding the future decisions of economic agents (politicians and investors), contributing to a better understanding of the behavior of the Brazilian stock market vis-à-vis the American stock market and the internal turbulences in the Brazilian economy, whether political or economic.

Keywords: United States; Brazil; Stock Market; Volatility; GARCH-BEKK.

JEL Classification: G17; C32; C58.

1. Introduction

According to Fuinhas, Marques e Noqueira (2014), with the development of information and communication technologies, globalization has been enhanced, integrating several economies around the world, driving, mainly, the integration of financial markets. The advancement of technologies has increased the speed, diffusion and availability of information, creating an environment with extreme speed for exchanging information and allocating capital across the world. This, together with the liberalization of emerging markets, helped to systematically increase capital flows to foreign markets, further intensifying the integration of financial markets. The integration process made access to international capital markets more viable, reducing costs for both foreign investors and national companies. The greater financial opening of economies reduces the costs of international transactions, facilitating and intensifying the process of economic integration.

Over the last two decades, the debates on financial integration have intensified, especially when global economic crises occur. According to Billio et al. (2015), it is fundamental to measure the co-movements (interrelationships) and to verify the evolution over time of the financial markets, since such correlations tend to guide economic agents (politicians and investors) in their future decisions. In terms of empirical analysis of the interrelationships in the financial markets, two main sets of studies can be cited: i) those based on the evolution models of financial assets, which assume that financial markets are efficient; and ii) studies on the analysis of the evolution of the correlations and co-movements of the prices of the traded assets. To Fuinhas, Marques and Nogueira (2014), globally, the degree of financial integration enables a perception about the behavior of the capital flow between the economies (countries); thus, being crucial in the understanding of the co-movement of markets.

To Lahrech and Sylwester (2013), Lee (2013) and Yu, Fung and Tam (2010), financial integration is beneficial to countries in terms of financial stability, contributing to economies to absorb shocks and promoting development. However, in times of crisis, the increase in risk

aversion and liquidity preference by foreign investors may lead to capital flight, influencing both real and financial side of economies (Ferreira and Mattos, 2014). In the case of the financial side, the negative impacts occur mainly due to the greater variability of stock returns. According to Lane (2012), once a crisis occurs, globalization (financial integration) serves as a buffer against the crisis for some countries, while amplifying the crisis for others.

It is important to say that with the integration of stock markets in different countries, as consequence of the advances in market opening policies and information technology, the volatility of one market may spread to others, a movement called a "contagion effect". The "contagion effect" reflects the behavior of agents in asset markets, such as risk aversion, influencing the composition of investment portfolios. Furthermore, the "contagion effect" mainly affects emerging markets that have the highest degree of risk and the least developed markets.

Forbes and Rigobon (2002) define financial contagion as a significant increase in interrelationships between markets after a shock in one country or group of countries. It is noteworthy that if two or more markets have high interrelations in periods of stability, even if these markets remain highly correlated after a market shock, this is not contagion. The correct term for this would be interdependence, which indicates a strong link between these markets. Therefore, to Forbes and Rigobon (2002), the consolidation of contagion occurs only if, after a shock, the interrelations increase significantly. This definition is in line with the very restrictive definition of the World Bank (Billio and Caporin, 2010): the "contagion effect" must be interpreted as a significant change in the mechanisms of transmission of international shocks, when a period of turbulence occurs. By this definition, contagion can be measured by the significant increase in correlations between markets in different countries.

Among the countries in Latin America, Brazil can be highlighted, which together with the other BRICS countries, showed greater economic growth after the 1990s and became more integrated with developed economies (Mensi et al., 2014). These countries account for more than a quarter of the territory, more than 40% of the population and about 15% of the world's GDP. For these reasons, in addition to the observation of accelerated growth and the expectation of great potential growth, international investors have shown greater interest in the BRICS. Brazil, at the center of the interests of international investors, has attracted huge capital flows since the economic liberation. This movement had important implications for the capitalization of the Brazilian stock market, as well as its financial interdependence with other stock markets.

In this context, the purposes of this paper is to verify the dynamic interdependence and transmission of volatility from the American (SP500) to the Brazilian stock market (São Paulo Stock Exchange Index – IBOVESPA (IBOV); Consumption Index – ICON; Electric Energy Index – IEE; Financial Index – IFNC; and, Industrial Sector Index – INDX), in some "critical events", as the subprime crisis (strong negative effects) and the United States debt-ceiling crisis (milder negative effects). As a secondary aim, the work estimates the conditional variances of the index returns, in order to verify whether internal turmoil, for example, economic or political, regardless of the international scenario ("critical events"), affected the volatility of the Brazilian stock market.

This research covers the period from 2007 to 2019 (daily data). The methodology adopted was the General Autoregressive Conditional Heteroscedasticity (GARCH) model, specifically the GARCH-BEKK method (Engle and Kroner, 1995).

This paper is structured as follows. In addition to this introduction, section 2 provides a literature review. Section 3 presents the GARCH-BEKK multivariate model. The results and discussions are demonstrated in section 4. Finally, concluding remarks are presented in section 5.

2. Literature review

Several works study the interrelationships between the international financial markets. This section shows some of these studies, specifically research for the Brazilian stock market[1].

Goetzmann, Li and Rouwenhorst (2005) analyzed the correlation structure of the main stock markets in the world, considering a period of more than 150 years. Results revealed that the correlations varied considerably over time, being higher during periods of economic and financial integration, such as the 19th and 20th centuries, and that the benefits of diversifying global investments are not constant. The authors divided the benefits of diversification into two parts: a component that is due to the variation in the average correlation between markets, and a component that is due to the variation in the set of investment opportunities. There are periods when the set of opportunities expands dramatically, and the benefits of diversification are mainly driven by the existence of marginal markets. For other periods (such as the two decades following World War II), the risk reduction comes from the low correlation between the main national markets. Therefore, periods of globalization present advantages and disadvantages for international investors. These periods expand the set of opportunities, but diversification increasingly depends on investments in emerging markets.

Carrieri, Errunza and Hogan (2007) studied eight emerging markets (Argentina, Brazil, Chile, India, Korea, Mexico, Taiwan and Thailand), from 1976 to 2000, and used the GARCH-M methodology to estimate the degree of integration between these markets, based on the Errunza-Losq model (1985). Results revealed that, although local risk was the most relevant factor to explain the temporal variation in returns from emerging markets, the global risk was also priced for some countries. The authors found that there are major differences in the markets with respect to the degree of integration. In addition, there was a significant increase in the degree of integration in the 1990s. Finally, the development of the financial market, the macroeconomic development and the financial liberalization played an important role in the integration of emerging markets.

Horvath and Paldalf (2012) studied the degree of interdependence between the main global equity markets, and whether the 2008 global financial crisis changed the interrelationships of global equity markets at general and sectoral level. The authors used daily stock market data from eleven countries (Australia, Brazil, Canada, China, Germany, Hong Kong, Japan, Russia, South Africa, the United Kingdom and the USA), for the period from 2000 to 2010. Sectoral interrelationships were also examined, based on the following sectors: energy, finance, health care, telecommunications and public services. Multivariate GARCH models were adopted. Results revealed that the degree of financial interrelation differs between the stock markets. The United States stock market proved to be strongly correlated with the stock markets of Brazil, Canada and Germany. On the other hand, the stock markets of China and Japan showed the lowest correlations with the rest of the world, although there has been an increase in this integration in the last years analyzed. In subprime crisis, there was an intensification of the interrelationships between the stock markets, demonstrating the severity with which the crisis hit the markets. Regard to results for the sectors, they indicated that although the sectorial indexes have less correlations than the market indexes, the correlation between them also increased during the crisis.

Perobelli, Vidal and Securato (2013) found evidence of a contagious effect between fifteen countries in eight periods of financial crisis, with the American subprime crisis being the last of these periods. The methods used by the authors were Principal Component Analysis (PCA) and the factor analysis (FA). Daily data from the stock market of each country were

[1] To analyze financial integration (and co-movements) between countries, the researches have used several methodologies and indicators. Billio et al. (2015) make a good description of the different methods adopted to analyze financial integration, demonstrating some of its advantages and disadvantages.

used, during the period of each global financial crisis. The period considered for the subprime crisis was from 07/26/2007 to 03/17/2009. Results showed that Brazil, USA, France and Japan were the countries most affected. These countries were negative affected in all periods studied. In addition, in the subprime crisis, Brazil was the country with the greatest indication of financial contagion.

Yunus (2013) used the recursive cointegration technique to analyze the dynamic interdependence between ten major stock markets in North America, Europe, Latin America and Asia. Using daily frequency data, the analysis covered a period from January 1993 to December 2008. Results indicated that the international stock markets are integrated and that the degree of integration between these markets has increased over time. The study found that the USA, Japan, India, China, the United Kingdom and Germany led the other markets, with the USA being the one that contributed most strongly to the common trend. In addition, the great financial crisis has increased the level of convergence between these markets, mainly between Brazil and the USA, indicating that lucrative portfolio diversification opportunities are limited in the main markets and that these benefits were further reduced during the global financial turmoil in 2008.

Donadelli and Paradiso (2014) analyzed the dynamics of the financial integration process through the stock market of an emerging global region (Argentina, Brazil, Chile, China, Colombia, Hungary, India, Malaysia, Mexico, Pakistan, Peru, Philippines, Poland, Russia, South Africa, Sri Lanka, Thailand and Turkey) and three emerging sub-regions (Asia, Eastern Europe and Latin America). The principal components analysis was used as methodology. Two main results were found: i) it was observed that the level of integration between the emerging stock markets in emerging regions is quite low, both at the country and industry levels; and ii) the form of the financial integration process was not homogeneous between different industries. It is noteworthy that, for the authors, a low level of financial integration tends to increase the benefits of portfolio diversification, but produces an inefficient international risk-sharing environment.

Mensi et al. (2014), using a quantile regression (QR) approach, examined the dependency structure between the emerging stock markets of BRICS countries and influential global factors. These global factors are: the main global stock market represented by the S&P 500; the price of crude oil WTI (West Texas Intermediate) in dollars; the price of gold in dollars; the implied volatility of the S&P 500 represented by the VIX index (Volatility Index); and the US economic policy uncertainty index. The analysis considered the period from September 29, 1997 to September 20, 2013. The main results for the Brazilian stock market revealed that the dependence between Brazil and the USA increases during the bull market and decreases in the bear market. In addition, volatility had a significant and negative impact on the Brazilian stock market throughout the period.

Fuinhas, Marques and Nogueira (2014) analyzed as the greater integration in the global financial markets affects the behavior of international capital flows and the returns of investors. The authors used the Vector Auto Regressive (VAR) and Vector Error Correction (VEC) models, using daily data, from January 1994 to November 2013, for the S&P 500, FTSE 100, PSI20, HSI and IBOVESPA indexes. Results rejected the existence of a long-term relationship between the indices, but confirmed that international diversification brought greater profitability as a benefit. Regarding to IBOVESPA, the results showed that the Brazilian stock market suffered contagion from all other indexes during the period studied, mainly from the S&P 500.

Nasser and Hajilee (2016) examined the integration of the stock market between five selected emerging markets (Brazil, China, Mexico, Russia and Turkey) and developed markets (USA, United Kingdom and Germany), using the period from January 2001 to December 2014. The cointegration approach (VEC) was used to determine the short and long-term relationship

between the emerging stock markets and the returns of developed stock markets. Results showed that, in the short term, all stock exchanges in emerging countries were integrated with developed markets. The long-term coefficients for stock exchange returns in all emerging countries showed a significant relationship only with the return of the German stock exchange.

It is important to say that there are some studies that specifically study the Brazilian financial market, either at the general level (IBOVESPA) or at the sectoral level (sectorial indexes). Among the studies, one can cite Jubert et al. (2008), which analyzed the univariate volatility pattern of following Brazilian market stock indexes: IBOVESPA, IEE, Corporate Sustainability Index (ISE), INDX and Telecommunications Index (ITEL). Medeiros (2012), by means of univariate conditional heteroscedasticity approach, analyzed the volatility of four sectoral financial indexes of BOVESPA: IEE, ITEL, IFNC and INDX. Ferreira and Mattos (2014) adopted the multivariate GARCH-BEKK model to verify the contagion effect of the subprime crisis on the Brazilian indexes: IBOVESPA, ITEL, Real Estate Index (IMOB), IEE, IFNC, INDX and ICON; period from January 2007 to December 2010. The authors used the conditional correlation and the results showed contagion effect.

The main differences regarding to other studies for Brazilian stock market, and, therefore, the contributions of this paper to the literature, especially in relation to Brazil, are: i) use of the multivariate GARCH model; ii) analyzes were carried out for the IBOVESPA and some sectoral indices, which allows to verify if there is heterogeneity in the effects of the American market on each sectorial index; iii) analyses covers the period from January 2007 to December 2019, in order to capture possible increases in interdependence in other periods beyond the subprime crisis; and iv) conditional estimates were performed for correlation, covariance and variances. Thus, by means of conditional variance, it is possible to verify whether internal turbulences, for example, economic or political, regardless of the international scenario ("critical events"), affected the volatility of the Brazilian stock market.

3. Multivariate GARCH-BEKK model

The general description of the multivariate GARCH model was based on Bauwens, Laurent and Rombouts (2006) and Bueno (2011). For this, suppose a stochastic vector $\{\boldsymbol{y}_t\}$ of dimension $N \times 1$, conditioned to a sigma space, denoted by $\boldsymbol{F}_{t-1}$, with past information available at time $t-1$. Let $\boldsymbol{\theta}$ be a finite vector of parameters. Then

$$\boldsymbol{y}_t = \boldsymbol{\mu}_t(\boldsymbol{\theta}) + \boldsymbol{\varepsilon}_t, \tag{1}$$

where $\boldsymbol{\mu}_t(\boldsymbol{\theta})$ is a conditional mean vector, and

$$\boldsymbol{\varepsilon}_t = \boldsymbol{\Sigma}_t^{\frac{1}{2}}(\boldsymbol{\theta})\boldsymbol{z}_t, \tag{2}$$

where $\boldsymbol{\Sigma}_t^{\frac{1}{2}}(\boldsymbol{\theta})$ is a positive definite matrix of dimension $N \times N$ and $\boldsymbol{z}_t$ is a white noise vector of dimension $N \times 1$,

$$E(\boldsymbol{z}_t) = 0, \tag{3}$$
$$Var(\boldsymbol{z}_t) = \boldsymbol{I}_N, \tag{4}$$

where $\boldsymbol{I}_N$ is a N-dimensional identity matrix.

The matrix $\boldsymbol{\Sigma}_t^{\frac{1}{2}}$, which represents the conditional covariance matrix, is represented by

$$Var(\boldsymbol{y}_t|\boldsymbol{F}_{t-1}) = Var_{t-1}(\boldsymbol{y}_t) = Var_{t-1}(\boldsymbol{\varepsilon}_t),$$
$$Var(\boldsymbol{y}_t|\boldsymbol{F}_{t-1}) = \boldsymbol{\Sigma}_t^{\frac{1}{2}} Var_{t-1}(\boldsymbol{z}_t)(\boldsymbol{\Sigma}_t^{\frac{1}{2}})',$$
$$Var(\boldsymbol{y}_t|\boldsymbol{F}_{t-1}) = \boldsymbol{\Sigma}_t. \quad (5)$$

Thus, $\boldsymbol{\Sigma}_t^{\frac{1}{2}}$ is a positive definite matrix of dimension $N \times N$, such that $\boldsymbol{\Sigma}_t$ is a conditional covariance matrix of $\boldsymbol{y}_t$. The vectors $\boldsymbol{\mu}_t$ and $\boldsymbol{\Sigma}_t$ depend on the unknown parameters vector $\boldsymbol{\theta}$. If $E(\boldsymbol{\varepsilon}_t\boldsymbol{\varepsilon}_t'|\boldsymbol{F}_{t-1}) = \boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}} > \boldsymbol{0}$, the process given in Equation (1) becomes a multivariate process with time-invariant covariance.

Bollerslev (1986) proposed one of the first multivariate GARCH models, called Full Vech. In this case, the variance-covariance matrix $\boldsymbol{\Sigma}_t$ is measured with past information available until time $t-1$, being parametrically generated by the process $\boldsymbol{F}_{t-1}$. The vector $\boldsymbol{\varepsilon}_t$ follows a multivariate GARCH process, considering the Full Vech specification, if

$$\boldsymbol{\varepsilon}_t|\boldsymbol{F}_{t-1} \sim N(0, \boldsymbol{\Sigma}_t), \quad (6)$$
$$vech(\boldsymbol{\Sigma}_t) = \boldsymbol{C} + \Sigma_{i=1}^{q} \boldsymbol{A}_i vech(\boldsymbol{\varepsilon}_{t-i}\boldsymbol{\varepsilon}_{t-i}') + \Sigma_{j=1}^{p} \boldsymbol{B}_j vech(\boldsymbol{\Sigma}_{t-j}), \quad (7)$$

where vech(.) denotes the half-vectorization operator which stacks the columns of a square matrix from the diagonal downwards in a vector; $\boldsymbol{\varepsilon}_{t-i}$, vector of random disturbances; $\boldsymbol{A}_i$ and $\boldsymbol{B}_j$ are coefficient matrices of dimension $\frac{N(N+1)}{2} \times \frac{N(N+1)}{2}$, with $i = 1, \dots, q$ and $j = 1, \dots, p$; $\boldsymbol{C}$ is a column vector of time invariant variance/covariance components of dimension $\frac{N(N+1)}{2} \times 1$; and, $\boldsymbol{\Sigma}_t$ is a conditional variance/covariance matrix of dimension $N \times N$.

The Full Vech model is quite general, having as one of its advantages the analysis of the (dynamic) dependence between the series with volatility. However, the model has some shortcomings, such as: i) the large number of parameters to be estimated; and, ii) imposition of strong constraints on the matrix $\boldsymbol{\Sigma}_t$ so that it is definite positive.

To guarantee that the matrix $\boldsymbol{\Sigma}_t$ be positive at each time point and to reduce the number of estimated parameters, Engle and Kroner (1995) proposed an alternative formulation known in the literature as BEKK model. The specification of the GARCH-BEKK model is given by:

$$\boldsymbol{\Sigma}_t = \boldsymbol{C}'\boldsymbol{C} + \Sigma_{i=1}^{q} \boldsymbol{A}'_i \boldsymbol{\varepsilon}_{t-i}\boldsymbol{\varepsilon}'_{t-i}\boldsymbol{A}_i + \Sigma_{j=1}^{p} \boldsymbol{B}'_j \boldsymbol{\Sigma}_{t-j}\boldsymbol{B}_j, \quad (8)$$

where $\boldsymbol{\Sigma}_t$ is a positive definite conditional covariance matrix of dimension $N \times N$, available at time $t-1$; $\boldsymbol{\varepsilon}_t$ is the vector of innovations; $\boldsymbol{C}$ is upper triangular matrix; $\boldsymbol{A}_i$ and $\boldsymbol{B}_j$ are coefficient matrices of dimension $N \times N$. The decomposition of $\boldsymbol{C}$ in $\boldsymbol{C}'\boldsymbol{C}$ ensures that $\boldsymbol{\Sigma}_t$ be positive definite. The BEKK model is a special case of the Full Vech model (see, Engle and Kroner, 1995).

It should be noted that each specific technique to be employed is linked to one of the definitions of the term contagion. Thus, GARCH family models have been used in studies that investigate the presence of contagion via changes in the dependency structure between a set of financial market returns, a definition proposed by Chang and Majnoni (2002)[2].

4. Results and discussions

[2] There is no consensus among economists about the definition of the "contagion effect" and the best way to test it empirically; therefore, there is no theoretical or empirical identification procedure, whose researchers are unanimous.

This section is structured as follows: firstly, the variables are presented; in the second part, the graphs of the indices and daily returns, the unit root tests and the descriptive statistics of daily returns; the third shows the results of the estimates by GARCH-BEKK model.

4.1. Variables

This study considered the period from January 2007 to December 2019, using daily data[3]. The financial indexes were collected from *Yahoo!Finance* and *BM&FBOVESPA* (Table 1). The Standard and Poor's 500 (SP500) represents the United State stock market, which is composed of the five hundred largest publicly traded companies in the USA, and widely used in studies to represent the American financial market.

The São Paulo Stock Exchange Index (IBOVESPA) is the leading indicator of the average performance of most active and benchmark stocks in the Brazilian equities market. The aim of the ICON is to be the indicator of the average performance of stocks for the most tradable and representative assets in the sectors of cyclical consumption, non-cyclical consumption and health. The objective of the Electric Energy Index (IEE) is to measure average performance tracking changes in the prices of the more actively traded and better representative electricity sector stocks. The aim of the IFNC is to be the indicator of the average performance of stocks for the most tradable and representative assets of the financial intermediaries, miscellaneous financial services, pension and insurance sectors. The objective of INDX is to be the indicator of the average performance of stocks for the most tradable and representative assets of the sectors of industrial activity comprised of basic materials, industrial goods, cyclical consumption, non-cyclical consumption, information technology and health[4].

Table 1

4.2. Graphs, unit root tests and descriptive statistics

Figure 1 shows the evolution of each index (level series) over the period of analysis. It possible to note that the indexes showed great volatility, with growth and decreasing phases, according to global economic conditions. The crisis that began in mid-2007 in the United States (subprime crisis), for example, affected several world economies in terms of economic growth, employment, etc., as well as the financial market. The effects of the subprime crisis were mainly observed in the years 2008 and 2009. Another period that deserves attention refers to the crisis related to the American debt-ceiling, occurred in 2011 (second semester), which led the Standard & Poor's rating agency to review the United State debt note with low bias. This affected investor behavior and generated an increase in volatility in the period.

Figure 1

One of the first steps in the analysis of time series is to verify the stationarity of series. If they are not stationary, some procedure must be applied to make them stationary (in general, the first difference is applied, given that the majority of economic series is I(1), that is, first-order integrated). It should be emphasized that all econometric procedures were performed with the variables expressed in natural logarithms. This research adopted the following unit root tests: Augmented Dickey-Fuller – ADF (Dickey and Fuller, 1981); Phillips-Perron – PP

[3] Since this research works with two distinct markets, United States and Brazil, dates that had no observations for the two markets simultaneously were taken from the sample.

[4] The information related to the indexes of the Brazilian stock market are available in http://www.bmfbovespa.com.br/pt_br/produtos/indices/.

(Phillips and Perron, 1988); and, Kwiatkowski-Phillips-Schmidt-Shin – KPSS (Kwiatkowski et al., 1992). Results revealed that all indexes are non-stationary in level (in logarithms), but they became stationary after applying the first difference in the natural logarithms of the series [$r_t = \ln(y_t) - \ln(y_{t-1})$, where y_t represents each index and r_t the daily returns].

Table 2 demonstrates the basic descriptive statistics of the indexes daily returns (first difference of the natural logarithms). For several index returns, the distributions appear to be asymmetric, since there are positive and negative estimates of skewness. All returns series have heavy tails and show a strong deviation from normality (the skewness and kurtosis coefficients are all different from those of the standard normal distribution, which are 0 and 3, respectively). In addition, Jarque-Bera (JB) test rejected the null hypothesis of normality at a significance level of 5%. According to Maldelbrot (1963) and Fama (1965), excess kurtosis and non-normality are stylized facts regarding financial returns.

Table 2

As previously described, in this paper, to verify if there was a significant increase in the interrelation between the American and Brazilian financial markets, two "critical events" related to the American economy were established: i) subprime crisis; and, ii) United States debt-ceiling crisis of the year 2011. To define the beginning of "critical events", daily newspaper news was used. In the case of the end of the events, an ad-hoc date was adopted, based on the stabilization of the volatility of the American and Brazilian indexes (see Figure 2). In addition, the most critical moments of the two crises were observed. Thus, the following periods were defined: i) subprime crisis, between 09/15/2008 and 03/09/2009; and, ii) United States debt-ceiling crisis, between 08/04/2011 and 12/29/2011. It is possible to see in Figure 2 that there was a significant increase in the volatility of the returns in the periods considered as "critical events", especially in the subprime crisis. Furthermore, in general, the Brazilian index returns followed a similar pattern to the United States index return in terms of volatility. Thus, international financial instabilities, specifically here, related to the United States economy, tend strongly to affect the Brazilian stock market, causing great volatility. According to Akyüs and Conford (1999), given the inherent instability of international capital movements, any country closely integrated with the global financial system is susceptible to financial crises and monetary turbulence.

Figure 2

4.3. Estimates of the GARCH-BEKK model

Firstly, it is worth to say that six bivariate GARCH-BEKK models ($N = 2$, in Equation (8)) were estimated, considering orders $p = q = 1$. The following variables were included in each model: Model 1: DLSP500 and DLIBOV; Model 2: DLSP500 and DLICON; Model 3: DLSP500 and DLIEE; Model 4: DLSP500 and DLIFNC; and, Model 5: DLSP500 and DLINDX.

Moreover, before estimating the bivariate GARCH-BEKK models, it was necessary to filter the series in order to remove the serial correlation. For this, for each bivariate model an autoregressive vector model (VAR) was estimated. The lag orders of the VAR models were determined using the Akaike information criterion (AIC), and verifying the presence of serial correlation by means of Portmanteau and Breusch-Godfrey Lagrange Multiplier tests. Furthermore, in the filtered series (residuals of the VAR models), the presence of conditional heteroscedasticity was verified through the ARCH-LM test (Engle, 1982). Finally, GARCH-

BEKK(1,1) models were estimated in order to verify the interrelationships (co-movements) between the United States and Brazilian stock markets.

Although the parameters do not have direct interpretations in the GARCH-BEKK model, it was observed that many of them were statistically significant at 5% significance (results can be provided upon request). In general, the tests performed for diagnosing the suitability of the models, confirmed their good fit for all indexes. The Ljung-Box and Portmanteau tests rejected the presence of correlation in the residuals of the models in the univariate and multivariate context, respectively, and the Lagrange Multiplier test indicated the rejection of the presence of the ARCH effect in the residuals of the estimated models. Thus, the GARCH-BEKK(1,1) specification was successful in modeling the volatility of returns.

By estimating the conditional covariance equation between markets, it becomes possible to identify significant changes in the pattern of the relationship between the indices, which suggests for the hypothesis of financial contagion. In this paper, in addition to the conditional covariance, the figures also show the conditional correlations between the index returns and the conditional variance of each return. By means of conditional variance, it is possible to verify whether internal turbulences, for example, economic or political, regardless of the international scenario ("critical events"), affected the volatility of the Brazilian stock market.

Figure 3 shows the conditional estimates for correlation, covariance and variance considering the variables DLSP500 and DLIBOV. The conditional correlation reveals that there was a strong link between these markets (interdependence), according to definition of Forbes and Rigobon (2002). However, from conditional covariance, it is possible to note that, in general, there was an increase in covariance between the Brazilian stock market (DLIBOVESPA) and the American market (DLSP500), in the "critical events", with a greater emphasis on the period of the subprime crisis, but also in the period of the United States debt-ceiling crisis, which suggests for the hypothesis of financial contagion.

Furthermore, regarding to estimated variances (DLSP500 e DLIBOV), the estimates show a high volatility increase in periods considered "critical events". This corroborates the studies by Bollerslev, Litvinova and Tauchen (2006) and Hibbert, Daigler and Dupoyet (2008), that is, negative news (events) are associated with a greater increase in volatility than positive news (events). Therefore, negative (positive) innovations of returns are correlated with positive (negative) innovations in volatility, with higher asymmetric effects when returns decline (volatility increases).

Moreover, by means of conditional variances, it is possible to verify that the volatility of the IBOVESPA was greater than the volatility of the variable SP500, when considered periods outside the "critical events". This may reflect the internal problems (economic and political) experienced by the Brazilian economy, especially between 2011 and 2016, which caused reduction in economic growth, fall in the level of employment and purchasing power, among other problems. Economic problems and political instability caused great volatility in the Brazilian stock market, with large falls in the indexes, especially of the IBOVESPA. The SP500 index grew in the same period (Figure 1). Thus, this demonstrates that internal turmoil, whether economic or political, regardless of the international scenario ("critical events"), affected the volatility of the Brazilian stock market.

Figure 3

In order to carry out a more specific analysis of the contagion pattern for each sector/segment of the Brazilian stock market, four Brazilian stock market indexes were selected and evaluated individually. Figure 4 shows the estimates taking into account the variables DLSP500 and DLICON. As in the case of IBOVESPA, the conditional correlation shows interdependence of the consumption index (DLICON) in relation to SP500 (DLSP500). There

was an increase in conditional covariance in the critical events, especially in the period of the subprime crisis. As the sub-prime crisis strongly affected the Brazilian economy, including the household consumption, there were strong negative effects of the subprime crisis on the consumption index (DLICON), even though the Brazilian government has taken measures related to consumption, in order to mitigate the effects of the crisis.

Furthermore, observing the estimated variances, it can verify that DLICON had greater persistence in its volatility than the DLSP500, including several periods of high volatility, which go beyond those considered as "critical events". As the Brazilian economy presented several internal problems after 2011 (economic and political), including problems that resulted in a strong reduction in the Gross Domestic Product (GDP), these problems must have contributed strongly to the high volatility in the consumption. Furthermore, it is worth remembering that ICON is formed mainly by companies of the segments of processed foods, beverages, commerce, services and civil construction, which also has a large representation in the industrial index. Thus, any factor (internal or external) that affects the level of consumption of the Brazilian economy tends strongly to influence both ICON and INDX.

Figure 4

Figure 5 shows the results for DLSP500 and DLIEE. It is possible to verify by the conditional correlation that the electricity sector is also interrelated with the United States stock market. However, in general, conditional correlations are lower than for other indexes. This is corroborated by the lower growth of conditional covariance during "critical events", when compared to other indexes. In addition, it is possible to observe that the Electric Energy Index (DLIEE) presented several periods with significant increases in volatility (including periods beyond to the "critical events" considered in this research), and these increases were maintained for relatively long periods. It is important to say that it is not the object of this research to study which internal factors caused this increase in the volatility of IEE. However, it is noteworthy that the electric power sector is regulated in Brazil, and the sector has undergone several governmental interventions in recent years (mainly between the years 2011 and 2016), including energy prices. Besides, the generation capacity of hydroelectric power plants has been affected by the reduction of rainfall, showing fragility and instability in the sector, which strongly affects the IEE.

Figure 5

Figure 6 shows the conditional estimates for correlation, covariance and variance considering the variables DLSP500 and DLIFNC. As can be noted, conditional correlations followed a pattern similar to the IBOVESPA index (DLIBOVESPA), especially during the subprime crisis. It is worth remembering that companies in the financial sector have a large participation in the formation of IBOVESPA index. In addition, the financial sector index (DLIFNC) showed the highest increase in conditional covariance among sector indexes during the subprime crisis. Regarding to the United States debt-ceiling crisis, the conditional covariance did not change significantly. In terms of estimated variances, the volatilities of DLSP500 and DLIFNC were affected, mainly, in the subprime crisis. Furthermore, in periods outside the "critical events", the volatility of DLINFC was higher than the volatility of DLSP500, demonstrating that the Brazilian financial sector was strongly affected, due to factors such as: risk aversion, capital flight and liquidity preference of foreign investors, among others.

It is worth to say that shocks that occur in the financial market tend to spread to the indexes of other sectors of the economy. As an example, financial market shocks tend significantly to influence the real side of the economy. Crises in the financial market may reduce

bank financing, increase the costs of taking credit, create difficulties in the capital market, reduce the level of savings, among others. These phenomena are propagated to the real side of the economy, affecting the level of economic activity and, consequently, investment decisions (Castro and Bandrão, 2008).

Figure 6

Figure 7 shows the conditional estimates for correlation, covariance and variance considering the variables DLSP500 and DLINDX. Among all the indexes analyzed, with the exception of IBOVESPA, the Industrial Index is the most diversified, consisting of stocks of companies that operate in different segments of the domestic and foreign markets. It is possible to note that conditional covariance increased significantly during the subprime crisis. Thus, the industrial sector, as well as other sectors of the Brazilian stock market, is not free from the shocks resulting from international turbulence, specifically, from those in the United States economy. It is important to say that the Food and Beverage segments represent the largest share in the industrial index. Therefore, negative impacts on these sectors, and consequently on the consumer sector, have a direct impact on the industrial index.

Figure 7

5. Concluding remarks

The aim of this paper is to verify the dynamic interdependence and transmission of volatility from the American (SP500) to the Brazilian stock market (São Paulo Stock Exchange Index – IBOVESPA (IBOV); Consumption Index – ICON; Electric Energy Index – IEE; Financial Index – IFNC; and, Industrial Sector Index – INDX), in some "critical events", as the subprime crisis (strong negative effects) and the United States debt-ceiling crisis (milder negative effects). As a secondary aim, the work estimates the conditional variances of the index returns, in order to verify whether internal turmoil, for example, economic or political, regardless of the international scenario ("critical events"), affected the volatility of the Brazilian stock market. Estimates were performed by GARCH/BEKK methodology, considering the period from January 2007 to December 2019 (daily data).

The conditional correlation reveals that there was a strong link between these markets (interdependence), according to definition of Forbes and Rigobon (2002). However, in periods considered as "critical events" there was a significant increase in the conditional covariance between SP500 and Brazilian stock indexes (IBOVESPA and sector indices), which suggests for the hypothesis of financial contagion. The covariance increased more intensely and persistently during the so-called subprime crisis, one that had a major impact on the Brazilian economy, especially for the returns of the indexes of financial and industrial sectors. In addition, the Electric Energy Index (IEE), which undergoes governmental intervention, and the indexes of the consumption and industry sectors, which received government benefits as a way to mitigate the negative effects of the subprime crisis, showed a significant increase in conditional covariance during the two "critical events". Results revealed that the effects of the American stock market on the sectors were heterogeneous.

Furthermore, the estimated conditional variances for the Brazilian indexes showed which internal turbulences, for example, economic or political, regardless of the international scenario ("critical events"), affected the volatility of the Brazilian stock market.

These results have important implications regarding the future decisions of economic agents (politicians and investors), contributing to a better understanding of the behavior of the Brazilian stock market vis-à-vis the American stock market and the internal turbulences in the

Brazilian economy, whether political or economic. Politicians can adopt as a basis for the provision of public policies. Investors to assist in the management of their investment portfolios.

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Appendix A. Tables

Table 1 – Variables, units, acronyms and sources

Variable	Unit	Acronym	Source
Standard and Poor's 500 Index	Index	SP500	*Yahoo!Finance*
São Paulo Stock Exchange Index	Index	IBOV	*BM&FBOVESPA*
Consumption Index	Index	ICON	*BM&FBOVESPA*
Electric Energy Index	Index	IEE	*BM&FBOVESPA*
Financial Index	Index	IFNC	*BM&FBOVESPA*
Industrial Sector Index	Index	INDX	*BM&FBOVESPA*

Source: own elaboration.

Table 2 – Descriptive statistics of daily returns

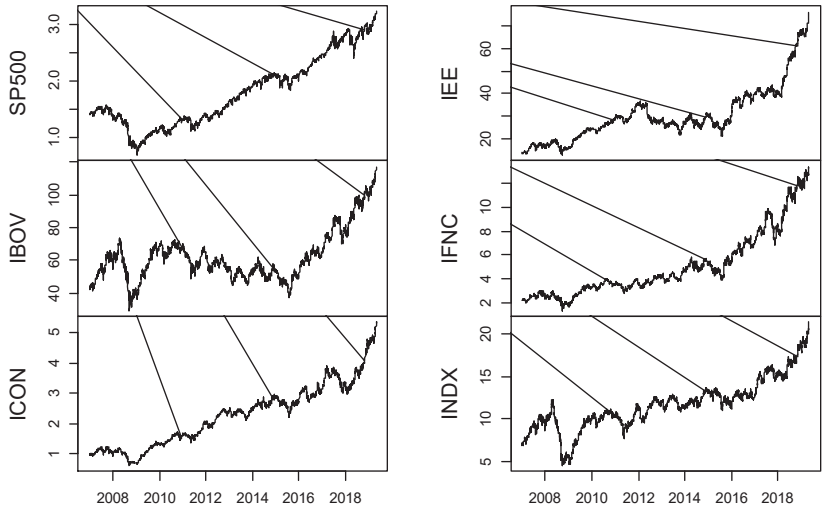
Variável	Mean	Median	Maximum	Minimum	Standard Deviation	Skewness	Kurtosis	Jarque-Bera	P-value
DLSP500	0,0002	0,0006	0,1096	-0,0947	0,0128	-0,3341	13,6400	12530,58	0,0000
DLIBOVESPA	0,0002	0,0007	0,1368	-0,1210	0,0179	0,0102	9,0978	4099,43	0,0000
DLICON	0,0005	0,0010	0,1183	-0,0967	0,0141	-0,1141	9,4548	4599,23	0,0000
DLIEE	0,0004	0,0007	0,1160	-0,1061	0,0135	-0,3525	10,3214	5964,52	0,0000
DLIFNC	0,0005	0,0006	0,1900	-0,1285	0,0200	0,3383	10,4548	6177,47	0,0000
DLINDX	0,0003	0,0007	0,1183	-0,1182	0,0156	-0,1600	10,6585	6477,7470	0,0000

Source: own elaboration based on research data.

Note: 1) D = indicates the first difference of the variable; and, 2) L = variables are in logarithms.

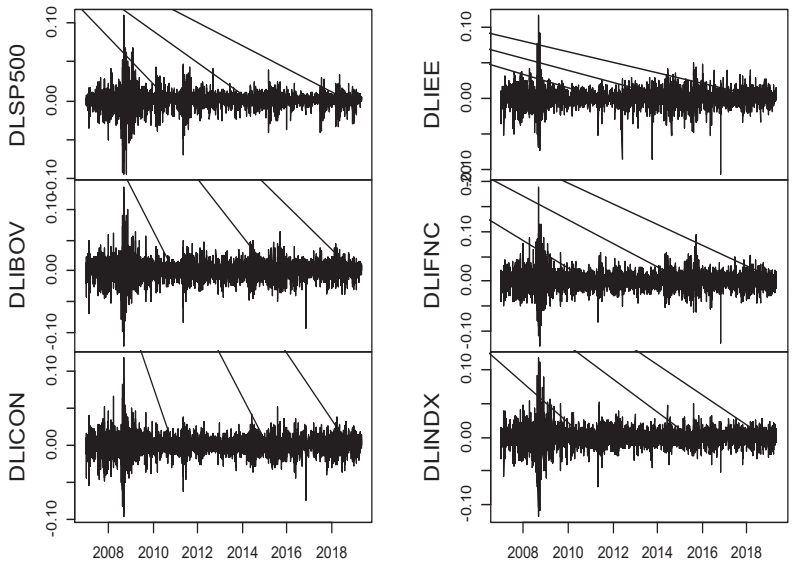
Appendix B. Figures

Figure 1 – Time series evolution (index/1000) in level, from January 2007 to December 2019



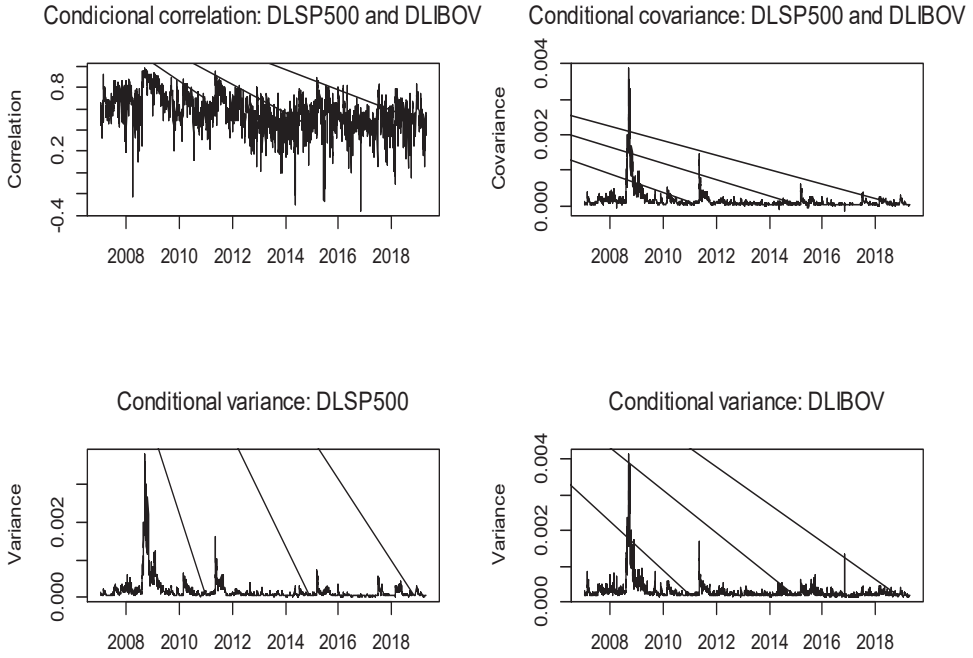
Source: own elaboration based on research data.

Figure 2 – Time evolution of the daily returns



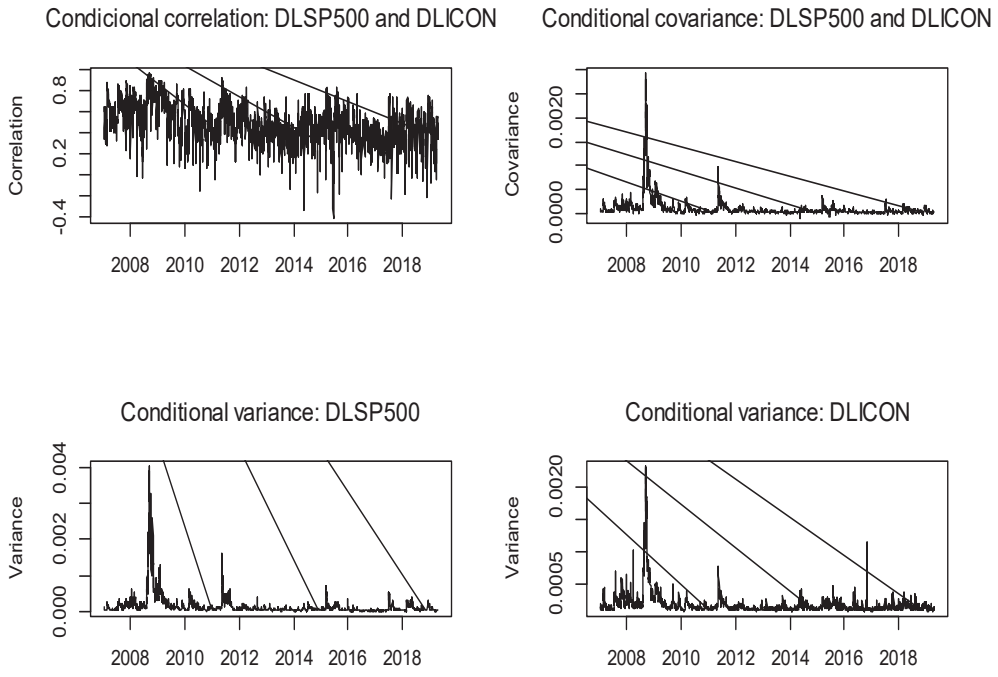
Source: own elaboration based on research data.

Figure 3 – Conditional estimates for correlation, covariance and variance considering the variables DLSP500 and DLIBOV



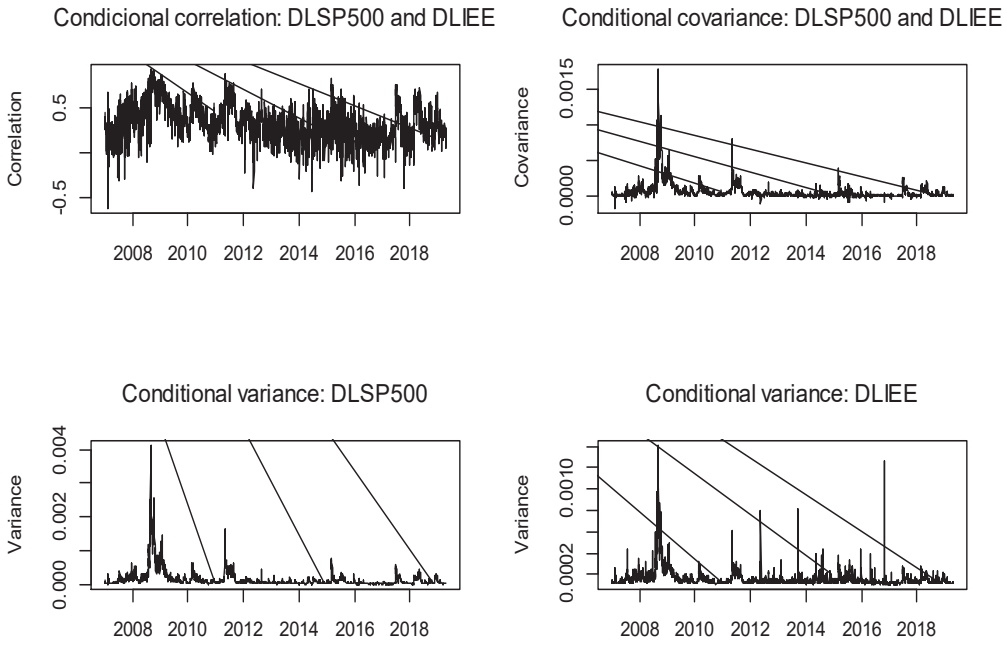
Source: own elaboration based on research data.

Figure 4 – Conditional estimates for correlation, covariance and variance considering the variables DLSP500 and DLICON



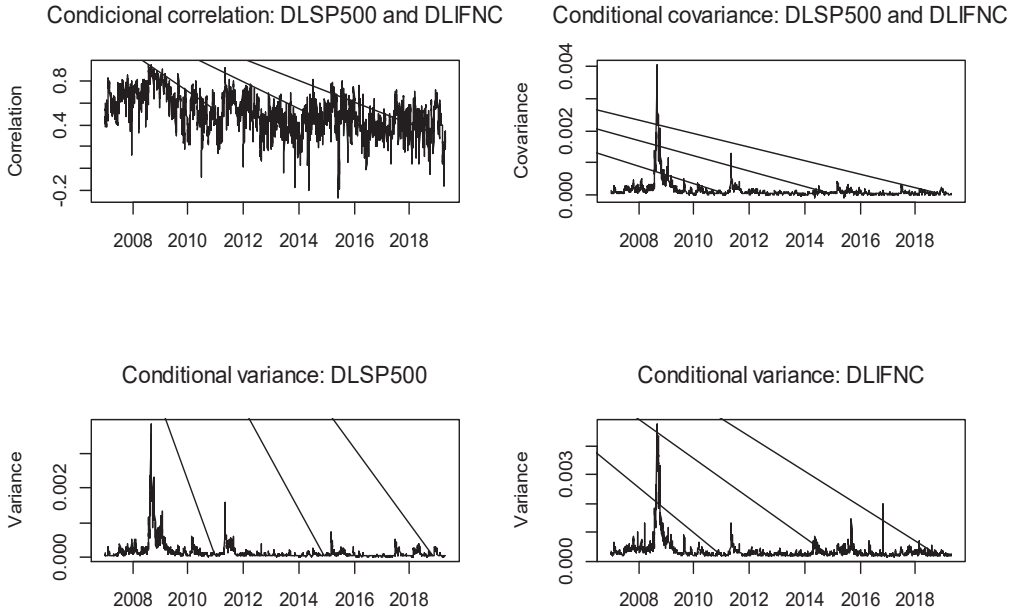
Source: own elaboration based on research data.

Figure 5 – Conditional estimates for correlation, covariance and variance considering the variables DLSP500 and DLIEE



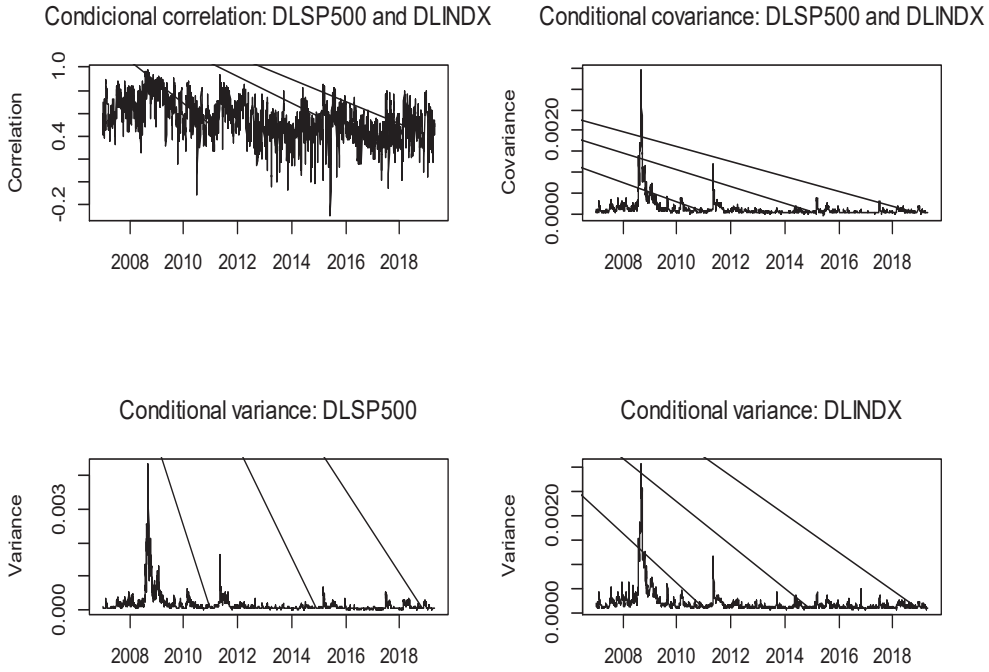
Source: own elaboration based on research data.

Figure 6 – Conditional estimates for correlation, covariance and variance considering the variables DLSP500 and DLIFNC



Source: own elaboration based on research data.

Figure 7 – Conditional estimates for correlation, covariance and variance considering the variables DLSP500 and DLINDX



Source: own elaboration based on research data.